Ph.D. Thesis

Title

Rapid Seismic Evaluation Method and Strategy for Seismic Improvement of Existing Reinforced Concrete Buildings in Developing Countries

発展途上国の既存鉄筋コンクリート造建物の簡略耐震診断と耐震性能向上戦略

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Abstract

Rapid Seismic Evaluation Method and Strategy for Seismic Improvement of Existing Reinforced Concrete Buildings in Developing Countries

Islam Md Shafiul

Past earthquakes in developing countries, such as the 2015 Nepal earthquake (Magnitude 7.8), the 2010 Haiti earthquake (Magnitude 9.0), the 2016 Ecuador earthquake, caused major destruction in structures which resulted in a huge number of fatalities and economic loss. This major destructive earthquake indicates the existence of a huge seismically vulnerable building stock in those earthquake-prone areas. Many nations in earthquake-prone areas are concerned about mitigation of future earthquake disasters to avoid huge loss in infrastructures as well as casualties.

Developing countries which are located in earthquake prone area, such as Bangladesh, do not have experience of recent major earthquakes; however, collapse of existing RC buildings such as Rana Plaza collapse (Dhaka city, Bangladesh) without earthquake also indicates the presence of a large stock of vulnerable buildings. The reason behind is an absence of updated seismic design codes and lack of legal enforcement of national building code. Furthermore, public awareness of safety is also lacking. Therefore, there is an urgent need to conduct seismic capacity evaluation of the existing RC building stock to identify cases where seismic capacity is deficient and take pragmatic action (such as strengthening and/or retrofitting) as countermeasure for future earthquakes. There are several seismic evaluation methods for evaluation of the seismic capacity of existing RC buildings. However, detailed seismic evaluations are very challenging for a large stock of existing RC buildings. There are several reasons for this, including requirements for detailed architectural and structural drawings along with other information that is not available in most of existing RC buildings in developing countries. In addition, there is a lack of expertise, budget, and time to conduct rigorous analysis and calculations, which is generally required for conducting the detailed seismic evaluation. In this regard, identification of the most vulnerable building is one of the effective ways to reduce the aforementioned limitations. Therefore, rapid seismic evaluation is very urgent and promising for managing these huge number of RC buildings stock with limited budget and time.

This research work focuses on the development of a rapid seismic evaluation method for identifying the most vulnerable buildings and proposes a strategy for further detailed

evaluation of existing RC buildings. The development of the rapid seismic evaluation procedure involves understanding and simplification of the fundamental parameters which are required for seismic capacity estimation of existing RC buildings.

The objectives of the research are as follows:

Objective 1: Understand the basic characteristics of existing RC buildings and determine correlations with seismic damage.

Objective 2: Identify the most fundamental parameters that influence the seismic capacity.

Objective (Main Goal) 3: Develop a rapid seismic evaluation method and propose a strategy of detailed evaluation of existing RC buildings.

Significance of the research work:

As mentioned earlier, developing countries have huge stock of vulnerable buildings and are exhibiting interest in preparedness for the future earthquake disasters. Therefore, it is necessary to prepare a strategy or roadmap for the seismic evaluation of huge existing RC buildings stock within limited resources and budget. In this aspects, preliminary screening of existing RC buildings before detail evaluation is an effective strategy for seismic evaluation scheme. Here, preliminary screening stands for the identification of the most vulnerable buildings and prioritizing for detail evaluation. This research proposes a rapid seismic evaluation method for preliminary evaluation to identify the most vulnerable building and provides recommendation for detail evaluation. Furthermore, this research output will be helpful for policy makers to make strategic plan for seismic evaluation scheme of large building stock.

The major findings of this research are as follows:

Chapter 1: Introduction

This chapter described background, problem identification, major objectives and significant of the research and research framework. In background, the requirement of an effective rapid seismic evaluation method has been presented. In this aspect, several existing rapid seismic evaluation methods in different countries have been briefly reviewed. The limitations and shortcomings of existing rapid seismic evaluation method has been explained. Addressing the existing limitations, the research objectives are presented as to development of a rapid seismic evaluation which is effective for preliminary evaluation of existing buildings.

Afterward, research significant and organization of the thesis are presented. Furthermore, several past researches and guidelines related to visual screening, simplified seismic evaluation and detail seismic evaluation of existing building, are discussed.

Chapter 2: Study on past earthquake damage databases

This chapter described the seismic capacity evaluation of past earthquake damaged RC building's database in different developing countries such as Ecuador, Nepal and Taiwan. The main objective of this chapter is to identify the most vulnerable parameters which influence the seismic capacity of RC buildings. This chapter has been divided into two major parts: understanding the basic characteristics of existing building and a correlation has been developed between seismic capacity and damage state of the investigated buildings.

The following conclusions are made as follows:

1) A correlation between basic parameters and seismic damage indicated that column area ratio and masonry infill wall area ratio has good correlation with damage ratio.
2) These simple parameters are regarded as the most influencing parameters for identifying the seismic capacity of existing buildings in other seismic region.
3) A correlation between seismic capacity and damage ratio is useful information to identify the seismic vulnerability of existing RC buildings of those countries where past earthquake recorded building database are not available.

Chapter 3 Study on existing RC buildings in Bangladesh

This chapter presented seismic evaluation of existing RC buildings in developing country where past earthquake damage database is not available. As a case study, existing RC building in Bangladesh have been collected for seismic capacity evaluation. These buildings database are originated from comprehensive disaster management program (CDMP) project of Government of Bangladesh. Seismic capacity has been evaluated based on basic information found from the database. The identified basic parameters of those existing RC buildings are compared with the earthquake damaged buildings as described in chapter 2 in other developing countries to identify a correlation between those parameters. Afterward, seismic capacity has also been compared with the damaged buildings databases for identifying the extent of damage level of existing buildings.

The summary of this chapter are as follows:

1) Column area ratio and masonry infill wall area ratio are found lower (1.2 to 1.6 times less) than other buildings database from different developing countries such as Ecuador, Nepal and Taiwan earthquake damage database.
2) The lower masonry infill ratio (≈1.7 times less) comparing with other databases indicates most of the investigated buildings in Bangladesh ground floor are open.
3) Seismic capacity of Bangladesh buildings is found much lower (≈1.5 times less) than comparing with other past earthquake damage databases of Ecuador, Nepal and Taiwan.
4) Probability of damage ratio for Bangladesh buildings has been estimated comparing with seismic capacity and ground motion intensity of each ground motion. Study shows that probability of severely damaged building is approximated about 36%, 43%, and 33% comparing with Ecuador, Nepal, and Taiwan earthquake damage database, respectively.

Chapter 4 Study on existing rapid visual screening methods

This chapter presents several existing rapid visual screening (RVS) methods such as FEMA P154, Turkish method, and other RVS methods. Main objective is to understand the background and application procedure of the existing RVS methods and to identify the effectiveness of such existing rapid visual screening methods in the world. However, these RVS methods have been applied in past earthquake damaged databases. In this study, Taiwan earthquake damage database has been chosen for application of the existing RVS method. The major findings from this chapter as follows:

1) Study shows that the score computed from these methods do not have correlation with corresponding seismic capacity of buildings.
2) The main limitation of these existing RVS methods is that those methods do not consider the basic parameter such as column area, wall area which are regarded as most influential parameters for seismic capacity estimation.
3) Thus, existing rapid visual screening methods are not effective for identifying the vulnerable buildings.

Chapter 5 Development of Visual Rating method

This chapter describes a proposal of rapid seismic evaluation method herein referred as Visual Rating (VR) method for screening of existing RC buildings. The proposed Visual Rating (VR) method considers fundamental parameters, buildings dimensions such as column and infill wall area ratio and their shear strength. The Visual Rating (VR) method approximately estimates the seismic capacity of existing RC buildings in terms of Visual Rating Index (I_{VR}). The development and application procedure have been described in this chapter.

The following conclusions are discussed as follows:

1) The Visual Rating (VR) method considers the simplified column area ratio and the simplified infill wall area ratio, which estimates the seismic capacity of existing RC buildings.
2) The inclusion of those column and infill wall area ratio in Visual Rating (VR) method is the new concept that have not been considered in the existing visual screening methods.
3) The Visual Rating Index (I_{VR}) proposed which approximates the seismic capacity of existing RC buildings.

However, the assumptions considered for column, masonry infill and concrete wall need further investigation for each countries according to local materials. Even though, this method is intended to buildings in Bangladesh, but could be easily adjusted to other countries by modifications for suitable characteristics of buildings and materials strength properties in the intended region.

Chapter 6 Survey of existing RC buildings in Bangladesh

This chapter presents the applicability and effectiveness of the proposed visual rating method. The main objective is to validate the effectiveness and applicability of the proposed method. In this regards, 22 existing buildings located at Dhaka, Bangladesh have been surveyed. The survey procedure has been subdivided into two major part. Part one is related into application of visual rating method. Part two is the preparation of as-built drawing because architectural drawings are not available of these surveyed buildings. As-built drawing is prepared due to conduct detail evaluation on these surveyed buildings.

A common survey datasheet is proposed for conducting of the visual rating method. The visual index has been calculated from information found from recorded survey datasheet. Detail evaluation has been done for first level and second level evaluation. The Visual Rating Index (I_{VR}) has been calibrated with the estimated first level and second level evaluation. Finally, a correlation has been established between visual rating index and seismic capacity of the surveyed buildings.

The following conclusions can be stated as follows:

1) The Visual Rating method considers the simplified column area ratio and the simplified wall area ratio, which estimates column area and infill wall area ratio efficiently. However, the normalized actual column area ratio by the simplified column area ratio, the average 1.19 and coefficient of variation 23% shows a good correlation between these parameters.
2) Visual Rating Index (I_{VR}) is efficient to estimate the seismic capacity of existing RC buildings. It has been observed that the normalized seismic index of first level evaluation and Visual Rating Index (I_{VR}), the average value is of 1.53 and coefficient of variation is of 35% shows a good estimation of seismic capacity of first level evaluation.
3) The average value of normalized seismic index (I_{S2}) by Visual Rating Index (I_{VR}) is 2.11 with coefficient of variation 33% indicates the Visual Rating Index (I_{VR}) score shows more conservative result with seismic index (I_{S2}) in second level evaluation. The reason is that I_{VR} assumes structural members as non-ductile members since ductility of column is difficult to be judged based only on visual inspection.

The proposed Visual Rating method is intended to estimate of seismic capacity of existing RC buildings in absence of detail seismic evaluation. From the above discussion, it has been observed that Visual Rating method provides lower boundary of seismic capacity of existing buildings. However, the estimated Visual Rating Index (I_{VR}) score is useful to provide judgement and prioritization of detail seismic evaluation which is the main of objective of the proposed Visual Rating Method.

Chapter 7 Judgement criteria for priority setting of detail evaluation

This chapter described about proposal of judgment criteria for classification of existing building that are required for detail seismic evaluation. First of all, some model RC buildings have been chosen as per strength index (C) and ductility index (F). A simplified response spectrum method is applied on these model buildings to estimate the capacity demand ratio. The capacity demand ratio is compared with seismic index of detail evaluation. These model buildings are investigated for establishing a correlation between capacity-demand ratio and seismic index of detail seismic evaluation. Furthermore, judgement criteria have been proposed according to seismic index (I_{S2}) based on capacity-demand ratio. Finally, judgement criteria according to visual rating index (I_{VR}) has been proposed considering the obtained correlation between seismic index (I_{S2}) and Visual rating index (I_{VR}) in chapter 6.

The conclusion of this chapter as follows:

1) This study proposes judgement criteria for seismic index (I_{S2}) is of 0.40 considering local seismicity and soil type, which is close to the judgement criteria proposed in CNCRP manual (CNCRP 2015) of Bangladesh.
2) The judgement criteria have been proposed according the Visual Rating Index (I_{VR}) and the buildings are to be categorized into 5 classes such as A, B, C, D and E describing from less vulnerable to most vulnerable buildings.
3) From the criteria, the existing RC buildings with Visual Rating Index (I_{VR}) lower than 0.24 are regarded as vulnerable buildings, and the buildings with I_{VR}<0.10 are categorized as the most vulnerable buildings and detail evaluation is required for these buildings.

The proposed judgement criteria based on seismic evaluation of 22 existing RC buildings in Bangladesh. In order to increase the accuracy and effectiveness of the proposed judgement criteria, additional RC building survey and investigation is required.

Chapter 8 Conclusions and recommendation

This chapter summarizes the major conclusions of all the chapters. This chapter discuss the limitations of the proposed method that needs further study such as material properties, modification factors for Visual Rating method and judgement criteria for priority settings.

Chapter 1
Introduction

1.1 Background

Past earthquakes in developing countries, such as the 2015 Nepal earthquake (Magnitude 7.8), the 2010 Haiti earthquake (Magnitude 9.0), the 2016 Ecuador earthquake (see Figure 1.1), caused major destruction in structures which resulted in a huge number of fatalities and economic loss. This major destructive earthquake indicates the existence of a huge seismically vulnerable building stock in those earthquake-prone areas. Many nations in earthquake-prone areas are concerned about mitigation of future earthquake disasters to avoid huge loss in infrastructures as well as casualties. Moreover, many researchers and policy makers are now trying to discern about the global issue for mitigation of the earthquake disaster risk and development of seismically resilient societies.

(a) The 2010 Haiti earthquake (Magnitude: 7.0)

(b) The 2015 Nepal earthquake (Magnitude: 7.8)

(c) The 2016 Ecuador earthquake (Magnitude: 7.8)

Figure 1.1 Past damaging earthquakes in developing countries (Photo: datcenterhub.org)

Reinforced concrete (RC) frame with masonry infill, such as in Figure 1.2, is a common structural system in those developing countries. Construction of this type of structure has been increasing rapidly due to very fast urbanization in major cities of those developing countries for meeting the requirement of urban inhabitants.

Figure 1.2 Building with Masonry infill (Photo: Janise Rodgers, Bhutan)

Developing countries which are located in earthquake prone area, such as Bangladesh, do not have experience of recent major earthquake. Although there have been no recent earthquake disasters, experts are now highly concerned due to repeated occurrence of this catastrophic event in surrounding countries. Recently, collapse of several existing buildings, as shown in Figure 1.3, without an earthquake triggers the necessity to strengthen existing buildings in Bangladesh. The main reason behind the sudden building collapse shown in Figure 1.3 is due to lack of enforcement of building code rules and regulations during the planning and construction stages of these buildings. At the same time, these structures do not meet the seismic requirements due to lack of updated building code and construction practices as well non-engineered construction practices. Therefore, there is a urgent need for seismic screening of the existing RC building for evaluation of seismic capacity and subsequently retrofitting and/or strengthening.

(a) Rana plaza collapse

(b) Spectrum sweater factory collapse

Figure 1.3 Building collapsed at Dhaka without earthquake

In this respect, a number of guidelines/manuals are available from different countries for seismic evaluation of existing buildings (such as Japanese standard, ASCE standard). In Bangladesh, seismic evaluation manual (CNCRP 2015) has also been developed for detailed evaluation of existing buildings. Those manuals and evaluation procedures are effective to understand the seismic capacity and proposal for strengthening or retrofitting. However, these evaluation procedures require professional engineers/experts for doing rigorous analysis and judgement for making decision. Moreover, seismic evaluation can be very challenging when dealing with large building stock (especially for developing countries) due to limited resources and/or experts. Therefore, seismic screening of a large number of buildings building stock is of major concern for policy maker when setting the strategy for earthquake disaster risk mitigation. Hence, there is a need to develop a very simple method in order to set priority for the detailed evaluation that requires limited expertise and time. It might also help policy makers to take decision of retrofitting by having an approximate estimation for the vulnerable buildings.

Identification of the most vulnerable buildings through rapid screening is an effective way to reduce the number of buildings to be investigated for detail seismic evaluation. In this regard, several number of guidelines/procedures are available from different countries for identifying the vulnerable buildings. The visual screening method such as FEMA P 154 (2015), Turkish Rapid Visual Screening method (BU-ITU-METU-YTU 2003; Sucuoglu et al. 2007) are commonly used in different countries. Those methods are developed based on investigation of past earthquake damages buildings in these countries. However, these methods provide a score which is combination of basic scores (structure type) and score modifiers (such as plan and elevation irregularities). Other visual screening methods have also been proposed which provide a seismic score based on a probabilistic approach (Albayrak et al. 2015; Jain et al. 2010; Demartion and Dirsons 2006). All aforementioned visual screening methods provide a score either in terms of probability of collapse or a performance score which does not reflect the seismic capacity of existing buildings.

Furthermore, the above rapid visual screening methods do not consider the basic parameters of buildings such as cross-sectional areas of vertical member (e.g., column area, RC wall area and masonry infill area) and corresponding strength which have been found to be critical parameters affecting the seismic capacity (O'Brien et al. 2011; Gur et al. 2009; Donmex and Pujol 2005; Yakut 2004; Ozcebe et al. 2004; Yakut et al. 2004; Hasan and Sozen 1997;

Shiga et al. 1968). Hence, a visual screening method considering these parameters is an effective approach for rapid evaluation of existing buildings.

In this context, this research proposes a rapid seismic evaluation method considering the aforementioned simple parameters observed from building survey or visual inspection. It would be helpful to set the strategy for future earthquake preparedness.

1.2 Objective of the study

This research work is an effort on understanding the most common features that influence the seismic capacity of RC buildings and seismic damage during earthquake. This study intends to develop a practical rapid seismic evaluation method for developing countries.

The major objectives of this research are as follows:

Objective 1

Understand the basic characteristics of existing RC buildings and determine correlations with seismic damage

Objective 2

Identify the most fundamental parameters that influence the seismic capacity

Objective 3

Develop a rapid seismic evaluation method and propose a strategy of detailed evaluation of existing RC buildings

Figure 1.4 Objectives of the Thesis

1.3 Significance of the research

Earthquake disaster has been becoming significantly severe, particularly in developing countries where disaster risks are not taken into account during development for future plan. At present, these developing countries are exhibiting keen interest in preparedness for future earthquake disaster. Those developing countries have been initiating several seismic evaluation schemes regarding seismic improvement of existing RC buildings. However, it is very challenging to deal with large buildings stock without proper strategic plan due to lack of guidelines and procedures. In this regard, this research outcome will be helpful to policy makers for preparing of strategic plan for seismic evaluation of large numbers of vulnerable RC buildings. Furthermore, this research outcome will show a way for developing a seismic resilience society in developing countries.

1.4 Organization of the study

Chapter 1: Introduction

This chapter describes general background, problem identification, major objectives and significant of the research and research framework.

Chapter 2: Study on past earthquake damage databases

This chapter describes the seismic capacity evaluation of past earthquake damaged RC building's database in different countries. The main objective of this chapter is to identify the most vulnerable parameters which influence the seismic capacity of RC buildings. First of all, buildings' characteristics have been investigated. A correlation between basic parameters and seismic damage have been established based on investigation of these buildings database. Furthermore, seismic capacity has also been estimated based on these simple parameters. Study shows that these simple parameters can easily estimate the seismic capacity which exhibits good agreement with damage ratio. Finally, a correlation between seismic capacity index and damage ratio has been proposed for individual buildings database. This correlation is useful information to identify the seismic vulnerability of existing RC buildings of those countries where past earthquake recorded building database are not available.

Chapter 3 Study on existing RC buildings in Bangladesh

This chapter presents seismic evaluation of existing RC buildings in developing country where past earthquake damage database is not available. As a case study, existing RC building in Bangladesh have been collected for seismic capacity evaluation. These buildings database are originated from comprehensive disaster management program (CDMP) project of government of Bangladesh and collected thorough an ongoing research project named SATREPS-TSUIB project which is research project between JICA/JST, Japan and the Government of Bangladesh. First, the basic parameters are identified. Seismic capacity has been evaluated based on this basic information found from the database. Besides, the basic parameters of those existing RC buildings are compared with the damaged buildings in other developing countries to identify a correlation between those parameters. Afterward, seismic capacity has also been compared with the damaged buildings databases for identifying the extent of damage level of existing buildings. Finally, probability of damage ratio has been estimated based on damage ratio of past earthquake damaged buildings considering local seismicity.

Chapter 4 Study on existing rapid visual screening methods

Chapter 2 and chapter 3 show simplified seismic capacity evaluation procedure which can rapidly estimate the seismic capacity based on the simple parameters. However, application of these method is difficult because most of existing buildings does not have drawings. Therefore, rapid visual screening is an effective way to identify the most vulnerable buildings rather than to do seismic evaluation of all buildings. This chapters identifies the limitations of existing rapid visual screening methods in the world. Several RVS methods such as FEMA P154, Turkish method and other RVS methods in different countries have been studied. The application procedures of those methods have been described in this chapter. However, these RVS methods have been applied in past earthquake damaged databases. Study shows that those method does not have correlation of seismic capacity of damaged buildings. The main limitation of these existing RVS methods is that those methods do not consider the basic parameter such as column area, wall area which are regarded as most vulnerable parameters in previous chapters. Therefore, inclusion of these simple parameters in rapid seismic evaluation is effective for estimating the seismic capacity.

Chapter 5 Development of Visual Rating method

This chapter describes a proposal of rapid seismic evaluation method. The proposed method is based survey thorough visually inspection of existing RC buildings. The method is referred herein as Visual Rating (VR) method. The visual rating method approximately estimates the seismic capacity of existing building in terms of visual rating index. The main concept of visual rating index is based on Shiga map (Shiga et al. 1968), considering column and wall area ratio and their shear strength. The development and application procedure have been described in this chapters.

Chapter 6 Survey of existing RC buildings in Bangladesh

This chapter presents the applicability and effectiveness of the proposed visual rating method. Visual Rating Method has been investigated thorough application on several existing RC buildings located at Dhaka, Bangladesh. Visual Rating index has been calculated based on survey information. Detail seismic evaluation has been done for those surveyed buildings. Furthermore, Visual Rating index has been compared with the result of detailed seismic evaluation procedure of the investigated buildings. Finally, a correlation has been established between visual rating index and seismic capacity of the surveyed buildings.

Chapter 7 Judgement criteria for priority setting of detail evaluation

This chapter describes guideline of criteria of priority settings for detail evaluation and retrofitting. The investigated buildings are to be categorized based as A, B, C, D and E. Herein, building in category E indicates the most vulnerable building and need detail evaluation and retrofitting. On the other hand, buildings are located at category A indicates that the buildings will be less vulnerable that means less priory for detail evaluation. Several RC frame has been designed based on basic parameters of existing RC building in Bangladesh. However, seismic capacity has been calculated of this designed frame. Seismic capacity has been compared with seismic demand based on local seismicity according to Bangladesh National building code.

Demand and capacity has been categorized based on the ratio and seismic index of second level screening. Further, boundaries for criteria has been chosen based on correlation between seismic demand index and visual rating index.

Chapter 8 Summary and conclusions

This chapter summarizes the major conclusion of the research. Limitations and recommendations for further research are also discussed.

1.5 Literature review

Many researchers from different countries proposed seismic evaluation method for estimation of seismic capacity of existing buildings. In addition, many countries have been applying seismic evaluation by following established technical manual/guidelines for seismic evaluation of existing buildings. The following sections describes the literature corresponding to existing seismic evaluation method and literature.

1.5.1 Past studies related to simplified seismic evaluation

In recent year, several preliminary assessment methods have been developed for the seismic assessment of existing RC building. Those methods are based on the dimensions of lateral load resisting members. These are as follows:

Shiga et al. (1968) proposed a simple evaluation method considering only two parameters such as average shear strength of column and RC wall, and RC wall area ratio. The simplified method has been developed after investigation of damage database of the 1968 Tokachi-oki earthquake. The simple parameters have been plotted and the plot in this method is well known as "Shiga Map" after investigating of damage database. For the Shiga Map, it has been observed that these simple two parameters effectively distinguish damaged buildings and undamaged buildings. After a decade, these simple parameters have also been investigated into earthquake damaged database after the 1978 Miyagiken-oki earthquake (Shibata 2010). It has been observed that the Shiga map shows good correlation between damaged and non-damaged buildings. However, Shiga map does not consider masonry infill wall because masonry infill wall is not common in Japan.

Hassan and Sozen (1997) presented a simplified evaluation method for ranking of existing RC buildings according to their seismic vulnerability to damage. This simplified method considers dimensions and floor area of the structure which is based on Shiga map concept (Shiga et al., 1968). The proposed method calculates a "Priority Index" for each building, which is based on column index (cross-sectional area of column divided by total floor area) and wall index (cross-sectional area of masonry infill and RC wall). The proposed method has been calibrated using a building database that suffered various level of damage during the 1992 Erzincan earthquake. The estimated priority index showed correlation with the observed damage satisfactorily. It has been concluded that the method is effective to identify the vulnerable buildings without the necessity of detail seismic evaluation.

Gulkan and Sozen (1999) proposed a rationalized method for ranking of existing buildings with masonry infill walls with respect to seismic vulnerability. This study showed the lateral drift of building at the ground floor is influenced by cross-sectional area of column and infill walls. Although the proposed method is simple and practical, the major disadvantage of the procedure is the basic assumption that construction and material quality as well as as-built properties of the buildings to be evaluated are uniform. Although the construction quality and code compliance might be considered reasonably uniform for countries where these are ensured, the effect of concrete strength on this force-based performance assessment is ignored. In addition, the proposed method does not consider the effect secondary factor such as soft story, short column, and vertical irregularity.

Yakut (2004) presented a preliminary evaluation procedure to assess existing RC buildings rapidly. The proposed method calculates Capacity Index (CPI) based on Basic Capacity Index (BCPI) and modification factors. Here, Basic Capacity Index (BCPI) is calculated considering dimension, orientation and material properties of the lateral load-resisting members of buildings. Besides, the modification factors are the coefficients that reflect some secondary parameters such as architectural features (i.e. buildings irregularities) and quality of materials and construction practices. The architectural features include soft story, Sort column, plan irregularity and frame irregularity. In addition, quality of construction is divided into three categories as poor, Average and good. However, in this study, the existing buildings are classified into two categories such as safe and unsafe based on Capacity Index (CPI) score. Safe building referred as low risk and thus these building might not suffer severe damage during earthquake. However, unsafe building indicates the building is at high risk and these building would not meet the life-safety performance level of present seismic design codes. The proposed method has been applied on three earthquake damage databases: the 1992 Erzincan earthquake, the 2002 Sutandagi earthquake and the 2003 Bingol earthquake. It has been observed that the presented evaluation method is useful for prioritizing buildings for further, more detailed assessments that would be needed to design a seismic evaluation and rehabilitation scheme.

Ozcebe et al (2004) proposed a model for preliminary assessment of existing buildings. The model is based on a statistical procedure called discriminant analysis. The proposed method considers six basic estimation variables such as: number of stories above the ground level (*n*), minimum normalized lateral stiffness index (*mnlstfi*), minimum normalized lateral strength index (*mnlsi*), normalized redundancy score (*nrs*), soft story index (*ssi*) and overhang ratio (*or*). These parameters are considered based on investigation of the 1999 Duzce earthquake damage database in Turkey. The proposed model is used to classify the buildings into 3 different classes: safe, unsafe and requires further evaluation. Afterward, the presented method is validated by using the seismic damage database associated with other earthquakes such as the 1992 Erzincan earthquake and 2002 Afyon earthquake. The results show good classification rates indicating the effectiveness and predictive ability of the proposed seismic evaluation method.

National Research Council, Canada (NRCC) proposed a ***Manual of screening of buildings for seismic investigation (NRC-IRC 1992)*** for simplified seismic evaluation of existing buildings. Like FEMA, the manual has divided the building or structural system into 15 types of existing buildings and the concept is adopted from FEMA method (developed by US is explained in the later section). The method estimates a score, denoted as the seismic priority index (SPI) following two components such as: (1) structural index (SI) describing to damage of the building structure and (2) Non-structural index (NSI) describing to damage of non-structural components. The Structural Index (SI) includes local seismicity and soil type (ground motion), structure type and irregularities, and importance of buildings. On the other hand, the Non-Structural Index (NSI) considers three different types of factors such as: falling hazards to life-safety or hazards to vital operations in post-disaster buildings, building importance and soil conditions. However, the seismicity and soil condition is selected based on the hazard maps of the Canada. Unlike FEMA, the proposed visual screening procedure correlates the final RVS score of the building with risk categories viz., low, medium and high priority. These divisions into low, medium and high priorities are somewhat arbitrary and depend on local resources and priorities as well as the kinds of buildings involved. The SPI score less than 10 suggests low priority and buildings with SPI more than 30 are of high priority and considered as potentially hazardous, hence detail evaluation is required.

From the above discussion, it is evident that these simplified method is easy to apply in existing building for rapid evaluation of building stock. However, the methods take into account the dimension and material properties of existing buildings. In most cases, architectural drawings are not available of existing building, therefore these method is not applicable due to such type of limitation.

1.5.2 Past studies related to visual screening method

This section describes some literature related to visual screening method for rapid evaluation of existing buildings. The following section describes as follows:

A number of guidelines for seismic assessment and rehabilitation of buildings are available developed by the US Federal Emergency Management Agency (FEMA). ***FEMA 310 (1998)*** proposes two levels of seismic performance evaluation developed by US Federal Emergency Management Agency (FEMA). The guideline has been first published in 1989 and revised in 1992 as FEMA 178 (1992). The evaluation procedure is based on rigorous approach to determine existing structural conditions. FEMA 310 considers two levels of seismic performance such as Life Safety (LS) and Immediate Occupancy (IO) during design earthquake. For life safety (LS) performance, the building can withstand significant damage to both structural and non-structural components with some margin against either partial or total structural collapse. Therefore, there are low level risk of life-threatening injury. Immediate occupancy (IO) building performance indicates very limited damage to both structural and nonstructural components during the design earthquake. The primary vertical and lateral-force-resisting systems hold nearly all of their original strength and stiffness. In this case, some minor injuries and damage have been considered, which could be easily repaired while the building has been occupied.

In addition, ***FEMA 154 (2015)*** is developed for rapid visual screening of existing buildings. The proposed method has been originally published in 1988 and revised in 2002. Later on, the proposed guideline has been further revised and published in 2015. FEMA estimates seismic performance score in terms of probability of collapse. FEMA considers a basic structural score for different types of structural system depending on lateral force-resisting system. However, the FEMA final score depends on basic structural score and performance score modifiers. Performance score modifiers depends on secondary parameters to take into account the irregularities of buildings (such as horizontal and vertical irregularities), soil type and pre-code or post-benchmark code detailing, and soil type. In this context, pre-code modification factor representing the buildings is designed and constructed before enforcement of seismic design code. Besides, post-benchmark is defined as the investigated building has been designed and constructed after significant improvement of seismic code. considered to defended as the building has been design sand constructed after significant improvement of seismic code is implemented and activated. The basic score and score modifier are proposed based on HAZUS methodology. FEMA describes judgement criteria for detail evaluation. In this instance, FEMA score 2 implies that the probability of collapse of investigated buildings is 1 in 100.

Sucuoglu and Yazgan (2003) first proposed two stage risk assessment procedure for evaluation of existing RC buildings. Stage one depends on visual inspection of existing building from outside such as street survey. The street survey is basically based on simple structural and geotechnical features by visual investigation.

Sucuoglu et al (2007) proposed a screening procedure to identify the most vulnerable building for seismic evaluation of large existing buildings stock. However, the proposed method estimates a performance score which helps to set risk priority of existing buildings.

The performance score is summation of basic score depending on number of stories, local seismicity and score modifiers considering the secondary parameters such as irregularity, buildings quality. The proposed method has been calibrated using building damage database after the 1999 Duzce earthquake, in Turkey. The proposed method is intended to serve as initial screening of large number of existing buildings stock.

The New Zealand Assessment of Existing Bulidings Guideline (NZSEE 2006) considers a two-tier seismic evaluation method of existing RC buildings. The initial evaluation procedure (IEP) includes doing an initial seismic evaluation procedure of existing buildings compared with the standard required for a new building, defined as percentage of new buildings standard. The percentage of new buildings standard herein mentioned (% NBS) is seismic performance assessment of a structure taking considering all available information and compared with a performance of new building. A percentage of new building standard (% NBS) of 33 or less indicating the building might have potential damage and detail evaluation is recommended. However, the evaluation procedure requires expertise in order to apply on existing buildings.

Demartinos and Dritsos (2006) proposed a fuzzy logic based visual screening procedure in Greece. This method is intended to categorize the existing building into five different damage grades with respect to the potential occurrence of a major earthquake. The proposed method has been developed based on information found from investigation on 102 existing damaged buildings experienced by the 1999 Athens earthquake. The fuzzy logic-based visual screening method (FL-RVSP) considered a probabilistic reasoning approach for rapid evaluation of existing method. The method provides a score that represents the level of seismic performance of an existing building during major seismic events producing ground accelerations equivalent to the values provided by the relevant seismic codes.

Jain et al (2010) proposes a visual screening method based on studies on past earthquake damage database in the 2001 Bhuj earthquake, in India. The proposed method also estimates performance score for evaluation of existing buildings. The performance score is the summation of basic score and score modifiers which is similar concepts as proposed by

Sucuoglu et al (2007). Basic score is based on statistical analysis. In addition, score modifiers include as a total of six vulnerability parameters is used in the proposed method such as number of stories, open stories, short columns, presence of basement, apparent quality of maintenance, and re-entrant corners. Seismic performance scores are based on local seismicity and type of soil. The proposed method has been applied on existing buildings database in Ahmedabad, India after the catastrophic earthquake (the 2001 Bhuj earthquake, India, magnitude: 7.0). A performance score consist of lower values indicates high risk of seismic vulnerability of existing buildings and hence, detail rigorous seismic evaluation is recommended.

Albayrak et al (2015) proposed a methodology for rapid seismic evaluation of existing RC buildings to detect the most vulnerable buildings and rank the buildings for further higher level evaluation. The proposed method is based on the concept developed by Sucuoglu et al (2003, 2007). The proposed method calculates performance score in terms of earthquake risk score (ERS). ERS is the summation of base score (BS) and score reduction value (S.R.V) and vulnerability parameter multiply (V.P.M). However, the building has been categorized into four categories as high, moderate, low and no risk according to earthquake risk score. It has been suggested that high risk buildings are recommended for more detail evaluation before conforming the buildings as earthquake risk.

Perrone et. al. (2015) proposed a rapid visual screening method for evaluation of RC hospital building in Italy. The proposed method estimates safety index (SI) for hospital buildings. The method considers six vulnerability indices to estimate seismic risks for hospital buildings. These are structural vulnerability, non-structural vulnerability and organizational aspects. In addition, parameter related to exposure and hazard are also considered for calculating the safety index. The procedure has been applied on two hospital buildings to understand the efficiency of the proposed method. The results exhibit a good agreement between the structural index and damage level after evaluated two existing building suffered by past earthquake damage.

However, the aforementioned method requires dimension (such as building plan, columns section, floor height) and also material properties of existing RC buildings. Therefore, these methods have limitation to identify the most vulnerable building and thereby, are not efficient to make priority setting for detail/or further evaluation of existing building.

1.5.3 Detail seismic evaluation method

A number of guidelines are available from different countries for detail evaluation of existing buildings. The following evaluation method are described as follows:

The Japan Building Disaster Prevention Association (JBDPA, 2001) proposed a practical seismic evaluation method for detail evaluation of existing RC buildings. In recent years, many developing countries are using the practical evaluation method for improvement of their existing building design code and evaluation method. However, the evaluation method considers three levels of seismic evaluation: First level, Second level and Third level evaluation. The JBDPA estimates seismic index (I_S) as the product of basic seismic index (E_o), irregularity index (S_d) and time index (T). Where, the basic seismic index is estimated as product of strength index (C) and ductility index (F). The strength index (C) is based on lateral strength of vertical members and buildings total weight. On the other hand, ductility index (F) is calculated considering inter-story drift angle at the ultimate deformation capacity in correspondence with failure pattern of the vertical element. The estimated seismic index (I_S) has been compared with the seismic judgement index (I_{SO}) for seismic improvement or retrofitting of vulnerable buildings. In this regard, this evaluation method standard, JBDPA standard considers seismic judgement criteria (I_{so}) regardless the number of story and direction of building for identifying the buildings are to be safe of unsafe. However, detailed information like architectural drawings and structural drawings along with properties of construction material are necessary for doing this seismic evaluation.

In recent, CNCRP (CNCRP 2015) developed seismic evaluation guideline for seismic assessment of existing RC building in Bangladesh. The evaluation manual is developed thorough a technical cooperation project between the Japan International Cooperation Agency (JICA) and Public Works Department (PWD). The proposed seismic evaluation manual has been developed based on the general concept and assumptions considered in Japanese seismic evaluation standard (JBDPA 2001). Like JBDPA standard, the CNCRP manual estimates seismic index (I_s) based on basic seismic index (E_o), irregularity index (S_d) and Time index (T). Similarly, Japanese seismic evaluation standard, the proposed method requires detail structural and architectural drawing for evaluation of existing buildings. Since the CNCRP manual is based on JBDPA standard, therefore, the seismic index has been estimated ignoring the effect of masonry infill. Because, the masonry infill is not common in Japan due to different structural system and construction practices comparing with Bangladesh building. However, study on past earthquake damage in developing countries shows that masonry infill contributes seismic capacity and change the damage behavior during earthquake. Therefore, it is necessary to consider the effect of masonry infill during seismic evaluation of existing buildings. Hence, seismic evaluation considering the effect of masonry infill is important aspect for RC buildings in Bangladesh.

Al-washali (2018) proposed a seismic evaluation method for RC buildings with masonry infill in developing countries. The proposed method is used the basic concept and assumption taken in the JBDPA standard (JBDPA 2001). However, the effect of masonry infill has been considered based on experimental investigation of RC frame with masonry infill representing masonry infilled RC buildings in Bangladesh as well as past experimental analysis from other researches in different countries. In this method, the seismic index (I_s) is estimated considering strength index (C) and ductility index (F) of vertical elements such as RC column, RC wall as well as masonry infills within the RC frame. However, the evaluation method proposes a procedure for estimating of strength and ductility index of masonry infill wall. The strength and ductility index of masonry infill are based on the proportion of lateral strength of surrounding RC frame and masonry infill. The seismic evaluation method has been developed under SATREPS-TSUIB project which is another technical cooperation project between Japan International Cooperation Agency (JICA) and Government of Bangladesh. However, the proposed seismic method requires detail architectural and structural drawing for seismic evaluation of existing buildings.

From discussion of past literature and research, it has been concluded that detail method also requires detailed drawing and other information of existing RC buildings.

1.6 Flow of thesis

<u>Figure 1.4 shows the flow of research and main chapter</u>

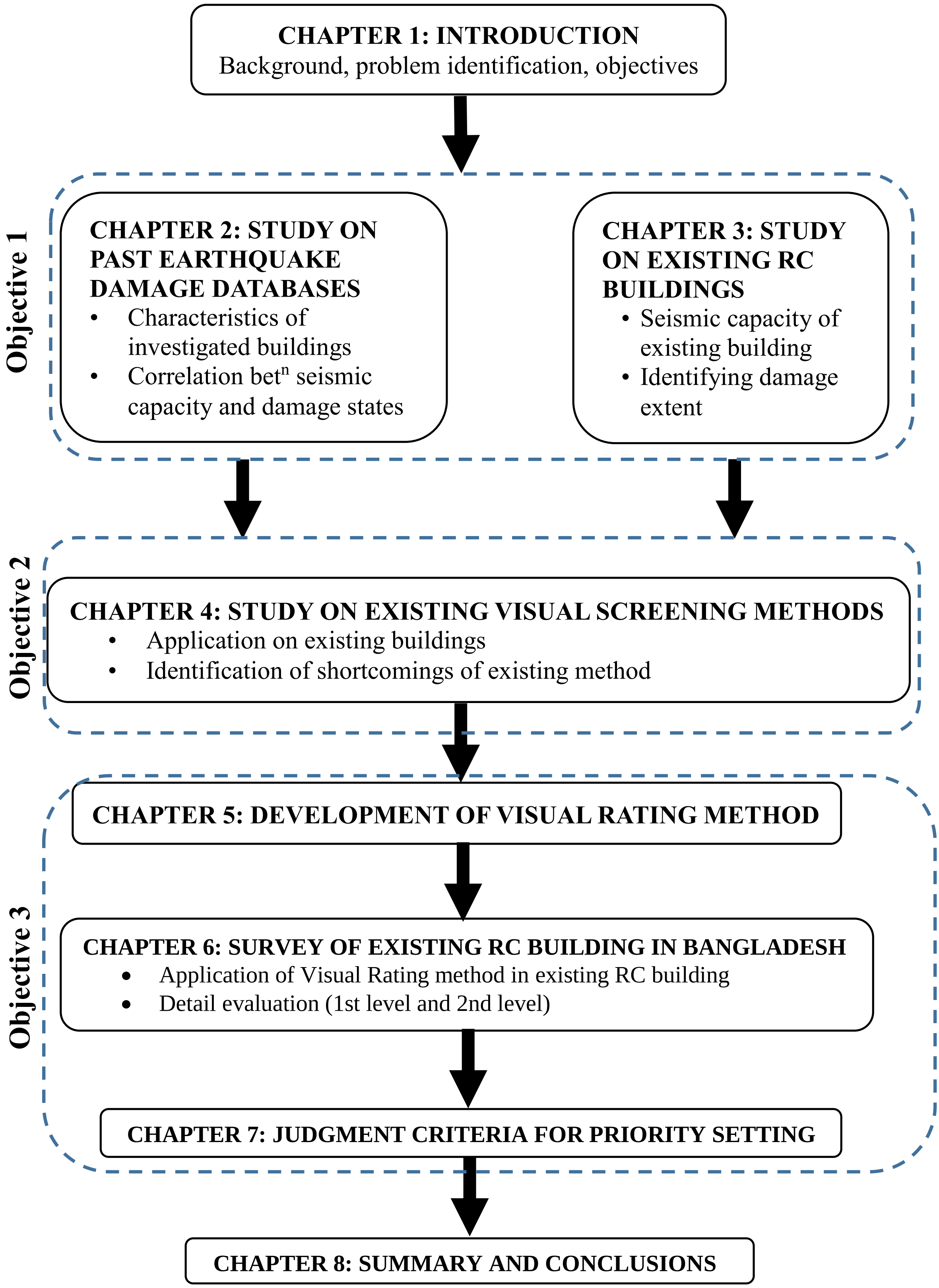


Figure 1.4 Flow of thesis

Chapter 2
Study on past earthquake damage databases

2.1 Introduction

This chapter aims to identify the fundamental parameters which influence the seismic capacity as well as seismic damages. In this context, this chapter covers the study and investigation of existing earthquake damaged RC buildings databases collected from past earthquake records. First of all, several of common parameters have been derived based on study of these buildings databases. Correlation between these parameters and damage status has been established. Simplified seismic capacity evaluation has been conducted based on some basic assumptions such as column area ratio, masonry infill area ratio and information found from the databases. Seismic capacity has been compared among each database. Finally, probability of damage ratio has been determined based on proportions of seismic damage.

2.2 Overview of buildings databases

Three past earthquakes surveyed buildings databases have been collected from past earthquake record database website www.datacenterhub.org . Those buildings databases are open and easy access for doing study and research in earthquake engineering field. These database consists of buildings floor plan (hand sketch) along with information such as number of stories, floor areas, location of masonry infill, year of construction, floor plan with length and width. There are some photos to show describe the state of damage or current status of the surveyed buildings. In the following sections, the details information and seismic evaluation are described in the following sections.

2.2.1 The 2015 Nepal earthquake

2.2.1.1 Introduction

The 2015 Nepal earthquake hit at Lamjung district with a magnitude of 7.8 on April 25, 2015 as shown in Figure 2.1. The earthquake and subsequent aftershocks caused more than

8,700 fatalities and damaged or collapsed about 700,000 buildings with several UNESCO World heritage buildings (GoN 2015a, GoN 2015b). The majority of the affected dwellings are reinforced concrete (RC) with masonry infilled structures as shown in Figure 2.2 and most of them are located in the central part of the country. The epicenter of the devastating earthquake was Barpak, Ghorkah district, located at 85.3◦E, 27.7◦N (USGS).

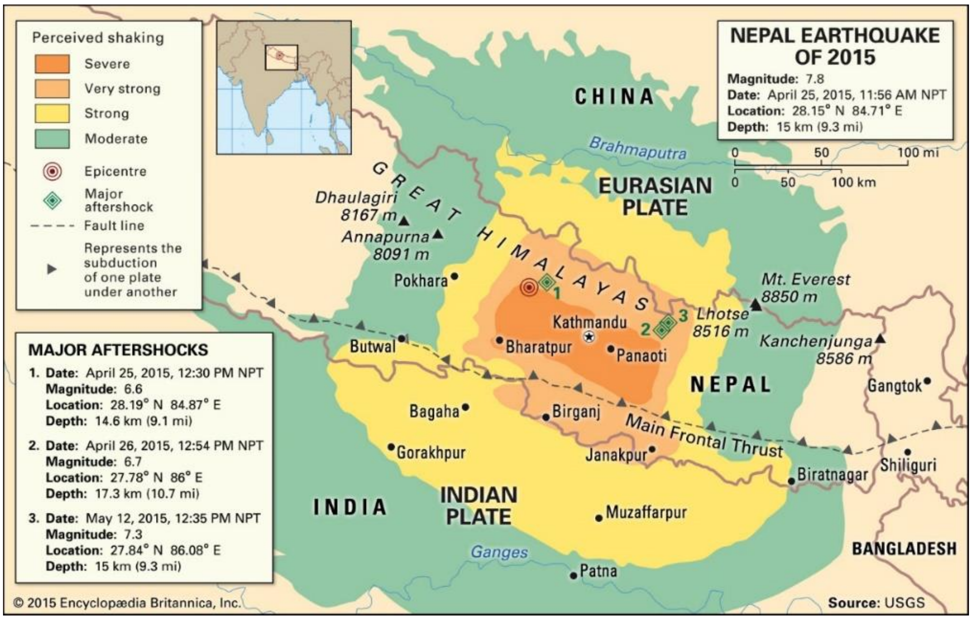


Figure 2.1 The Nepal earthquake, 2015(Source: USGS)

Figure 2.2 The Nepal earthquake, 2015 (Source: USGS)

2.2.1.2 Ground motion characteristics

The strong ground motion recorded at Kantipath (KATNP) station, Kathmandu as shown in Figure 3, by the United States Geological Survey (USGS) strong motion observation through the center for Engineering Strong Motion Data (CESMD) (Dhakal et al. 2016). The recorded acceleration time histories are shown in Figure 2.3. From the Figures, it has been observed that the peak ground acceleration (PGA) for 149.7 cm/s^2 and 155 cm/s^2 for NS and EW direction, respectively.

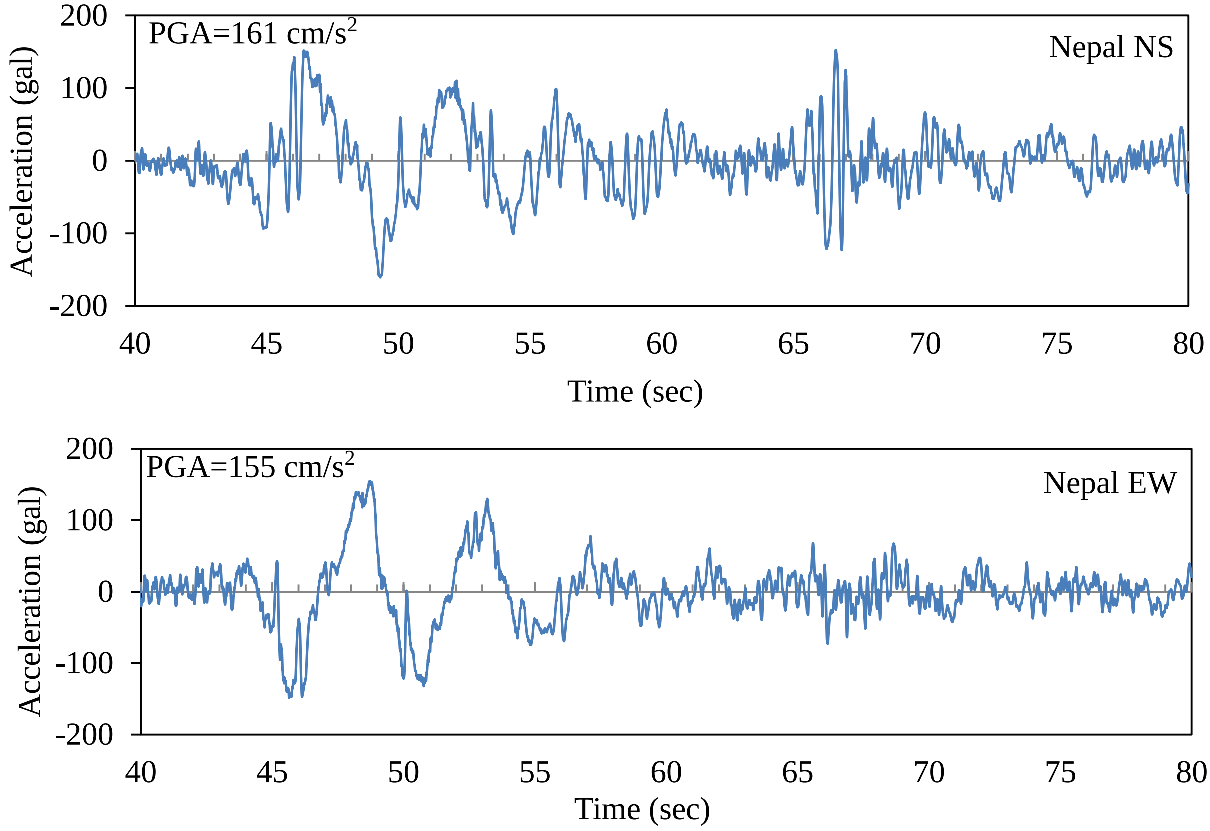


Figure 2.3 Time history of ground motion of Nepal EQ 2015 (Station name: Kantipath station)

Acceleration response spectrum is shown in Figure 2.4 for the earthquake ground motion. The response acceleration spectra have been based recorded ground motion at Kantipath station, Kathmandu. From the Figure, it has been observed that response acceleration has been found 0.6g and 0.3g in EW and NS direction, respectively.

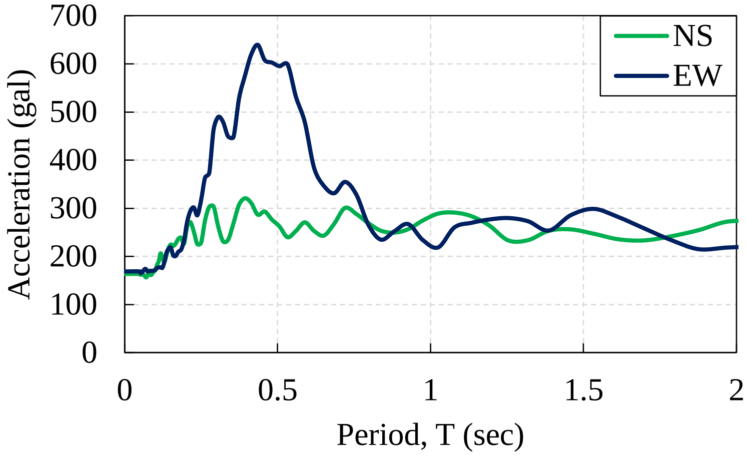


Figure 2.4 Acceleration response spectrum of Nepal earthquake, 2015

2.2.1.3 Location of investigated RC buildings

A total of 133 low-rise RC buildings has been selected for this study. Those buildings have been investigated by a group of researchers from different universities and research institutions from Purdue University, American Concrete Institute (ACI) and Government of Nepal (www.datacenterhub.org). All of those buildings are located at Kathmandu, the capital city of Nepal near the earthquake observation station Kantipath, Kathmandu as shown in Figure 2.5. Most of those buildings are located at Sitapaila city and Banasthali city, which are the most developed area in the capital, Katmandu. The epicentral distance of the earthquake from the surveyed buildings are about 55 km. The strong ground motion station (i.e, Kantipath earthquake observation station) is located near the investigated building. The distance among them are within the range of 2 to 4 km from the station.

2.2.1.4 Buildings characteristics

All surveyed buildings listed in Table 2.1 are masonry infilled RC buildings. Most of them are residential occupancy category. Many of them are mixed occupancy category due to function of buildings. Generally, ground floor has been used for commercial purpose and upper floor are residential purpose. Open storefront is also common in these mixed functioned category. Most of the investigated buildings are square or rectangular shaped in floor plan. Generally, the floor plan dimensions for residential buildings with an approximate length of 9 to 12 m and an approximate width of 6 to 8 m (Brzev et al. 2017). The Typical RC column are

230mm X 230 mm and sometimes 230mm X 300mm (Shakya and Kawan, 2016). Similar dimension has been found 270 mm. Thickness of all exterior walls are found 230 mm and all interior walls are found 115 mm. Typical RC columns were 227 mm square, and RC beams were 227 mm wide and 305 mm depth.

Figure 2.5 Location of investigated buildings found from the database (datacenter hub.org)

The number of stories ranged in between 2 to 6 storied as shown in Figure 2.6 and also shown in Table 2.1. From the Figure 2.6, it has been seen that more than 40% surveyed buildings are 3 storied and 30% buildings are 4 storied buildings. The floor height has been found ranges from 2.4 m to 3.0 m for these investigated buildings (datacenterhub.org).

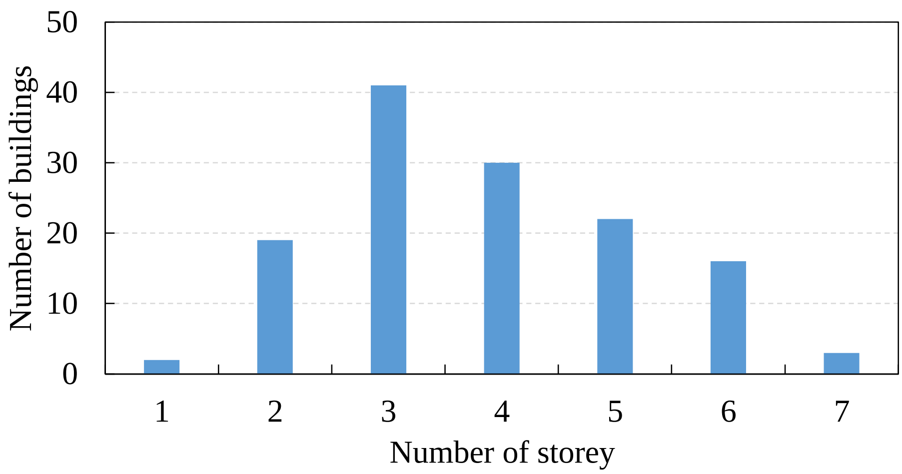


Figure 2.6 Distribution in percentages according to number of stories

Table 2.1 List of investigated building after the Nepal EQ 2015

Id	Latitude	Longitude	No. Floors	Floor Area [m^2]	Total Floor Area [m^2]	Column Area [m^2]	Masonry Wall Area (NS) [m^2]	Masonry Wall Area (EW) [m^2]	Structural Damage
17352	27.65	85.33	6	289	1736	4.99	5.34	3.19	None
17353	27.65	85.33	2.5	88	219	0.84	0	0	None
17354	27.65	85.33	2	80	159	0.84	4.15	0.72	None
17355	27.65	85.33	2	80	159	0.84	4.15	0.72	None
17356	27.65	85.33	3	67	201	0.84	2.21	0	None
17357	27.65	85.33	2.5	71	177	0.84	4.34	0	None
17358	27.73	85.31	5.5	80	440	0.84	3.28	0.21	Severe
17359	27.73	85.31	6	118	710	1.24	0.79	0.93	Light
17360	27.73	85.31	3	154	461	1.7	9.6	7.54	None
17361	27.73	85.31	5	89	443	1.21	0.73	2.15	Light
17362	27.73	85.31	4.5	272	1225	1.62	2.23	0.34	Severe
17363	27.73	85.31	4	120	479	0.84	8	1.74	Severe
17365	27.73	85.31	3.5	531	1859	5.02	3.06	17.02	Severe
17366	27.73	85.31	6	63	377	1.05	2.66	0.31	None
17369	27.73	85.31	4	102	408	1.74	4.73	1.23	Moderate
17370	27.73	85.31	4	106	424	2.23	5.75	1.93	Moderate
17371	27.73	85.31	4	88	352	1.05	5.39	4.45	Severe
17374	27.73	85.31	3	35	106	0.84	0.82	0	None
17375	27.73	85.31	5.5	130	715	0.94	3.48	0	Severe
17376	27.73	85.31	6	139	834	1.41	5.4	1.35	Severe
17377	27.73	85.31	5.5	54	299	0.77	2.62	2.74	Severe
17378	27.74	85.31	4.5	52	234	0.63	1.89	2.21	Light
17379	27.74	85.31	5.5	143	789	1.86	0	0	Severe
17380	27.74	85.31	4.5	75	338	1.39	2.73	1.44	Severe
17381	27.74	85.31	7.5	126	946	1.11	1.72	4.61	Severe
17382	27.74	85.31	4.5	64	290	0.57	6	2.33	Moderate
17384	27.69	85.30	6	250	1498	2.3	4.16	1.11	Severe
17385	27.73	85.31	4	101	403	1.05	3.47	0	None
17386	27.74	85.31	5.5	158	870	1.46	8.9	0	Severe
17387	27.74	85.31	6	81	486	0.84	2.64	0.3	Severe
17388	27.74	85.31	5	84	418	0.84	4.73	0.31	Severe
17389	27.74	85.31	5	160	801	1.33	3.05	0	Severe
17390	27.69	85.30	6	122	729	1.25	5.14	0.49	Light
17391	27.74	85.31	5.5	45	248	0.63	1.1	1.12	Light
17392	27.74	85.31	5.5	93	510	1.11	5.28	1.85	None

Id	Latitude	Longitude	No. Floors	Floor Area [m^2]	Total Floor Area [m^2]	Column Area [m^2]	Masonry Wall Area (NS) [m^2]	Masonry Wall Area (EW) [m^2]	Structural Damage
17393	27.74	85.31	5	99	496	1.11	6.99	0	Severe
17394	27.74	85.30	3.5	105	369	0.78	0	1.73	Severe
17395	27.74	85.30	3	102	306	0.78	4.13	0	Moderate
17396	27.74	85.31	5.5	97	532	1.05	7.71	1.34	None
17397	27.69	85.30	6.5	126	818	1.25	3.72	0.55	Severe
17398	27.69	85.30	6.5	126	818	1.25	3.72	0.55	Severe
17399	27.69	85.30	6.5	250	1623	2.3	4.46	1.11	Severe
17400	27.73	85.31	3	53	160	1.03	0	0	Severe
17401	27.74	85.31	5.5	87	478	0.77	3.87	0	Moderate
17402	27.74	85.31	4	438	1752	3	8.41	4.68	None
17403	27.74	85.31	5	99	495	1.24	5.87	0.97	Light
17404	27.74	85.31	7	110	771	1.04	1.69	3.06	Severe
17405	27.74	85.31	1.5	98	147	1.67	4.18	2.55	None
17406	27.74	85.31	3	124	371	1.08	2.79	5.25	None
17407	27.69	85.30	6	250	1498	2.3	4.29	1.11	Severe
17408	27.69	85.29	3.5	59	207	1.02	2.23	3.76	Severe
17409	27.69	85.30	3.5	66	232	0.63	5.31	2.97	Severe
17410	27.69	85.30	3.5	128	447	1.01	6.04	2.88	Severe
17411	27.69	85.29	3.5	60	211	0.63	1.35	0.84	Light
17412	27.69	85.29	3.5	49	170	0.84	2.74	1.68	Severe
17414	27.69	85.30	3.5	22	75	0.42	0	0.82	Severe
17415	27.69	85.29	3	37	110	0.63	1.34	0	Light
17416	27.69	85.29	3	56	168	0.77	4.41	1.38	Light
17417	27.69	85.29	4	75	298	0.84	4.31	3.73	Light
17418	27.69	85.30	3	59	176	0.63	1.9	0	Severe
17419	27.69	85.29	4	63	253	0.91	2.38	0.62	Severe
17420	27.69	85.28	4	81	322	1.11	7.15	0.6	None
17421	27.69	85.28	2	60	121	0.63	1.77	0.75	Light
17422	27.69	85.28	6	106	634	1.18	1.55	0	Severe
17423	27.69	85.28	4.5	55	249	0.63	2.57	0.2	Severe
17424	27.69	85.28	5.5	269	1482	2.23	4.18	0	Severe
17425	27.69	85.28	2.5	120	301	1.18	2.46	1.5	None
17426	27.69	85.28	3.5	62	219	0.57	2.79	0	None
17427	27.69	85.28	3	63	190	0.63	3.75	1.36	None
17428	27.69	85.28	3	70	210	0.73	0	0	None
17429	27.69	85.28	2.5	53	132	0.63	4.29	0	None
17430	27.69	85.28	5	116	582	0.99	3.97	1.22	Severe

Id	Latitude	Longitude	No. Floors	Floor Area [m^2]	Total Floor Area [m^2]	Column Area [m^2]	Masonry Wall Area (NS) [m^2]	Masonry Wall Area (EW) [m^2]	Structural Damage
17431	27.69	85.29	3.5	41	143	0.52	2.25	0.66	None
17432	27.69	85.29	3	76	228	0.73	4.55	0.05	Severe
17433	27.70	85.28	3.5	52	182	0.47	0.81	0.89	Moderate
17434	27.70	85.28	4	73	291	0.77	1.88	1.65	Severe
17435	27.70	85.28	2.5	64	159	0.47	0	0.71	Moderate
17436	27.70	85.28	3	102	307	0.63	0	3.3	Severe
17437	27.70	85.28	4.5	56	253	0.63	5.23	0	Severe
17438	27.71	85.28	4	65	261	0.63	4.51	0	Severe
17439	27.71	85.28	4.5	118	533	1.58	4.78	1.94	Severe
17440	27.71	85.28	5.5	165	908	1.49	7.62	0	Severe
17443	27.71	85.28	4	83	333	1.3	6.96	1.2	None
17444	27.71	85.28	4	148	593	1.67	5.62	4.62	Severe
17445	27.71	85.28	2.5	105	261	1.52	6.02	0.3	None
17446	27.71	85.28	4	151	604	1.46	6.79	5.64	Severe
17447	27.71	85.28	3.5	165	576	1.15	7.26	3.53	None
17448	27.71	85.28	4	130	520	1.24	2.54	0.34	Severe
17449	27.71	85.28	3.5	43	152	0.76	2.07	0	Moderate
17450	27.71	85.28	5.5	71	388	0.93	4.6	0	None
17451	27.71	85.28	3.5	45	158	1.08	2.21	1.33	None
17452	27.71	85.28	3.5	265	929	2.6	5.41	0	Severe
17453	27.71	85.28	2.5	68	170	0.65	1.79	0.63	None
17454	27.71	85.28	3.5	83	291	0.84	4.88	0	Severe
17455	27.71	85.27	2.5	87	217	0.84	5.02	0	None
17456	27.71	85.27	3.5	69	241	0.73	5.05	0	Moderate
17457	27.71	85.28	4.5	83	372	1.11	2.39	0.62	None
17458	27.71	85.28	3.5	81	285	1.3	2.58	0	Severe
17459	27.71	85.28	3.5	113	396	0.52	3.83	0	Moderate
17460	27.71	85.28	3.5	136	476	0.84	2.08	1.37	None
17461	27.71	85.28	3	110	330	0.73	0	0.78	None
17462	27.71	85.28	4	96	384	0.73	3.29	0	Severe
17463	27.71	85.28	2.5	95	237	0.72	0	0	Severe
17464	27.71	85.28	1.5	67	100	0.84	1.47	2.32	None
17465	27.71	85.28	2	91	182	0.81	0.33	2.27	None
17466	27.71	85.28	2.5	78	196	0.49	0	0.4	Severe
17467	27.72	85.30	4	59	234	0.77	3.12	1.89	Severe
17468	27.72	85.30	2	70	139	1.18	5.31	2.28	None

Id	Latitude	Longitude	No. Floors	Floor Area [m^2]	Total Floor Area [m^2]	Column Area [m^2]	Masonry Wall Area (NS) [m^2]	Masonry Wall Area (EW) [m^2]	Structural Damage
17469	27.72	85.30	2	49	98	0.84	1.45	0.95	None
17471	27.72	85.30	3	76	229	0.91	5.06	1.45	Severe
17472	27.71	85.30	4	166	665	1.86	1.99	2.96	Severe
17473	27.71	85.30	4	51	204	0.47	2.31	1.25	Moderate
17474	27.71	85.30	2	49	98	0.63	1.64	0	None
17475	27.71	85.30	4	105	421	1.56	2.13	0	Severe
17476	27.71	85.30	4.5	96	432	0.98	4.76	1.71	Light
17477	27.71	85.30	3.5	51	179	0.7	2.23	0	Severe
17478	27.72	85.30	3	63	189	0.84	5.46	0.34	Light
17479	27.72	85.30	3.5	69	243	0.93	5.06	0	None
17480	27.72	85.30	4.5	62	278	0.52	1.71	2.01	None
17481	27.72	85.30	3.5	50	174	0.47	2.59	0	Severe
17482	27.72	85.30	2.5	68	170	0.84	3.22	1.64	None
17484	27.72	85.30	2	81	163	1.22	0.7	1.38	None
17485	27.72	85.30	3.5	65	229	0.98	1.15	0	None
17486	27.72	85.30	3.5	69	242	0.95	3.11	0	Severe
17488	27.72	85.30	6.5	72	471	0.63	1.64	1.73	None
17489	27.73	85.34	6	243	1460	3.07	2.35	1.73	Light
17490	27.73	85.34	5	351	1757	3.25	2.21	1.73	Light
17491	27.73	85.34	6	164	983	1.67	0.25	1.11	None
17492	27.73	85.34	6	243	1460	3.07	1.93	1.73	None
17493	27.73	85.34	7	302	2114	3.81	2.95	1.73	Light
17495	27.73	85.34	5.5	149	820	1.86	2.35	1.67	Light
17496	27.72	85.30	5	243	1217	3.07	1.59	1.73	None
17497	27.73	85.34	5	123	615	1.67	1.58	1.11	Light

2.2.2 The 2016 Ecuador earthquake

2.2.2.1 Introduction

The 2016 Ecuador earthquake occurred on April 16 with a moment magnitude of 7.8. The earthquake struck at Muisine as shown in Figure 2.7, the coast of Ecuador at a depth of approximately 21 km, causing widespread severe damage to buildings and infrastructure. The most of coastal towns- particularly Pedernales, Canoa, Bahia de Caraquez, Manta and Portoviejo experienced severe damage after the major shock (see Figure 2.8). The earthquake caused about 700 people killed and 80, 000 people were homeless due to severely damaged or collapse of buildings (Source: Build change, 2016).

Figure 2.7 Location of the Ecuador earthquake (source: USGS)

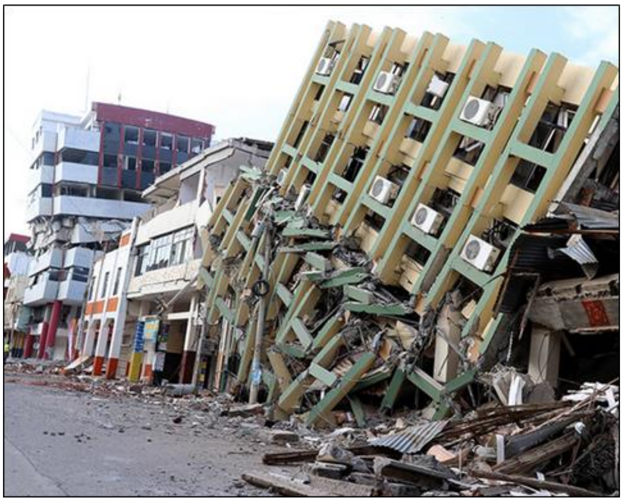


Figure 2.8 Location of the Ecuador earthquake (source: USGS)

2.2.2.2 Ground motion characteristics

Figures 2.9 show accelerograms (two components) recorded at AMANTA station (Latitude: -0.941, Longitude: -80.735) at Manta city near the investigated buildings for earthquake main shock. An inspection of the time histories data indicated that the Peak Ground Acceleration (PGA) of recoded ground motion is about 400 cm/s^2 and 500 cm/s^2 for EW and NS direction respectively (Build Change, 2016).

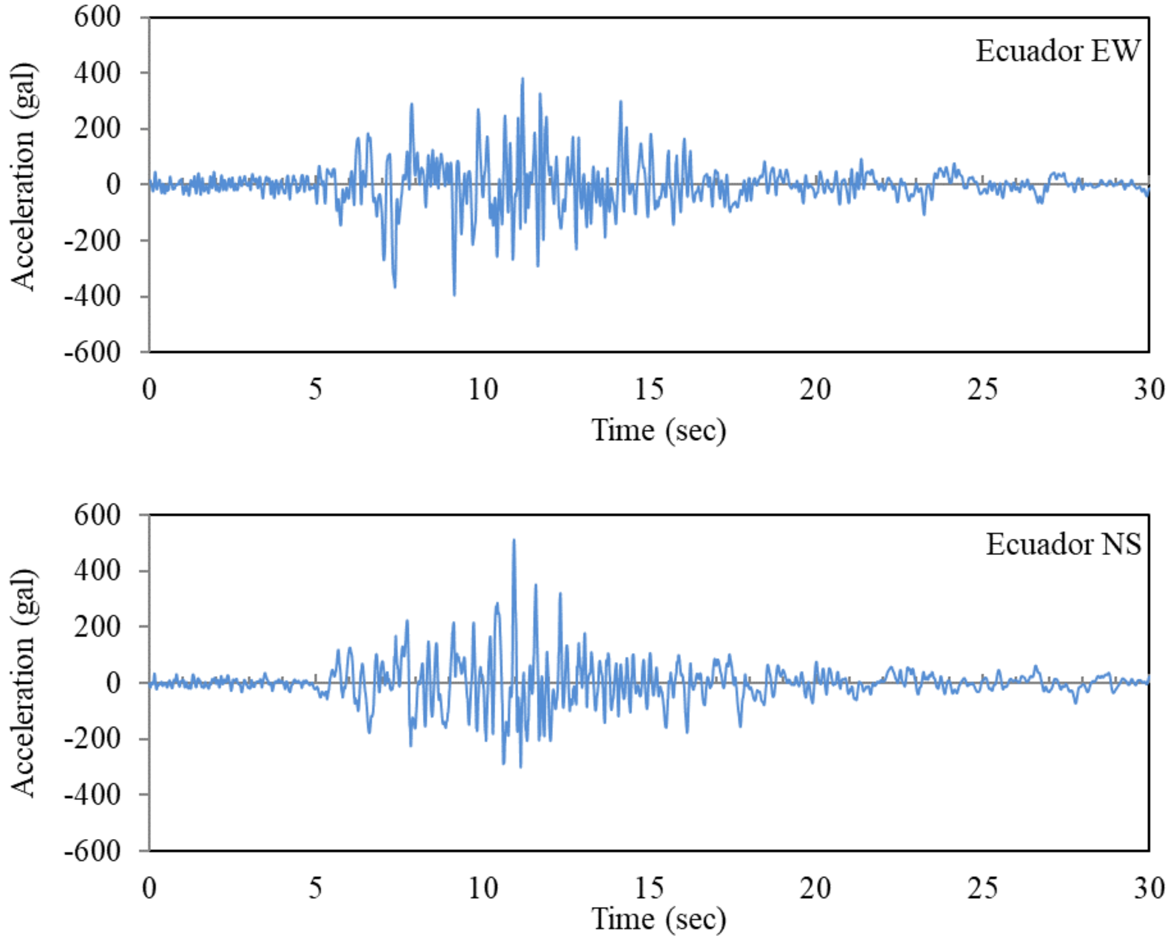


Figure 2.9 Ground motion time history recorded at Manta station in Ecuador earthquake

Acceleration response spectra has been plotted as shown in Figure 2.10, for the ground motion recorded at Manta station, Ecuador. It has been observed that the response acceleration 1.0 g for both directions (Juan et al. 2016).

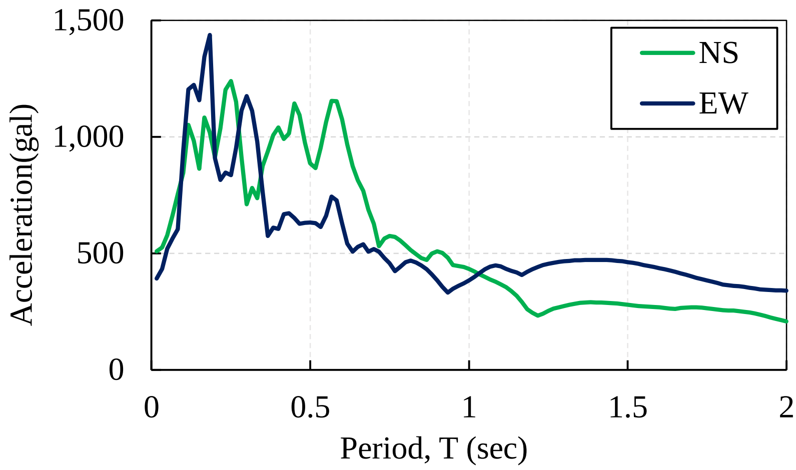


Figure 2.10 Acceleration Response Spectrum of the Ecuador EQ 2016

2.2.2.3 Location of investigated RC buildings

A number 171 of RC with masonry infilled buildings have been collected from the earthquake damage database. The investigated buildings are located at 4 (four) cities such as Manta, Portoviejo, Bahia de Caraquez and Chone as shown in Figure 2.11. However, most of them are located at Manta city near Manta earthquake ground motion station. The buildings are located four different cities which are about 50 km from the epicenter of the earthquake.

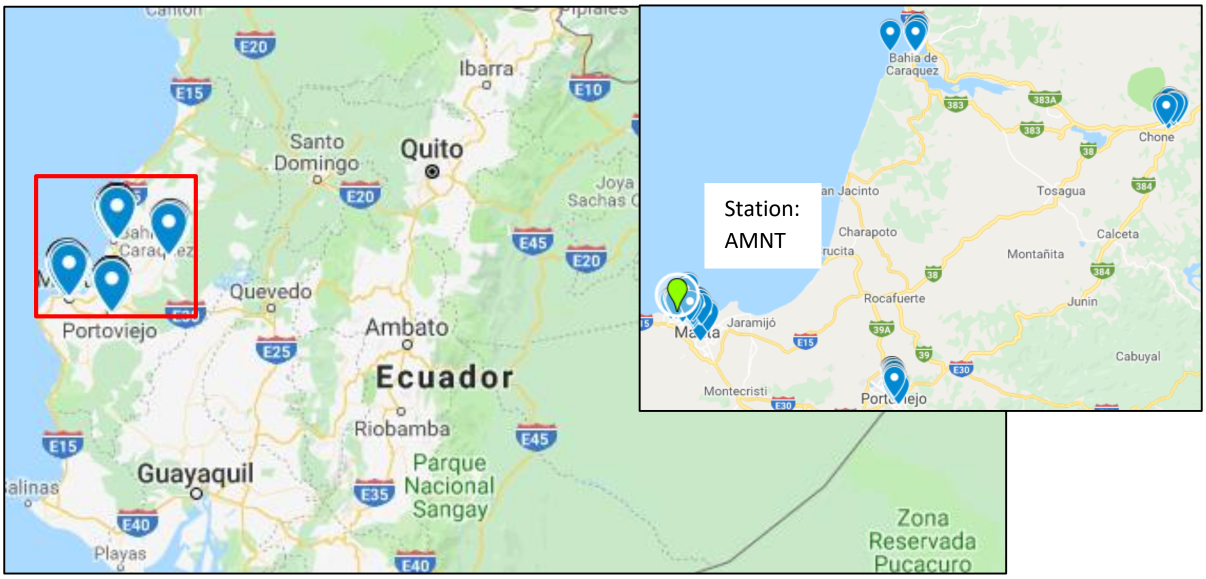


Figure 2.11 Location of surveyed buildings in Ecuador earthquake

2.2.2.4 Buildings characteristics

The investigation of surveyed buildings demonstrates that most of the buildings are RC with masonry infill. The basic information is shown in Table 2. From the table, it has been seen that the total floor area is ranging from 150 m^2 to 3000 m^2.

Figure 2.12 shows distribution of number of stories. Most of the buildings are 2 to 3 storied buildings. Floor plan ranges 22 to 1341 sq. m with average and standard deviation are 218 and 155 sq. m. Typical column size is about 200 mm x200mm. Thickness of masonry infill is of 230mm which is commonly found.

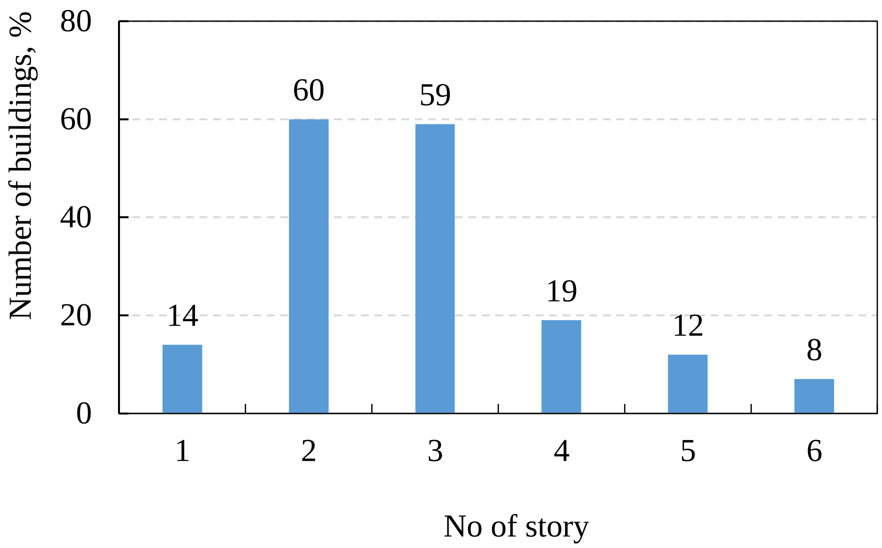


Figure 2.12 Distribution according to number of stories.

Table 2.2 List of RC buildings for Ecuador earthquake

Building Id	Latitude	Longitude	No. Floors	Floor Area [m^2]	Total Floor Area [m^2]	Column Area [m^2]	Masonry Wall Area (NS) [m^2]	Masonry Wall Area (EW) [m^2]	Structural Damages
124115	-0.95	-80.72	6	527	3160	9.7	4.3	3	Severe
124116	-0.95	-80.72	2	84	168	0.5	2.9	0.5	Moderate
124117	-0.95	-80.71	2	321	642	1.6	3.7	2.9	Light
124118	-0.95	-80.72	2	87	174	0.9	4.4	0.7	Light
124119	-0.95	-80.71	3	102	307	0.9	0.9	3.1	Moderate
124120	-0.95	-80.71	4	107	430	1.4	3.7	0.8	Severe
124121	-0.95	-80.71	4	143	570	3	1.2	2.3	Moderate
124122	-0.96	-80.72	2	300	599	3.7	3.2	3	Severe
124124	-1.05	-80.45	5	205	1026	2.8	2.6	3.7	Severe
124125	-1.06	-80.45	4	686	3169	5	4	4.3	Severe
124126	-1.06	-80.45	3	109	327	2.2	0.9	1.1	Moderate
124127	-1.06	-80.45	3	159	477	1.9	13.2	1.2	Severe
124128	-1.06	-80.45	2	170	339	2.2	1	4	Light
124129	-1.06	-80.45	1	114	114	1	1.6	0.9	Moderate
124130	-1.06	-80.45	3	139	417	1.8	7.3	0.7	Severe
124131	-1.06	-80.45	2	448	897	2.2	5	1.7	Severe
124132	-1.06	-80.45	3	242	726	3	4.4	1.9	Severe
124133	-0.95	-80.72	3	48	144	0.5	2.2	0.5	Moderate
124134	-0.95	-80.72	2	44	88	0.4	1.1	0.3	Moderate
124135	-0.96	-80.72	4	206	824	2.8	3.1	4.5	Severe
124136	-0.98	-80.71	1	150.48	150.48	0.7	2.4	0.7	Severe
124137	-0.95	-80.74	3	522	1566	5.4	7.2	6.1	Severe
124138	-0.94	-80.73	1	1027	1027	3.6	6.9	7.2	Light
124139	-0.70	-80.09	2	328	657	2.2	2.8	5.3	Moderate
124140	-0.70	-80.09	2	312	623	3.3	5.9	5.2	Light
124141	-0.70	-80.09	2	351	702	2.8	5	6.5	Severe
124142	-0.70	-80.08	2	317	635	2.3	3.3	3.1	Severe
124143	-0.70	-80.08	2	113	226	1.4	0	2.7	Light
124144	-0.69	-80.09	2	157	314	2	2	3.9	Light
124145	-1.04	-80.46	3	229	688	1.1	0	2.7	Severe
124146	-1.04	-80.46	3	225	676	1.1	0	2.8	Moderate
124147	-1.04	-80.46	3	284	852	1.7	3.4	0	Severe
124148	-1.04	-80.46	4	218	874	3	1.9	2.1	Severe
124149	-1.04	-80.46	3	229	688	1.7	3.4	0	Light
124150	-1.05	-80.45	3	237	712	5	3.9	0	Light

Building Id	Latitude	Longitude	No. Flors	Floor Area [m^2]	Total Floor Area [m^2]	Column Area [m^2]	Masonry Wall Area (NS) [m^2]	Masonry Wall Area (EW) [m^2]	Structural Damages
124151	-1.06	-80.45	5	262	1310	3.2	2.9	1.9	Severe
124152	-0.96	-80.72	2	164	328	1.6	0	1.7	Severe
124153	-0.96	-80.72	2	43	86	0.6	0.9	4.1	Severe
124154	-0.95	-80.72	2	161	323	0.6	2.7	0.4	Light
124155	-0.96	-80.72	1	258	258	0.8	1.5	7.9	Severe
124156	-0.96	-80.72	2	178	356	2.4	0.5	3.4	Moderate
124157	-0.96	-80.71	1	164	164	1.4	2.8	2.1	Light
124158	-0.94	-80.73	3	271	813	2.3	2	4.1	Severe
124159	-0.95	-80.71	3	66	197	1	1.1	0.5	Light
124160	-0.95	-80.71	2	138	276	1.5	4	0.8	Severe
124161	-0.60	-80.42	4	180	719	1.9	3.6	3.4	Severe
124162	-0.60	-80.42	6	183	1098	3.7	2.2	6.2	Severe
124163	-0.60	-80.42	4	358	1433	3.4	2.5	5.8	Severe
124164	-0.60	-80.43	2	157	315	1.2	3.1	0	Severe
124165	-0.60	-80.43	2	136	272	1.1	0	1.7	Moderate
124166	-0.60	-80.43	2	116	232	1.1	0	1.3	Moderate
124167	-0.60	-80.43	2	218	437	1.7	4	0	Severe
124168	-0.60	-80.43	2	173	346	2.1	2.1	1.4	Moderate
124169	-0.60	-80.43	2	156	312	2	2.4	0	Moderate
124170	-0.60	-80.43	2	145	290	2	2	1.5	Moderate
124171	-0.60	-80.42	5	248	1242	2.9	3.5	1.3	Moderate
124172	-0.60	-80.42	6	258	1545	5.3	2.3	1.3	Severe
124173	-0.60	-80.42	3	179	537	1.8	1	0	Light
124174	-0.60	-80.42	3	171	514	2.2	1.5	1.2	Light
124175	-0.95	-80.72	3	475	1425	4.3	5.2	3.2	Moderate
124176	-0.95	-80.72	4	60	238	1	0.8	0	Moderate
124177	-0.95	-80.72	5	60	299	1.2	2.1	1	Light
124178	-0.95	-80.72	5	77	387	0.9	0.3	1.4	Light
124179	-0.95	-80.72	5	83	414	1.3	0.9	0.3	Severe
124181	-0.95	-80.71	2	77	155	1.4	0	2.1	Light
124182	-0.95	-80.71	2	366	731	3.1	5.9	2	Light
124183	-0.95	-80.71	5	61	305	2.4	2	1.4	Severe
124184	-0.95	-80.71	2	162	324	1.5	3.1	2.2	Light
124185	-0.95	-80.71	3	89	266	1.6	3.9	8.2	Light

Building Id	Latitude	Longitude	No. Floors	Floor Area [m^2]	Total Floor Area [m^2]	Column Area [m^2]	Masonry Wall Area (NS) [m^2]	Masonry Wall Area (EW) [m^2]	Structural Damages
124186	-0.96	-80.72	2	157	315	1.4	2	1	Light
124187	-1.05	-80.45	2	209	418	3.2	4.8	1.4	Light
124188	-1.05	-80.45	5	131	657	3.6	1.4	2	Moderate
124189	-1.05	-80.45	4	164	656	2	1.3	1.2	Moderate
124190	-1.05	-80.45	3	176	528	1.8	1.6	7.6	Severe
124191	-1.05	-80.45	5	130	583	1.8	1	1.1	Severe
124192	-1.05	-80.45	3	129	388	1.8	1	1.1	Severe
124193	-1.05	-80.45	6	222	1333	3	3.1	0.1	Severe
124194	-1.05	-80.45	4	123	493	1.4	0.6	1.4	Severe
124195	-0.96	-80.71	3	264	792	3.2	1	2.7	Severe
124196	-0.96	-80.72	3	153	460	1.4	5.3	1.8	Severe
124197	-0.95	-80.71	2	87	175	0.8	2	1.1	Moderate
124198	-0.94	-80.73	2	229	459	3.6	0	1.4	Light
124199	-0.94	-80.73	1	223	223	1.7	1.4	0	Light
124200	-0.95	-80.74	3	344	1031	3.5	1.6	2.4	Severe
124201	-0.96	-80.70	3	254	762	2.1	1.1	0	Light
124202	-0.70	-80.10	2	432	864	2.3	2.3	5	Light
124203	-0.70	-80.10	2	474	947	2.7	2.3	5.1	Light
124204	-0.70	-80.10	1	184	184	1.4	3	0.3	Light
124205	-0.70	-80.10	2	229	459	1.8	0.6	0.8	Light
124206	-0.70	-80.09	1	231	231	1.8	4	0	Light
124207	-0.70	-80.09	2	146	292	2	2.4	2.4	Light
124208	-1.05	-80.46	3	230	689	2.1	1.3	0	Light
124209	-1.04	-80.45	3	221	663	4.2	1.6	1.9	Severe
124210	-1.04	-80.45	3	368	1105	4.8	1.8	2.3	Severe
124211	-1.04	-80.45	3	322	965	3.8	2.6	1.9	Severe
124212	-1.04	-80.45	3	235	704	1.7	5	0	Moderate
124213	-1.04	-80.45	3	233	700	2.1	5.8	0	Light
124214	-1.04	-80.45	3	229	688	1.7	0.8	2.6	Light
124215	-1.06	-80.45	2	336	672	2.3	2.4	0	Severe
124216	-1.06	-80.45	2	181	362	2.2	2.2	0	Light
124217	-0.95	-80.74	2	221	443	1.7	3.6	0.4	Light
124218	-0.95	-80.74	1	221	221	1.7	0.4	3	Light
124219	-0.95	-80.74	2	349	699	2.1	3.1	1.7	Severe
124220	-0.96	-80.73	3	224	672	1.7	3.8	0	Light
124221	-0.96	-80.73	2	158	317	1.2	1.8	0	Light

Building Id	Latitude	Longitude	No. Floors	Floor Area [m^2]	Total Floor Area [m^2]	Column Area [m^2]	Masonry Wall Area (NS) [m^2]	Masonry Wall Area (EW) [m^2]	Structural Damages
124222	-0.96	-80.73	2	226	451	1.8	4.2	3.4	Light
124223	-0.95	-80.73	2	146	292	2	2.7	0	Light
124224	-0.95	-80.73	1	159	159	1.3	2.3	1.2	Light
124225	-0.96	-80.72	4	138	550	1.2	0.9	1.5	Severe
124226	-0.95	-80.71	3	108	325	1.4	4.3	0	Severe
124227	-0.96	-80.72	5	125	625	1.6	1.3	1.2	Severe
124228	-0.60	-80.43	2	279	572	2.3	0.7	0.6	Severe
124229	-0.59	-80.42	6	309	1781	5.6	5.7	1.2	Moderate
124230	-0.61	-80.42	3	192	514	1.6	1.3	1.5	Severe
124231	-0.60	-80.42	1	175	175	1.2	3.1	0	Moderate
124232	-0.60	-80.42	1	183	183	2.2	3.7	4.2	Light
124233	-0.93	-80.72	3	296	889	2.2	2	2.8	Severe
124234	-0.96	-80.72	3	85	254	0.4	0.4	1.5	Severe
124235	-0.95	-80.72	2	135	270	1.2	0	2.5	Light
124236	-0.97	-80.70	2	165	330	1.1	4.7	1.5	Severe
124237	-0.95	-80.72	6	527	3160	9.7	4.3	3	Severe
124238	-0.95	-80.72	4	75	301	1.5	0.8	0.4	Moderate
124239	-0.95	-80.72	3	201	603	1.7	2.6	2.6	Moderate
124240	-0.96	-80.71	3	276	827	1.4	3.6	4.9	Moderate
124241	-0.96	-80.71	3	149	447	1.2	2.3	0.5	Severe
124242	-0.96	-80.71	5	248	1240	0.9	1	2.4	Severe
124243	-0.96	-80.72	2	139	278	1.5	2.5	1	Severe
124244	-1.06	-80.45	3	92	277	1	2.7	0.7	Moderate
124245	-1.06	-80.45	3	92	275	1.6	1.5	1	Severe
124246	-1.06	-80.45	3	114	343	1	2.8	0.9	Severe
124247	-1.06	-80.45	4	51	205	1.2	0.6	1.3	Moderate
124248	-1.06	-80.45	4	686	3169	5	4	4.3	Severe
124249	-1.06	-80.45	3	137	412	0.94	3.8	1.3	Severe
124250	-1.06	-80.45	4	93	374	1.9	1.8	1.5	Moderate
124251	-1.06	-80.45	3	82	245	1.3	4.1	0.4	Moderate
124252	-0.70	-80.10	2	175	350	1.1	3.1	2.7	Light
124253	-0.70	-80.10	1	259	259	1.3	1.9	1.8	Severe
124254	-0.70	-80.09	3	332	996	3.5	2.5	0.4	Severe
124255	-0.70	-80.09	2	276	551	1.4	3.6	4.9	Severe
124256	-0.70	-80.10	3	283	850	1.9	7.1	3.7	Severe
124257	-1.05	-80.45	3	146	437	1.1	2.6	2.5	Severe

Building Id	Latitude	Longitude	No. Floors	Floor Area [m^2]	Total Floor Area [m^2]	Column Area [m^2]	Masonry Wall Area (NS) [m^2]	Masonry Wall Area (EW) [m^2]	Structural Damages
124257	-1.05	-80.45	3	146	437	1.1	2.6	2.5	Severe
124258	-1.05	-80.45	3	266	799	2	0.7	0.8	Severe
124259	-1.05	-80.45	3	235	704	1.8	2.7	0	Light
124260	-1.05	-80.45	3	227	680	1.8	0.4	2.7	Severe
124261	-1.05	-80.45	3	206	619	1.6	0	2.8	Severe
124262	-1.05	-80.45	3	198	594	1.9	2.7	0.3	Moderate
124263	-1.05	-80.45	3	174	523	1.3	0	2.7	Light
124264	-1.05	-80.45	4	148	523	2.6	4.8	3	Light
124265	-1.05	-80.45	2	201	403	1.5	2.7	2.7	Light
124266	-1.05	-80.45	3	235	705	1.7	4.1	2.3	Severe
124267	-0.95	-80.74	1	413	413	4.2	8.2	12.3	Moderate
124268	-0.95	-80.74	2	179	357	1	2.9	2.2	Moderate
124269	-0.95	-80.74	2	215	429	1.7	2.9	0.4	Light
124270	-0.95	-80.74	2	215	429	1.7	3.6	3.3	Light
124271	-0.95	-80.74	3	113	339	1.4	1.6	3	Severe
124272	-0.96	-80.71	2	81	162	0.8	2.5	0.3	Moderate
124273	-0.60	-80.42	5	324	1438	8.6	4.5	1.5	Severe
124274	-0.60	-80.42	4	403	1428	3.4	4	5.8	Severe
124275	-0.60	-80.42	4	89	356	0.6	4	0.8	Light
124276	-0.60	-80.42	4	356	1424	4.1	2.7	6.8	Moderate
124277	-0.60	-80.46	2	101	202	0.9	0.6	2	Severe
124278	-0.60	-80.43	2	1341	2606	8.8	10.4	6.6	Moderate
124279	-0.61	-80.42	3	301	903	2.3	2.6	6.2	Severe
124280	-0.60	-80.43	6	349	2094	3.6	0.5	1.1	Moderate
124281	-0.94	-80.72	2	53	105	1.1	1.5	1.2	Light
124282	-0.94	-80.72	2	103	205	1.8	1.4	1.8	Moderate
124283	-0.95	-80.72	2	99	199	0.8	0.8	1.5	Moderate
124284	-0.95	-80.72	3	107	322	0.8	4.4	2.7	Severe
124285	-0.95	-80.72	3	147	442	1	4.4	1.5	Severe
124286	-0.95	-80.72	3	155	464	0.9	2.7	0.7	Moderate
124287	-0.95	-80.72	2	78	156	0.9	5.7	1.4	Light

2.2.3 The 2016 Taiwan earthquake

2.2.3.1 Introduction

On 6 February 2016, an earthquake of 6.6 occurred in southern Taiwan. The epicenter is located in the Meinong District at a depth of approximately 14.6 km as shown in Figure 2.13. The earthquake caused widespread damage, resulting huge casualties. Many low rise RC buildings were collapsed due to this catastrophic earthquake. A large amount on building severely damaged in Tainan city which is near the epicenter of the earthquake as shown in Figure 2.13.

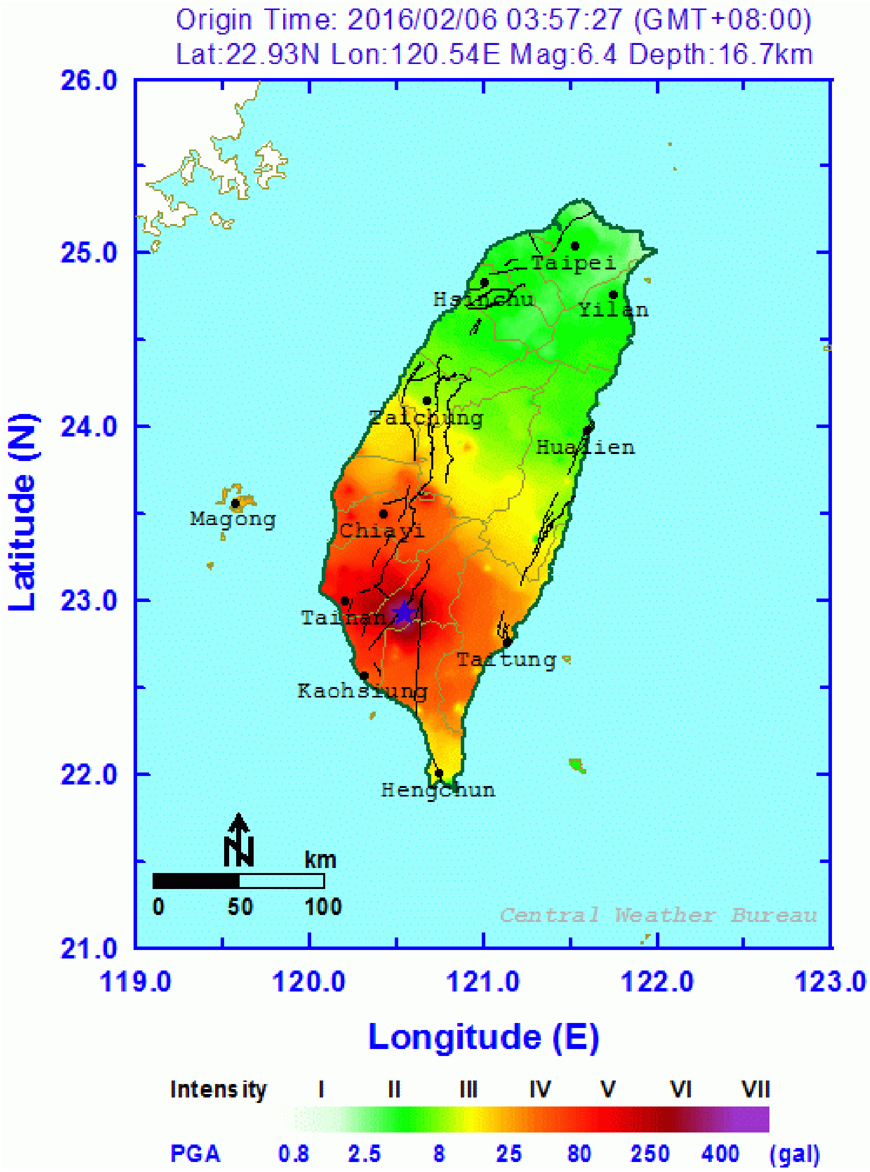


Figure 2.13 Shake map of Taiwan earthquake (USGS, 2016)

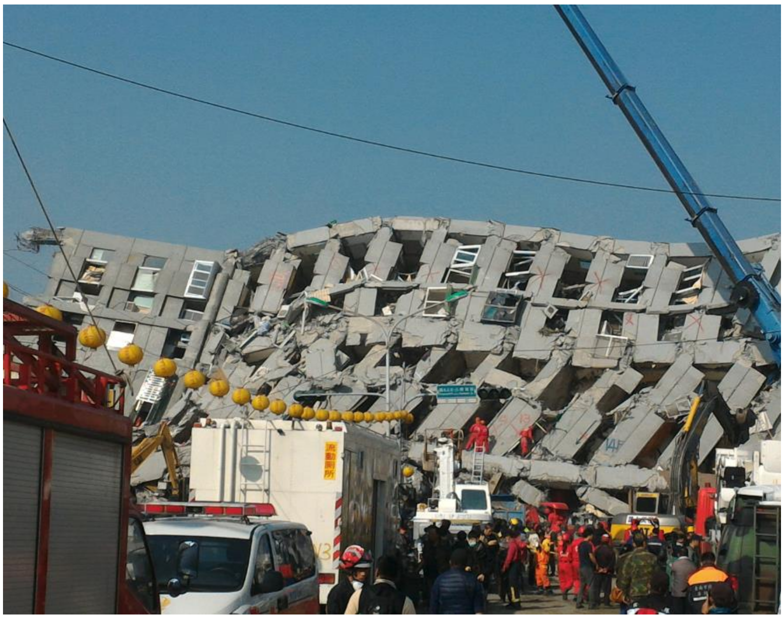


Figure 2.14 Severely damaged buildings in Taiwan earthquake (datacenterhub.org)

2.2.3.2 Ground motion characteristics

The accelerograms recorded at station CHY062 (Latitude 23.12 N, Longitude120.45 E) located near investigated buildings as shown in Figure 2.15. The ground motion inspection states that the peak ground acceleration (PGA) has been considered 444 gal and 426.2 gal in NS and EW directions, respectively as shown in Figure 2.15(a) and 2.15(b).

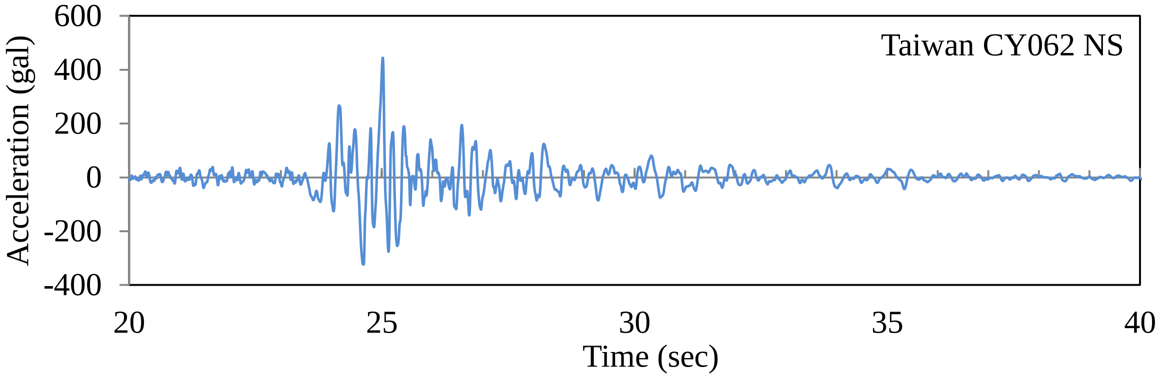


Figure 2.15 (a) Ground motion at Station CH062 at Tainan City (USGS)

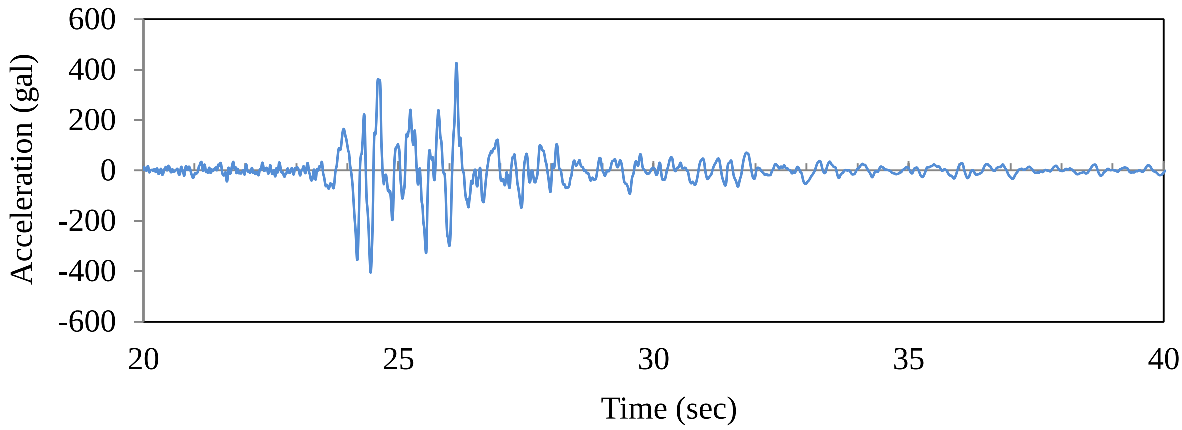


Figure 2.15 (b) Ground motion at Station CH062 at Tainan City (USGS)

Figure 2.16 shows acceleration response spectra for different stations of the 2016 Taiwan earthquake. The station CHY062 is located near the investigated buildings. It has been observed for station CHY062 that the acceleration response 1.0 g for both EW and NS direction respectively.

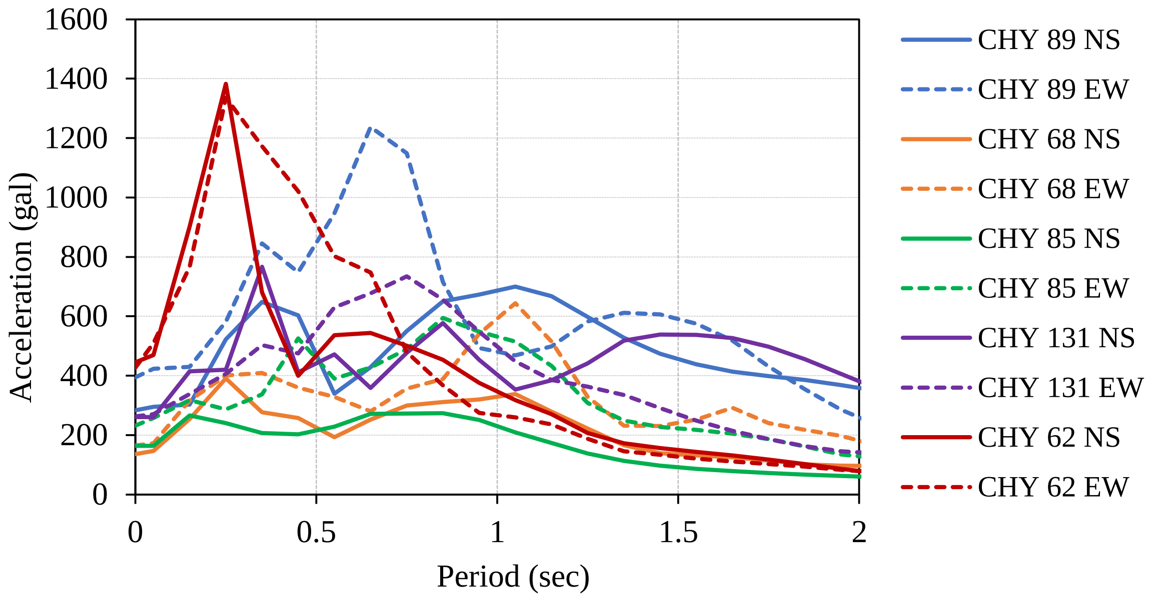


Figure 2.16 Acceleration response spectrum at different stations for Taiwan EQ 2016 (USGS)

2.2.3.3 Location of investigated RC buildings

A total number of 63 masonry infilled RC buildings have been selected for this study. All of buildings are school buildings located at Tainan city as shown in Figure 2.17. The buildings are located about 60 km from the epicenter of the earthquake. The ground motion observation station CHY062 is located near the investigated buildings.

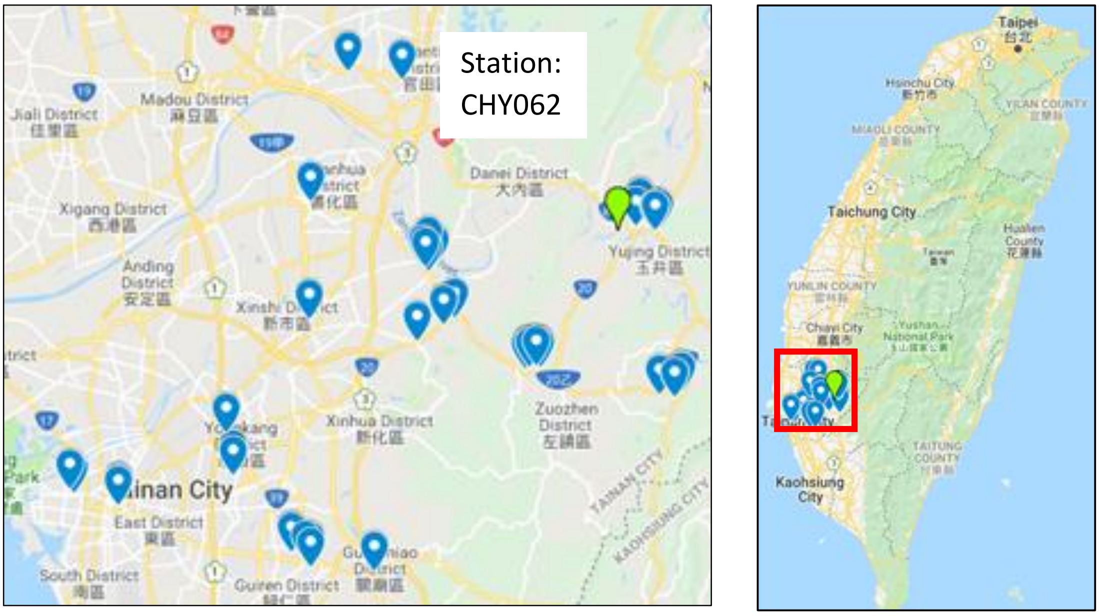


Figure 2.17: Location of surveyed buildings and ground motion observation station in the 2016 Taiwan earthquake (datacenterhub)

2.2.3.4 Buildings characteristics

All investigated buildings are RC buildings with masonry infill. As all investigated buildings are school buildings, therefore the buildings shape are almost rectangular in plan. Table 3 shows the basic information of the investigated buildings. It has been seen that the floor area ranged 140m^2 to 5000m^2. All surveyed buildings are school buildings. Figure 2.18 shows the distribution according to number of stories. Most of the investigated buildings are 2 to 3 storied buildings.

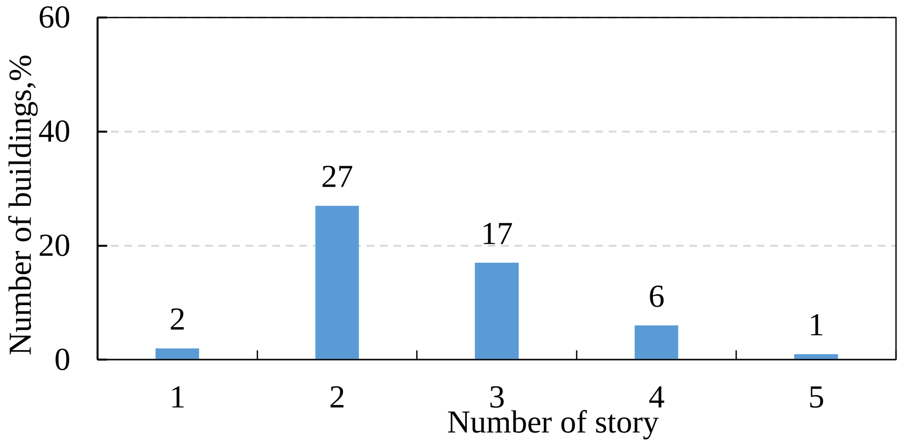


Figure 2.18 Distribution of building according to number of stories

Table 2.3 List of investigated buildings

Experiment or Case ID	Latitude	Longitude	No. Floors	Floor Area [m^2]	Total Floor Area [m^2]	Column Area [m^2]	Masonry Wall Area (NS) [m^2]	Masonry Wall Area (EW) [m^2]	Structural Damage
A03	23.12	120.46	2	633	1265	5.54	14.59	6.53	Light
A08	23.10	120.36	2	788	1576	9.19	18.36	6.37	No Damage
A10	23.07	120.35	2	297	594	4.19	4.44	0.00	No Damage
A12	23.01	120.26	3	47	140	0.38	0.68	2.64	Moderate
A21	23.19	120.32	3	443	1328	6.00	6.11	1.45	Light
B02-D02	23.12	120.47	2.5	191	478	3.15	4.10	0.10	Light
B05	23.12	120.46	2	615	1230	5.20	14.75	3.50	Light
B06	23.12	120.46	3	807	2421	8.60	0.00	18.48	Light
B10	23.10	120.35	3	700	2100	37.00	18.30	0.00	No Damage
B11	23.10	120.36	3	921	2763	8.70	21.10	0.00	Moderate
B13	22.99	120.20	5	97	485	3.00	0.00	10.50	Light
B14	22.99	120.20	4	193	772	3.60	5.00	0.00	Light
B15	22.99	120.20	4	1447	5788	40.00	3.40	11.00	No Damage
B16-A	23.01	120.26	3	1300	3900	15.80	16.80	4.25	No Damage
B16-B	23.01	120.26	3	1643	4929	21.15	18.48	10.92	No Damage
B20	23.06	120.41	2	153	305	1.58	5.50	2.83	No Damage
B22	23.04	120.48	2	240	480	4.20	7.10	3.70	Light
C09	23.10	120.35	3	400	1200	3.30	22.70	6.80	No Damage
C11	23.08	120.37	2	87	174	1.22	3.70	3.12	No Damage
C15	23.07	120.37	4	49	196	1.90	2.00	0.23	Light
C16	22.97	120.30	2	246	492	2.20	11.00	2.00	No Damage
C18	22.97	120.29	2	564	1128	6.60	14.00	3.70	Light
C19	23.06	120.40	2	355	710	3.40	6.50	4.70	No Damage
C23	23.06	120.40	3	302	906	8.80	8.50	0.42	No Damage

Experiment or Case ID	Latitude	Longitude	No. Floors	Floor Area [m^2]	Total Floor Area [m^2]	Column Area [m^2]	Masonry Wall Area (NS) [m^2]	Masonry Wall Area (EW) [m^2]	Structural Damage
D10	23.10	120.35	2	69	138	0.69	1.90	4.06	No Damage
D16	22.97	120.29	2	180	360	1.30	6.40	2.60	No Damage
D18	23.06	120.41	1	179	179	1.59	4.57	1.50	No Damage
D19	23.06	120.41	2	581	1162	5.30	15.58	7.38	No Damage
D20	23.06	120.41	2	109	218	1.80	0.00	3.93	No Damage
D21	23.04	120.47	2	915	1830	9.70	17.38	4.14	No Damage
D24	23.03	120.25	4	404	1616	6.80	0.00	11.52	No Damage
D25	23.19	120.34	2	686	1372	10.60	13.63	1.18	No Damage
E06	23.12	120.46	2	63	126	0.90	4.00	0.64	No Damage
E07	23.13	120.46	4	410	1640	5.13	8.00	10.90	No Damage
E08	23.11	120.36	1.2	482	578	7.30	3.10	4.60	No Damage
E14	23.06	120.41	2	475	950	9.18	0.00	0.40	No Damage
E15	23.06	120.41	2	300	600	1.64	5.60	2.50	Light
E16	23.06	120.41	2	172	344	2.01	4.30	3.10	No Damage
E17	23.04	120.48	2	321	642	2.80	11.40	2.10	No Damage
E19	23.13	120.30	3	171	512	2.48	3.40	1.94	Light
E22	23.00	120.18	2	81	161	1.00	5.10	0.00	No Damage
E23	23.00	120.18	3	207	621	2.49	2.80	10.66	No Damage
F05	23.12	120.47	3	188	564	1.49	5.60	2.30	Light
F06	23.10	120.36	2	560	1120	4.17	9.65	0.00	No Damage
F10	23.05	120.48	1	930	930	5.60	0.00	10.40	No Damage
F11	23.05	120.48	1	231	231	2.48	1.40	2.10	No Damage

Experiment or Case ID	Latitude	Longitude	No. Floors	Floor Area [m^2]	Total Floor Area [m^2]	Column Area [m^2]	Masonry Wall Area (NS) [m^2]	Masonry Wall Area (EW) [m^2]	Structural Damage
G02	23.08	120.36	4	504	2016	8.10	12.00	0.00	No Damage
A04	23.12	120.46	2	416	833	4.02	8.58	0.00	Severe
A07	23.10	120.35	3	479	1436	5.60	6.60	0.77	Severe
A16	23.06	120.41	3	571	1713	7.15	9.43	1.51	Severe
A17	23.04	120.48	3	531	1593	6.37	5.38	0.79	Severe
B03-D03	23.12	120.47	3	321	963	3.10	3.00	7.50	Severe
B04	23.12	120.46	3	820	2460	7.90	0.00	21.00	Severe
B09	23.10	120.35	3.5	580	2030	5.30	16.00	0.00	Severe
B21	23.04	120.48	2	508	1016	2.49	0.00	1.58	Severe
C04	23.12	120.47	2	362	724	2.40	9.70	6.80	Severe
C14	22.97	120.29	5	112	560	2.25	0.00	0.00	Severe
C17	22.96	120.30	3	145	435	2.53	9.80	1.07	Severe
D06	23.12	120.47	2	297	594	1.80	0.50	5.98	Severe
D07	23.12	120.47	3	352	1056	2.15	13.00	8.70	Severe
E10	23.08	120.36	3	345	1035	3.03	3.40	0.00	Severe
E13	22.96	120.33	3	56	168	0.58	0.50	1.80	Severe
F03	23.12	120.47	3	143	429	0.95	2.30	3.80	Severe
F04	23.12	120.47	2	480	960	2.50	9.64	7.40	Severe

2.3 Seismic capacity evaluation

2.3.1 Introduction

In this section, a simplified evaluation procedure has been described. First of all, some literature related to simplified evaluation procedure has been studied. Literature review are shown in the subsequent sections. Based on past literature, a simplified evaluation method has been proposed for rapid seismic evaluation.

2.3.2 Literature Review

Many researchers developed simplified methods for quick identification of the vulnerable buildings using some building parameters based on survey of past earthquake-damaged buildings (Shiga, et al. 1968, Hasan and Sozen, 1997, Ozcebe et al. 2004, Donmex and Pujol, 2005, Gur et al. 2009). These methods consider a rough measure of the ratio of the capacity of structures to resist lateral loads to the seismic demand. In addition, these methods require only the dimensions of the vertical members and floor plan and define the rank based on a two-dimensional plot using column and infill area ratios (column and wall indices).

Shiga et al. (1968) proposed a practical method named as 'Shiga Map' as shown in Figure 2.19 to rank low-rise RC buildings according to their seismic vulnerability after investigating the damaged buildings in the 1968 Tokachi-oki earthquake, in Japan.

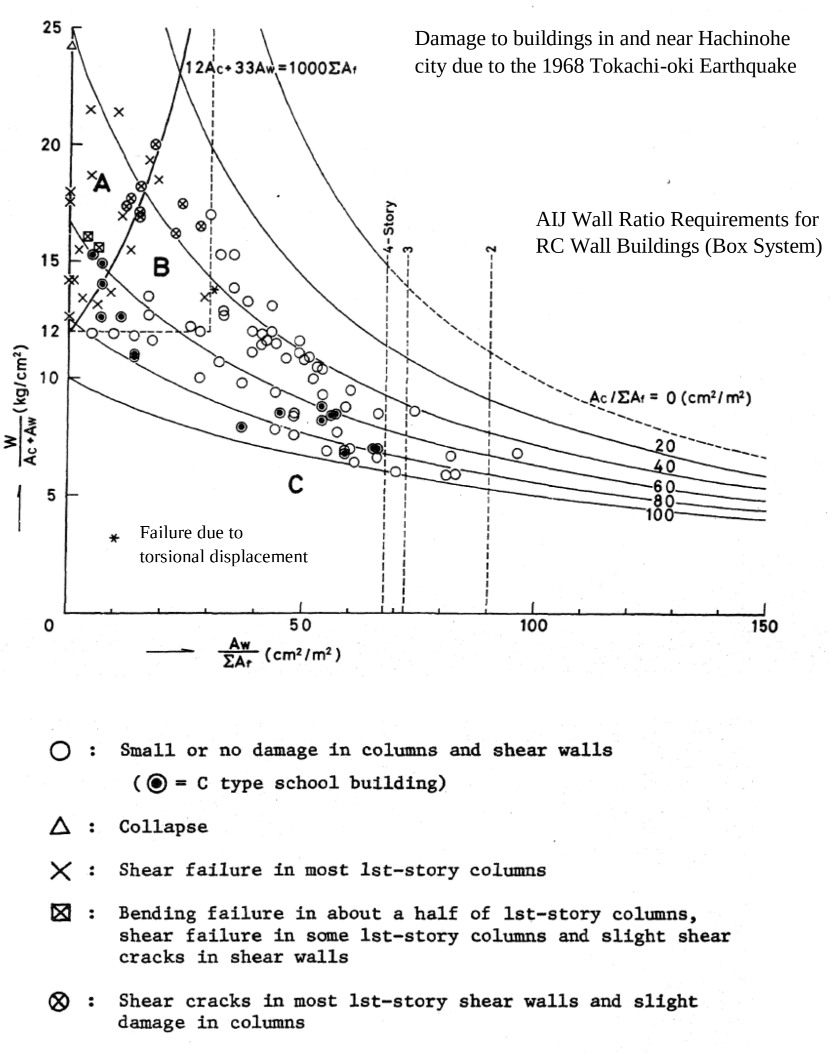


Figure 2.19 Shiga map (Shiga et al. 1968)

This proposed method based on the average shear stress of columns and RC walls, and wall area ratio, which represents a ratio of the cross-sectional areas of RC walls to total floor area. This method also considers seismic demand to set up boundaries for identifying buildings as unsafe or safe. This map is well known to show good agreement with the damage status of RC buildings in the 1978 Miyagiken-oki earthquake (Shibata, 2003). However, this method is applicable only for buildings with RC shear walls, which does not consider the effects of masonry infills.

Hasan and Sozen (1997) presented a simplified method with vulnerability indices (column and wall area index) to rank RC building according to their vulnerability against seismic damages. They investigate a group of damaged buildings in the 1992 Erzincan Earthquake, Turkey and found correlation between column index and wall index with damage states as shown in Figure 2.20.

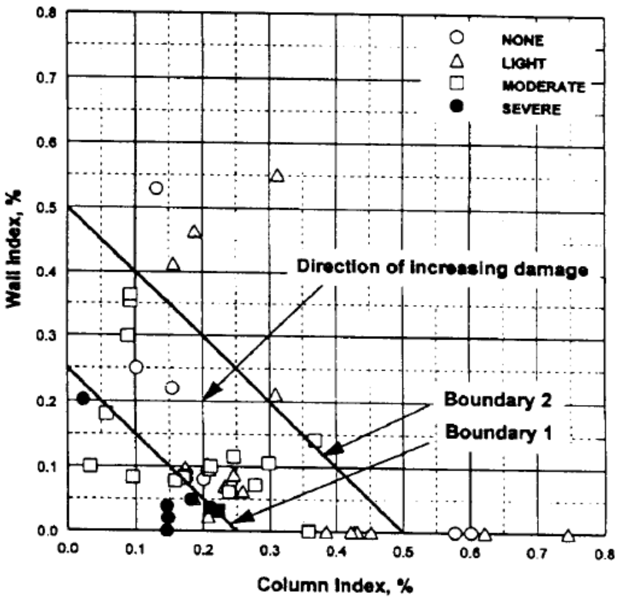


Figure 2.20 Proposed evaluation method by Hasan and Sozen (1997)

Furthermore, this method has been used to classify the damage extent of existing buildings for future earthquake in Istanbul, Turkey (Ozcebe et al. 2004). Donmez and Pujol (2005) also verified the method with the database of 1999 Duzce and Bolu earthquake, Turkey. The indices were further tested to identify the performance of school buildings in the 1999 (Marmara, Duzce) and the 2003 (Bingol) earthquakes, Turkey (Gur et al. 2009).

O`brien et al. (2011) conducted post-earthquake survey on 2010 Haiti earthquake to investigate the extent to which these indices are sensitive to properties of local materials. In addition, they compared the results with those of the 1999 Duzce, Turkey earthquake, and concluded that this method is an appropriate tool to estimate the seismic vulnerability.

All the aforementioned studies proposed their method criteria after earthquake damage where these damage databases were used to recalibrate the existing vulnerability indices.

However, there are no clear indication about theoretical background or application those methods in other developing countries where in many cases recent damage database is not available.

2.3.3 Simplified evaluation procedure

The main concept comes from Shiga Map (Shiga et al 1968). The seismic capacity is calculated with column and wall strength, which is product of the average shear stress and cross sectional areas of columns and walls, as shown left side in Equation (2.1) which is based on Shiga Map (Shiga et al, 1968). The seismic demand which is the product of the total building weight (W), the response acceleration (C_a) and the reduction factor (D_s) considering the building ductility in Equation (2.1).

Seismic Capacity ≥Seismic Demand

$$\tau_c . A_c + \tau_c . A_{inf} + \tau_{cw} . A_{cw} \geq W . C_a . D_s \qquad (2.1)$$

where,

τ_c = The average shear strength of RC columns.

τ_{inf}= The shear strength of masonry infill.

τ_{cw} =The shear strength of columns and walls.

A_c= Cross-sectional area of column

A_{inf}= Cross-sectional area of masonry infill

A_{cw}= Cross-sectional area of RC wall

W= Total buildings weight

C_a= Response acceleration

D_s= Response modification factor (ductility factors)

Dividing the Equation (2.1) by total floor area ($n.A_f$), the Equation (2.2) can be could as follows:

$$\tau_c . \frac{A_c}{A_f} + \tau_{inf} . \frac{A_{inf}}{A_f} + \tau_{cw} . \frac{A_{cw}}{A_f} \geq \frac{W}{A_f} . C_a . D_s \qquad (2.2)$$

where,

$\frac{A_c}{A_f}$= Column area ratio

$\frac{A_{inf}}{A_f}$= Masonry infill area ratio

$\frac{A_{cw}}{A_f}$= RC wall area ratio

2.3.4 Basic assumptions for the simplified seismic evaluation

The simplified method considers some basic assumptions for parameters such as material properties, buildings unit weight and thickness of masonry infill and structural wall as well as seismic capacity modification factors. These assumptions might vary based on construction practices with different material properties in different countries.

The following assumptions are considered for the seismic capacity evaluations using in Equation (2.2):

(a) Average shear strength of column (τ_c)

The Japan Building Disaster Prevention Association (JBDPA 2001) proposed seismic evaluation standard which considers average shear strength of column is 1.0 MPa for first level screening procedure based on shear span ratio, where h_o/D ranged 2 to 6 (h_o is the clear height of column, D is the column width). However, Tsai et al. (2008) summarized the detailed assessment results of school buildings after the 1999 Chi-Chi earthquake and proposed the average ultimate shear strength of RC column is 15 kgf/cm^2 (1.47 MPa) for preliminary evaluation. Figure 2.21 shows a relationship between shear strength of column and h_o/D ratio based on analysis of existing buildings located at Dhaka, Bangladesh (SATREPS 2015) as a case study of developing countries. From above discussion, the average shear stress for columns could be assumed as 1.0 MPa.

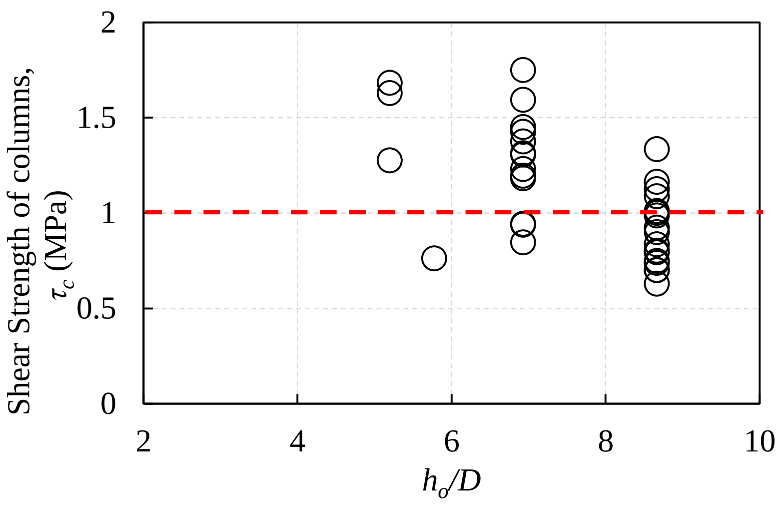


Figure 2.21 Average shear strength for column vs. h_o/D ratio for investigated RC buildings in Bangladesh

(b) Average shear strength of masonry infill (τ_{inf})

ASCE seismic guideline (ASCE/SEI 41-06 2007) prescribed 34 psi (0.24 MPa) for good masonry condition. Besides, the average lateral strength for masonry infill wall is assumed of 0.28 MPa based on past experimental studies in Nepal (Karmacharya, U 2018). Chiou et al. (2017) proposed lateral shear strength for masonry infill, after experimental verification and theoretical formulas, as 4.0 kgf/cm^2 (0.39 MPa) for preliminary assessment of low-rise RC Buildings in Taiwan. Figure 2.24 shows maximum shear strength of masonry infill corresponding to compressive strength of masonry prism (Alwashali, 2018). In this study, a value of shear strength of masonry infill, τ_{inf}, is considered as 0.2 MPa, which is a conservative value for masonry with compressive strength of less than 10 MPa, as shown in Figure 2.22.

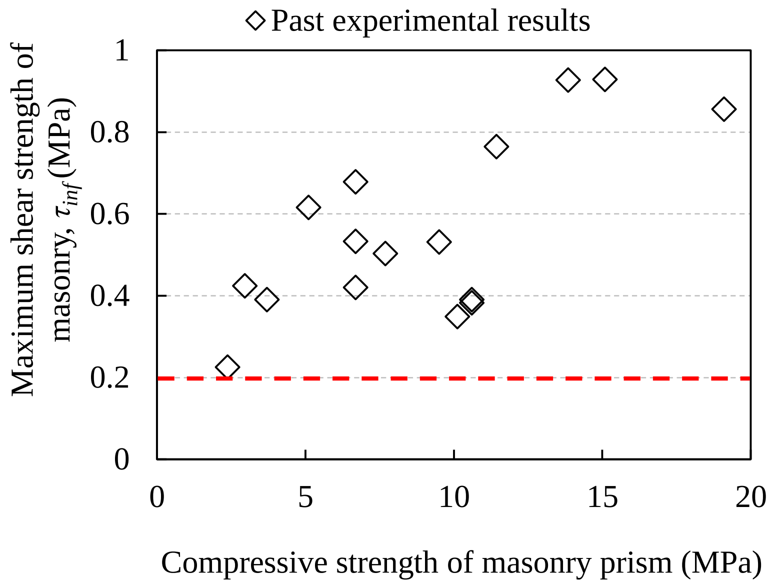


Figure 2.22 Average shear strength for masonry infill with compressive strength of masonry

(c) Average shear strength of concrete wall (τ_{cw})

JBDPA standard (2001) proposed average shear strength of concrete wall is 1.0 MPa considering without boundary column based on past damage investigation and experimental data. In this study, average shear strength of concrete wall (τ_{cw}) has been assumed 1.0 MPa for very preliminary evaluation.

(d) Average unit weight per floor area (w)

The unit floor weight (w) of existing buildings is found ranges from 10 to 12 kN/m^2 based on study of existing RC building located in Bangladesh (SATREPS 2015). Similarly, the unit floor weight has also been found based on study on existing buildings in Taiwan (Purdue University and NCREE 2016). However, in this study, the average unit weight per floor area, w, is set as 11kN/m^2.

2.4 Application of the simplified seismic evaluation method in past earthquake building databases

Seismic evaluation has been carried on surveyed building mentioned in previous sections. The basic information such as column area, masonry infill area and floor area are found from the survey datasheet. Column area ratio and masonry infill area ratio are calculated using survey datasheet available in the recorded survey database. Column area ratio and masonry wall area ratio have been compared with damage state and correlation with damage as discussed in the following sections.

2.4.1 Application in the 2015 Nepal earthquake buildings database

As previously mentioned, 133 of RC with masonry infill buildings are selected in this study. Generally, the contribution of masonry infill has not been considered during structural design process of these buildings. Therefore, the lateral load is taken by RC column which are considered as prime parameters for lateral force element.

2.4.1.1 Column area ratio

Column are ratio has been calculated as shown in Figure 2.23. The column area ratio ranges 0.1 to 0.5% of the investigated buildings. However, it has been observed that, most of the buildings contains the column area ratio is about 0.2%. Narrow column size is very common practice results the lower value of column area ratio. This is due to lack of seismic design and non-engineered buildings construction practice.

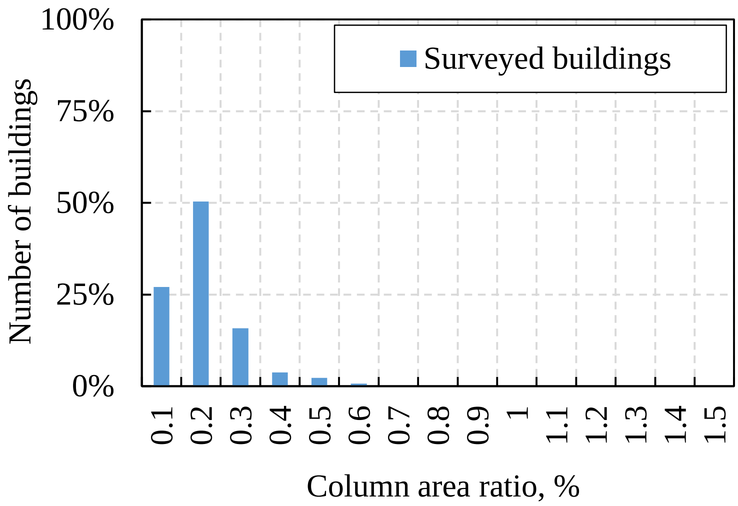


Fig 2.23 Distribution of buildings according to column area ratio (%)

2.4.1.2 Masonry infill area ratio

Figure 2.24 shows a histogram of the masonry wall area ratio for investigated buildings. More than 50% surveyed buildings showing lower masonry infill area ratio. The masonry infill area ranges 0.1% to 1.5%. Wall area ratio 0.1% indicates that most of the buildings are partially or full opening at ground floor. Which is a common practice in developing countries. The thickness of masonry infill ranged 100 to 230 mm. Generally, the outer periphery wall contains double layered brick masonry which is usually 230 mm thickness. On the other hand, inner wall contains single layer wall thickness is 100 mm.

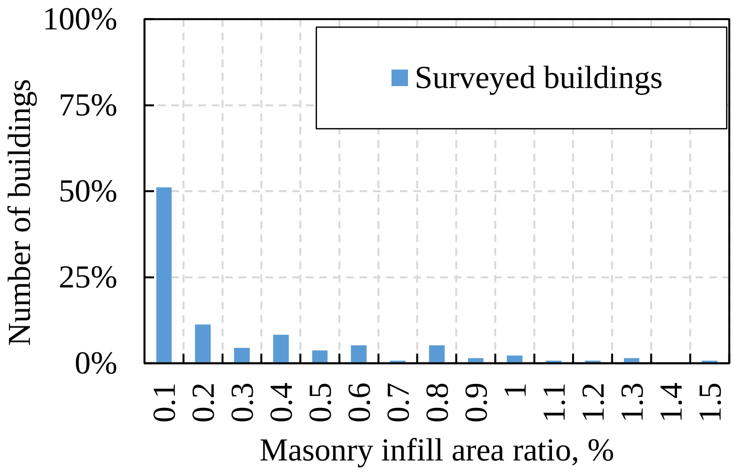


Figure 2.24 Distribution of buildings according to infill wall area ratio (%)

2.4.1.3 Relation between column area ratio and wall area ratio with damage state

In order to study the correlation column area ratio and wall area ratio with damage state, these simple parameters have been plotted in both principle directions along with damage states as shown in Figure 2.25. The lines are drawn in the plot according to seismic demand for ground motion of the corresponding earthquake. These lines designated as upper boundary and lower boundary, defining the map into three different zones namely Zone A, Zone B and Zone C for describing light, moderate and severe respectively. Buildings placed at zone C are considered the most vulnerable and expected to have severe damage. Buildings located at zone A are considered to have enough seismic capacity to avoid severe damage.

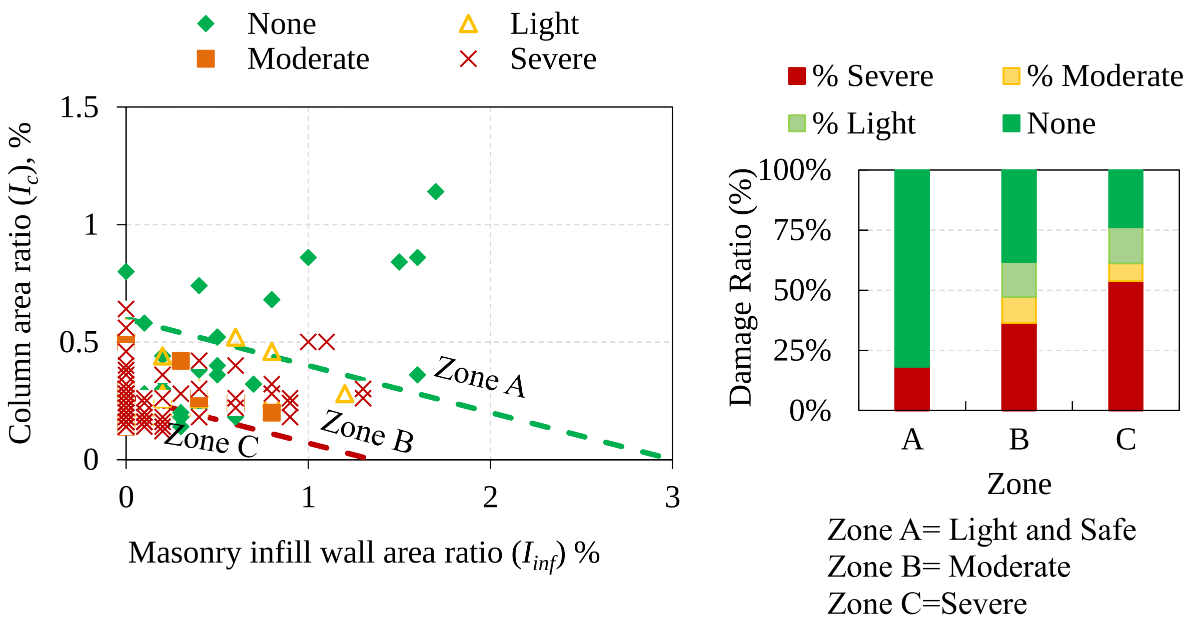


Figure 2.25 Column area ratio and infill wall area ratio with damage state

Damage ratios for each zone are calculated according to the seismic capacity and seismic demand for each ground motion. It has been observed that approximately 70% of total severely damaged buildings are located at Zone C and more than 55% of buildings are severely damaged at this Zone. From the damage ratio, it is found that there are a few severely damaged buildings in Zone A. It means that these simple parameters can easily separate damaged and non-damaged building efficiently.

2.4.2 Application in the 2016 Ecuador earthquake buildings database

A total 171 masonry infilled RC buildings selected for this study. Basic characteristics and seismic evaluation has been calculated are described as follows.

2.4.2.1 Column area ratio

Column area ratio has been calculated as shown in Figure 2.29. The column area ratio ranges 0.1 to 0.3 %. However, 50% of total buildings contains lower column area ratio as lower as 0.2%. Field observation shows that, most of the buildings are non-engineered which is the common practice in this region. In addition, the column size is about 200 x 200 mm which is lower than Ecuador design code of practice (NEC 15). Eventually, the result lower column size results lower column area ratio.

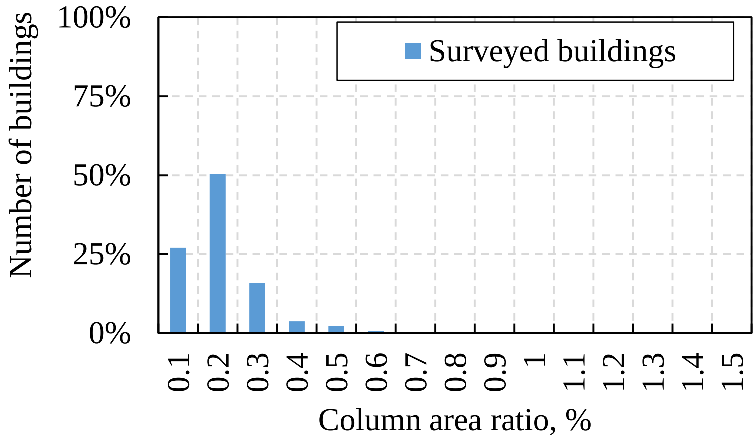


Figure 2.29 Distribution of buildings according to column area ratio (%)

2.4.2.2 Masonry infill area ratio

There are different types of masonry infill used in this area. These are concrete block, clayed brick etc. The usual thickness of masonry infill is about 100 mm to 230 mm. Generally, other wall thickness is 230 mm and inner wall thickness 120mm. Figure 2.30 shows the masonry infill wall area ratio of investigated buildings. It has been seen that most of buildings masonry infill area contains 0.1%. It reveals that most of buildings consists of ground floor opening.

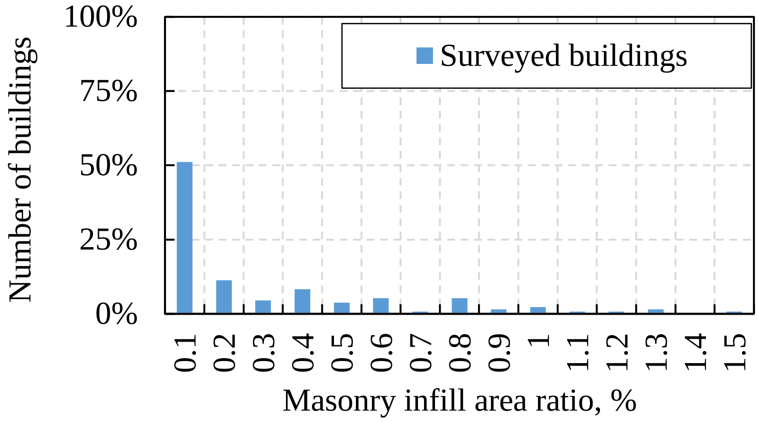


Figure 2.30 Distribution of buildings according to infill wall area ratio (%)

2.4.2.3 Relation between column area ratio and wall area ratio with damage state

Column area ratio and wall area ratio has been plotted with damage states of the investigated buildings as shown in Figure 2.31. The boundary lines considered based on seismic demand of the earthquake divided the plots into three zone defined as A, B, and C as Light and Safe, Moderate and Sever zones, respectively. It has been observed that more than 50% of total buildings at Zone C have been identified as Severely damaged buildings. In contrast, more than 50% of total buildings located at Zone A have been recognized as light and Safe buildings according to actual damage state. It has been restated that these simple parameters can identified the most vulnerable buildings.

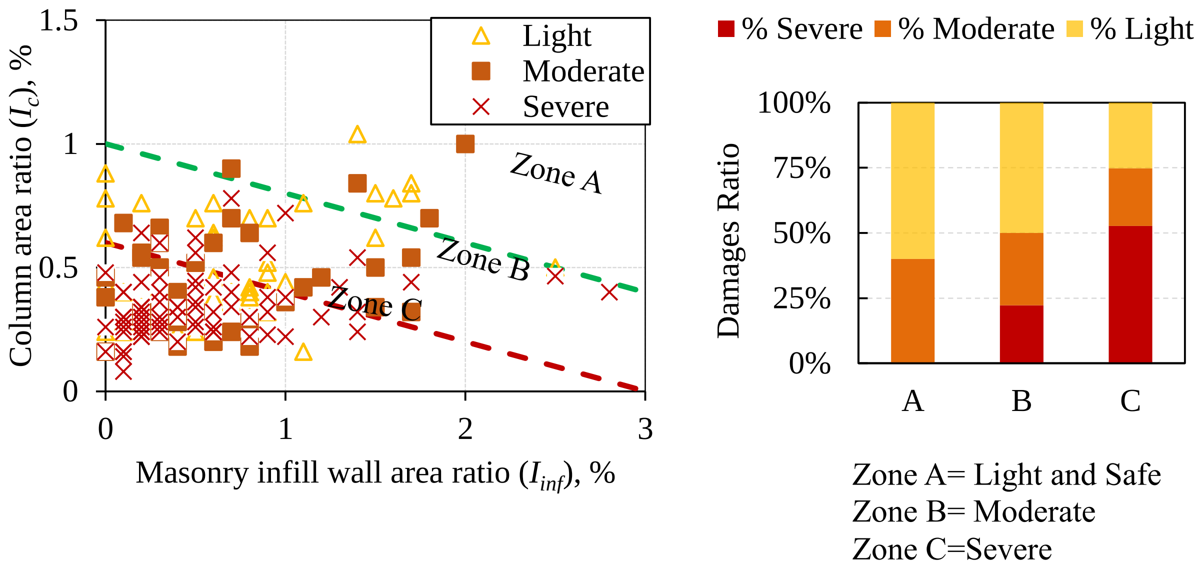


Figure 2.31 Column area ratio and infill wall area ratio with damage state

2.4.3 Application in the 2016 Taiwan earthquake buildings database

As previously mentioned, total of 63 surveyed buildings have been chosen in this study. All buildings are also Masonry infilled RC Buildings. The basic characteristics and seismic capacity evaluation have been described in the subsequent sections.

2.4.3.1 Column area ratio

Figure 2.26 shows column area ratio of these investigated buildings. Column area ratio ranges 0.1% to 1.1 %. However, most of the buildings ranges 0.4% to 0.6 %. The average value of column area ratio is of 0.51. Taiwan is located high seismic area and investigated buildings are special categories (i.e school buildings), therefore column area ratio showing larger than other developing countries.

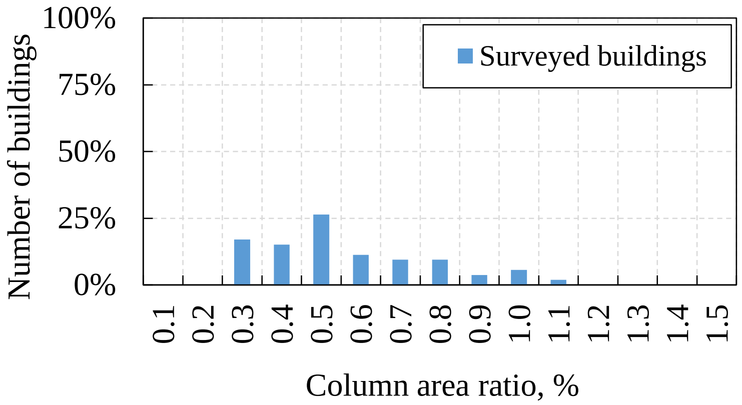


Figure 2.26 Distribution of buildings according to column area ratio (%)

2.4.3.2 Masonry infill area ratio (%)

Masonry wall area ratio has been calculated as shown in Figure 2.27. Investigation shows that lower masonry infill wall area ratio. This is because of most of school building has large class room with less masonry infill wall. However, the ranges are within 0.1% to 1.1%. Few of them are 1.4% masonry wall area ratio. The average values of infill wall ratio is of 0.46 with large standard deviation is of 0.43.

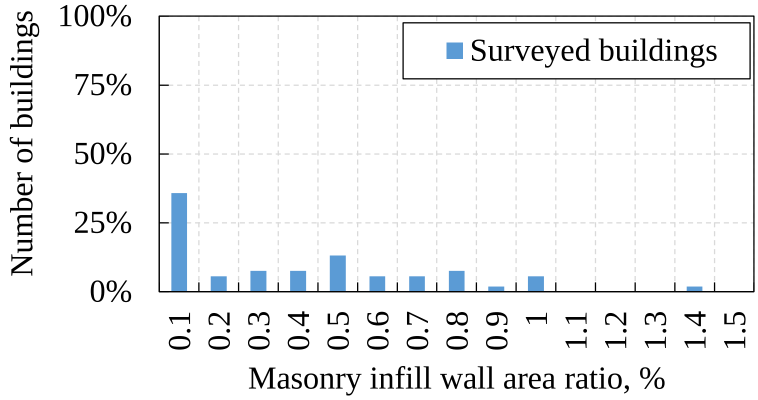


Figure 2.27 Distribution of buildings according to infill wall area ratio (%)

2.4.3.3 Relation between column area ratio and wall area ratio with damage state

The simple parameters described in aforementioned section have been plotted as shown in Figure 2.28. The two lines has also drawn into the plot according to seismic demand of this earthquake. These lines also have divided the plots into three zones A, B and, C for describing light, moderate and severe zone respectively. From this figure it has been seen that, more than 60% buildings located at zone C are moderate to severely damaged due to this earthquake. On the other hand, 80% buildings are non-damaged buildings located at zone A. It means that these simple parameters can have good correlation with damage status.

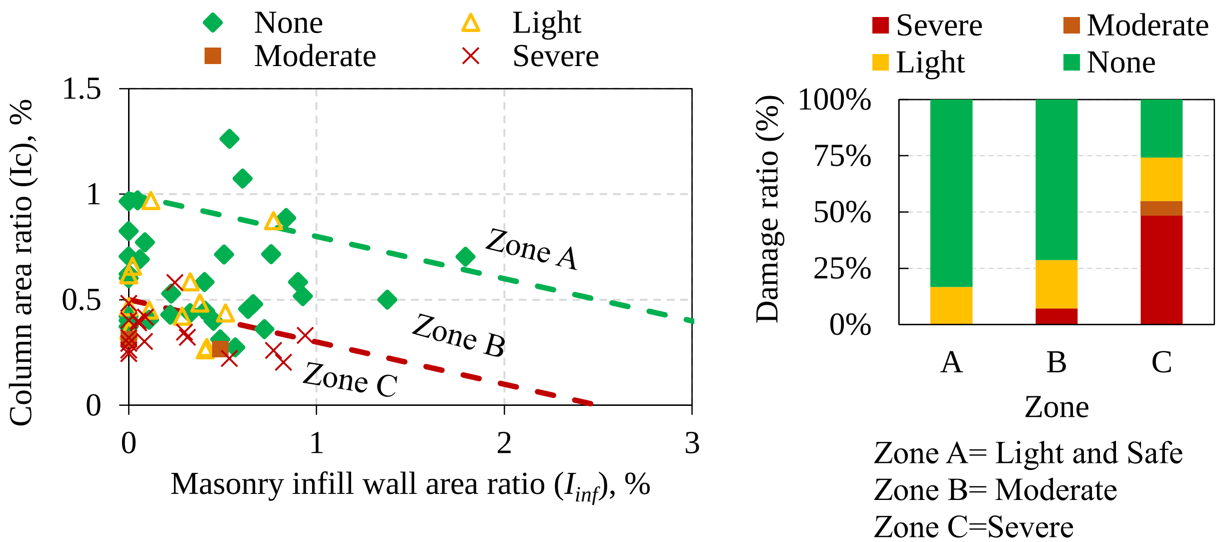


Figure 2.28 Column area ratio and infill wall area ratio with damage state

2.5 Seismic capacity evaluation of investigated buildings

In order to understand the correlation between observed damage levels of surveyed buildings and their seismic capacities, seismic performance indices of those buildings have been calculated. As long as those buildings database contains simple information, therefore, the seismic capacity has been evaluated in a simplified way based on those simple information and parameters.

The simplified seismic capacity index has been calculated by using simple parameters such as column area ratio and masonry infill wall area ratio. However, the seismic capacity is the summation of the lateral strength of RC column, masonry infill and concrete wall normalized with total building weight (Maeda et al. 2018) as expressed by following Equation (2.3). The lateral capacity of each structural element (i.e. RC column, masonry wall and concrete wall) refers to the product of cross-sectional area and corresponding shear strength.

$$\text{Seismic capacity} = \left[\tau_c \frac{A_c}{n.A_f.w} + \tau_{\inf} \frac{A_{\inf}}{n.A_f.w} + \tau_{cw} \frac{A_{cw}}{n.A_f.w} \right] \quad (2.3)$$

In the above Equation 3, column area ratio and masonry infill area ratio have been calculated from information found from the database. The basic assumption for shear strength of RC column and material properties of shear strength have been described in the section 2.3.4.

2.6 Application in existing earthquake damaged databases

The simplified seismic evaluation procedure described in the aforementioned section, has been applied the existing EQ damaged databases. Based on the ratio of different damage levels, a correlation between damage ratio and seismic capacity index has been developed to identify the probability of damage ratio. The following sections described application and comparing with damage ratio.

2.6.1 Application in the 2015 Nepal earthquake buildings database

2.6.1.1 Seismic capacity of investigated RC buildings

As previously mentioned, a total 133 number of RC buildings have been investigated for seismic capacity evaluation. Column area ratio has been calculated and mentioned in the previous section. However, masonry infill area ratio has been calculated in both longitudinal and transverse direction (herein mention NW and EW direction). To be conservative, minimum direction has been considered for calculation of seismic capacity index. Figure 2.35 shows distribution of seismic capacity index of the investigated buildings. The ranges of seismic capacity index are 0.1 to 1.1. It has been seen that most of the buildings showing lower values 0.2 to 0.4. The average value of seismic capacity index is 0.35 and standard deviation is 0.20. Figure 2.36 shows the distribution of seismic capacity index of severely damaged buildings and other buildings (moderate, light and no damage). The average values of severely damaged buildings are about 0.28 and standard deviation 0.13.

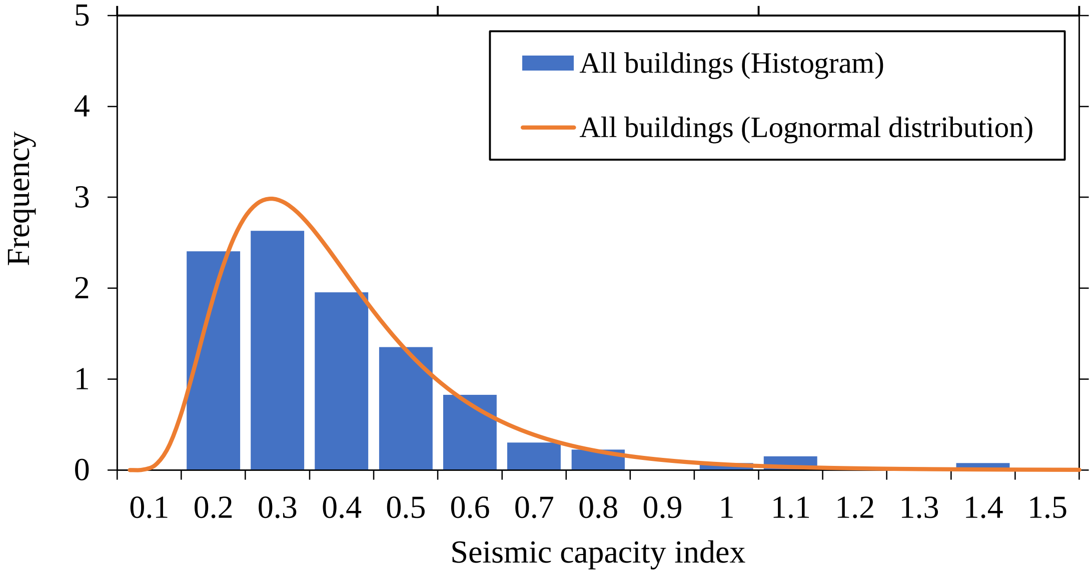


Figure 2.35 Seismic capacity index of investigated buildings

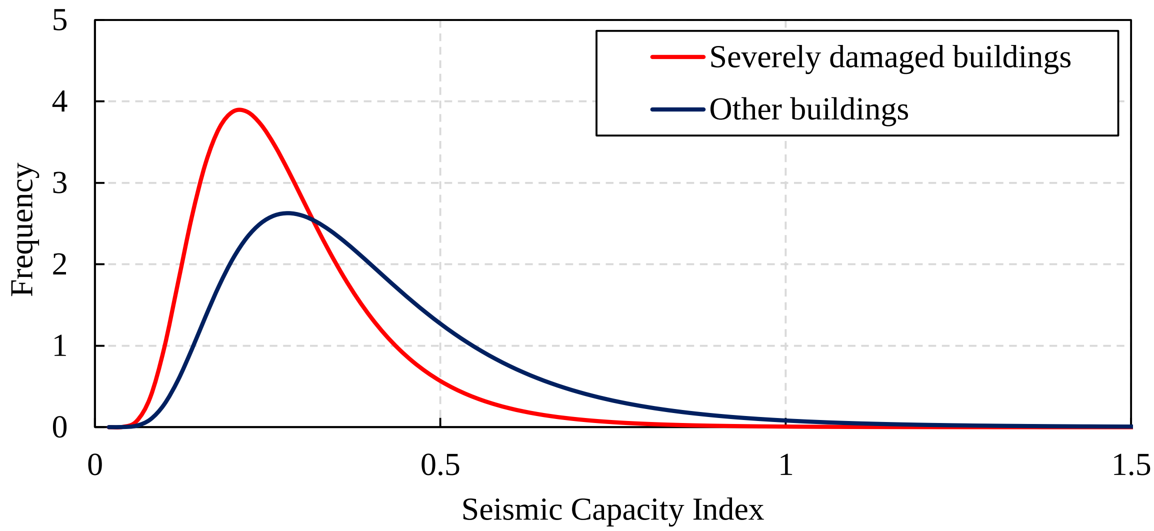


Figure 2.36 Distribution of seismic index for different damage levels in Nepal database

Figure 2.37 shows distribution of seismic capacity index of total investigated buildings and severely damaged buildings. It has been observed that the seismic capacity index of 0.6 includes all severely damaged buildings. However, the seismic capacity of buildings beyond the judgement criteria shows non damaged buildings.

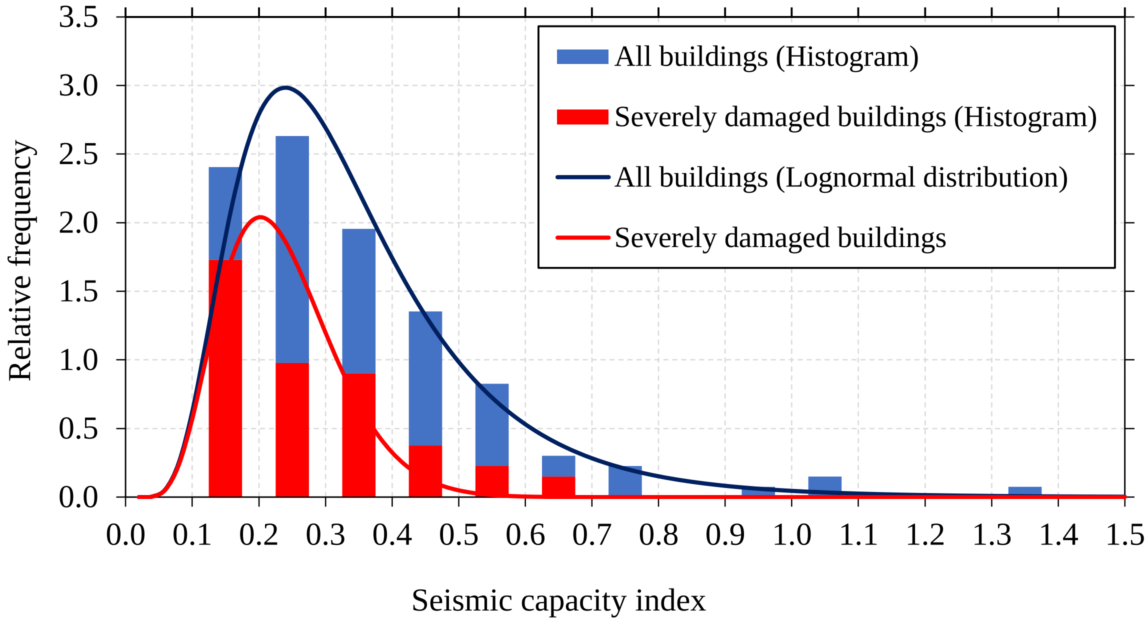


Figure 2.37 Distribution of seismic capacity index for total buildings and damaged buildings.

2.6.1.2 Evaluation of relationship between seismic capacity index and damage probability

Probability of damage ratio with seismic capacity has been developed for Nepal EQ damage database. Figure 2.38 shows the correlation of damage ratio and seismic capacity index. As seen in Figure 2.38, it has been observed that the seismic capacity index is higher than 0.6 showing no severely damaged buildings. However, this boundary can be set as judgement criteria for seismic capacity investigation.

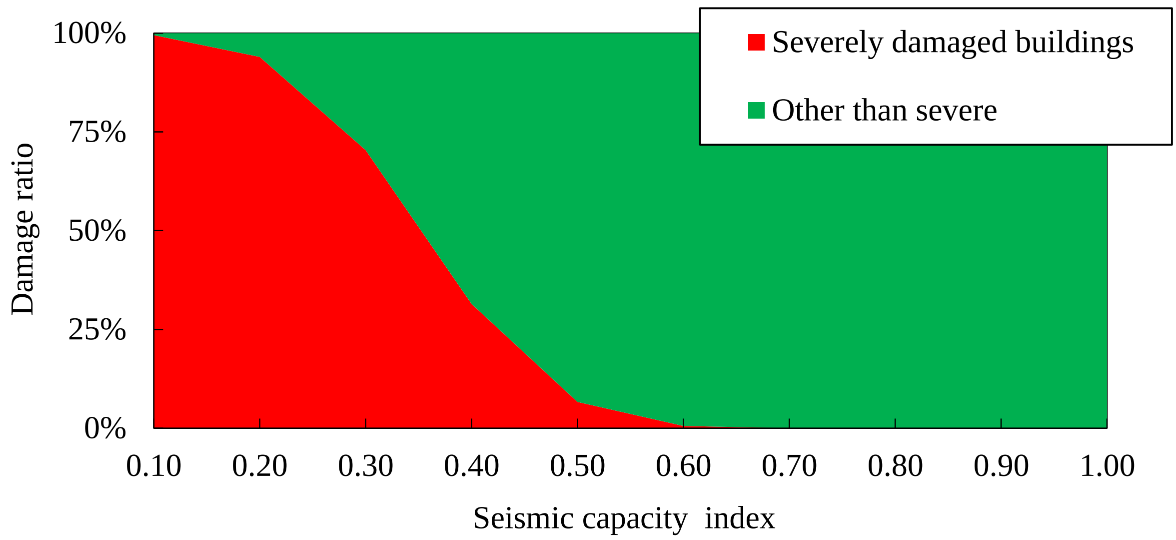


Figure 2.38 Correlation the seismic capacity with damage ratio based on investigated buildings.

2.6.2 Application in the 2016 Ecuador earthquake buildings database

2.6.2.1 Seismic capacity of investigated RC buildings

Seismic capacity has also been investigated for 171 number of RC buildings in Ecuador EQ database. Figure 2.39 shows distribution of the calculated seismic capacity index. The seismic capacity of the investigated buildings showing the ranges 0.1 to 1.2 with average value 0.48 and standard deviation 0.21.

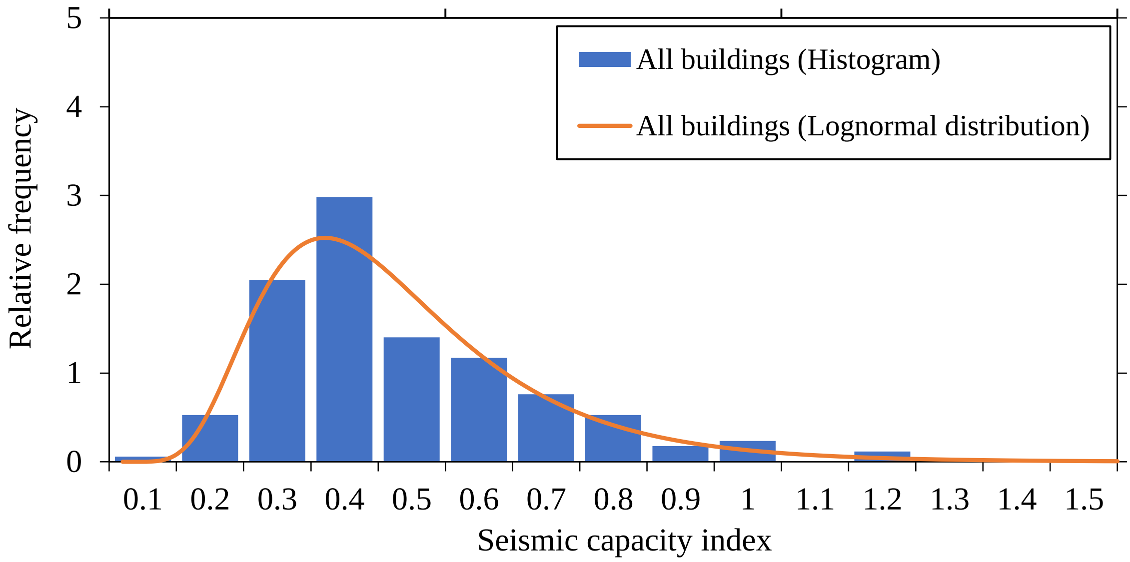


Figure 2.39 Seismic capacity index of investigated buildings

According to survey information of the investigated buildings, a number of 58 buildings are reported as severely damaged of total surveyed buildings. Other 95 numbers of buildings are regarded as light and moderately damaged buildings. However, the percentage of severely damaged buildings are about 55 % as shown in Figure 2.40. Figures 2.40 shows the distribution of seismic capacity according to different damage level according to the survey report. It has been noted that in this database, only damaged buildings are taken into account for field investigation. However, observation depicts that the average values for severely damaged buildings are about 0.28 whereas others buildings provided 0.35. It seems that the distribution is quite similar in seismic capacity evaluation.

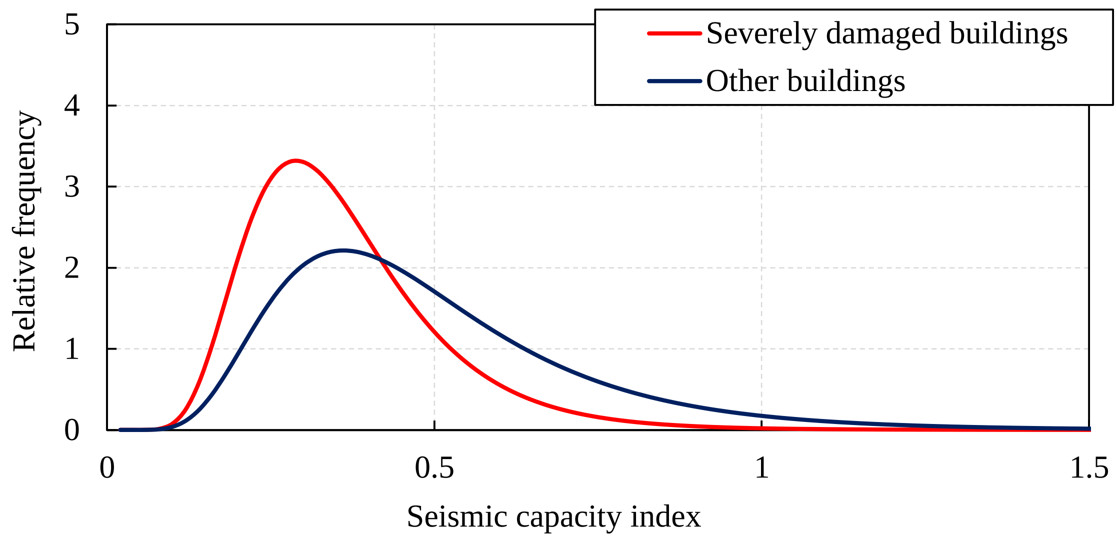


Figure 2.40 Distribution of seismic index for different damage level in Ecuador

The distribution of seismic capacity index of severely damaged buildings is shown in Figure 2.41. The seismic capacity index has been compared with the seismic capacity of all surveyed buildings. It has been observed that the seismic capacity index lower than 0.5 covers all severely damaged buildings. It means that at this point the probability of seismic damage will be less compared with other than severely damaged buildings.

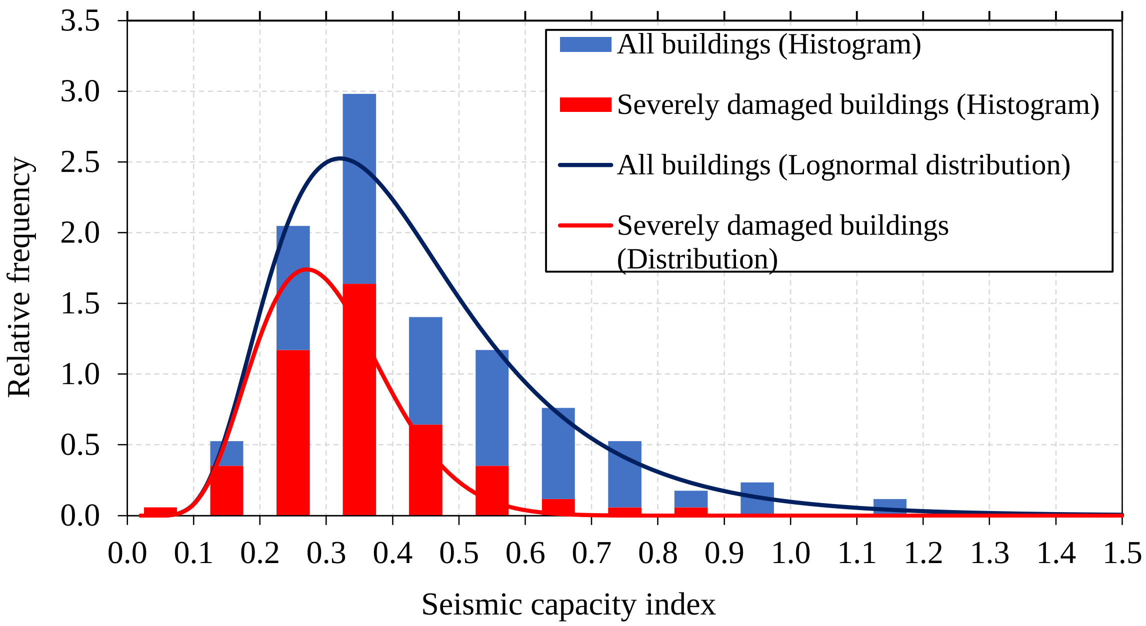


Figure 2.41 Distribution of seismic capacity index for total buildings and damaged buildings

2.6.2.2 Evaluation of relationship between seismic capacity index and damage probability

A correlation between damage ratio with seismic capacity index has been plotted to identify the extent of damage for target seismic capacity. Figure 2.42 showing the correlationship between damage ratio and seismic capacity index for the investigated buildings. Figure 2.42 suggests that about at seismic capacity index is of 0.5, 20 % of buildings will be severely damaged and 80 % of buildings will be other than severe. At seismic capacity index is of 0.6 has been assumed boundary for no severely damaged buildings.

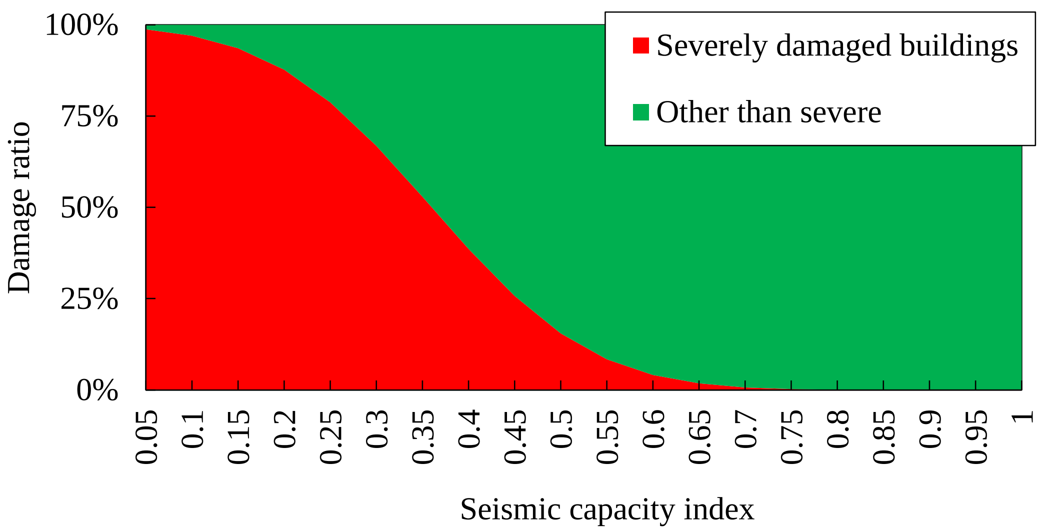


Figure 2.42 Correlation the seismic capacity with damage ratio based on investigated buildings

2.6.3 Application in the 2016 Taiwan earthquake buildings database

2.6.3.1 Seismic capacity of investigated RC buildings

Seismic capacity evaluation has been also conducted for the investigated buildings in the Taiwan EQ surveyed database. Seismic capacity index has been estimated using Equation (2.3) as shown in previous section. The estimated column area and masonry infill are ratio in earlier sections, have been considered for estimating the seismic capacity. It should be noted that the average shear strength of column has been considered as 1.0 MPa which is similar for Nepal and Ecuador buildings database. However, the local construction practice and design code might differ country to country. Figure 2.43 shows distribution of seismic capacity index of the investigated buildings. It has been seen that the estimated seismic capacity index shows ranges 0.3 to 1.1. The average values are 0.53 and standard deviation is about 0.21. Figure 2.45 shows than about 40 % of buildings contain seismic capacity ranges 0.4 to 0.5. The estimated seismic capacity index is higher than that of for Nepal earthquake database due to low rise buildings and buildings weight are also lower.

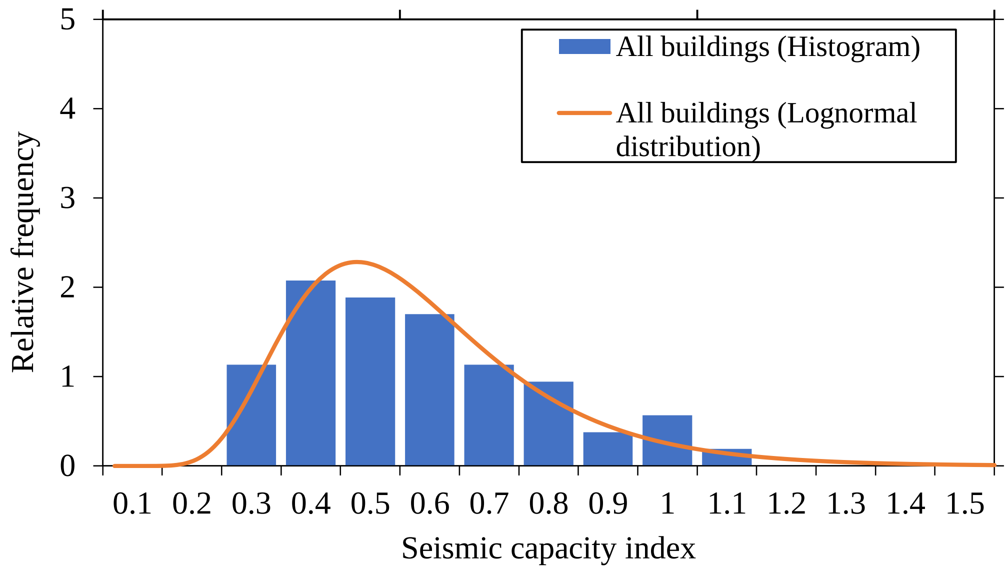


Figure 2.43 Seismic capacity index of investigated buildings

Study shows that, about 23% of buildings are severely damaged buildings and 77% of buildings are other than severely damaged buildings. Figure 2.44 shows the distribution of seismic capacity index of severely damaged buildings. The average value of seismic capacity index is 0.35 with standard deviation is 0.09. Other buildings with the average seismic capacity index is of 0.58 with standard deviation is 0.19.

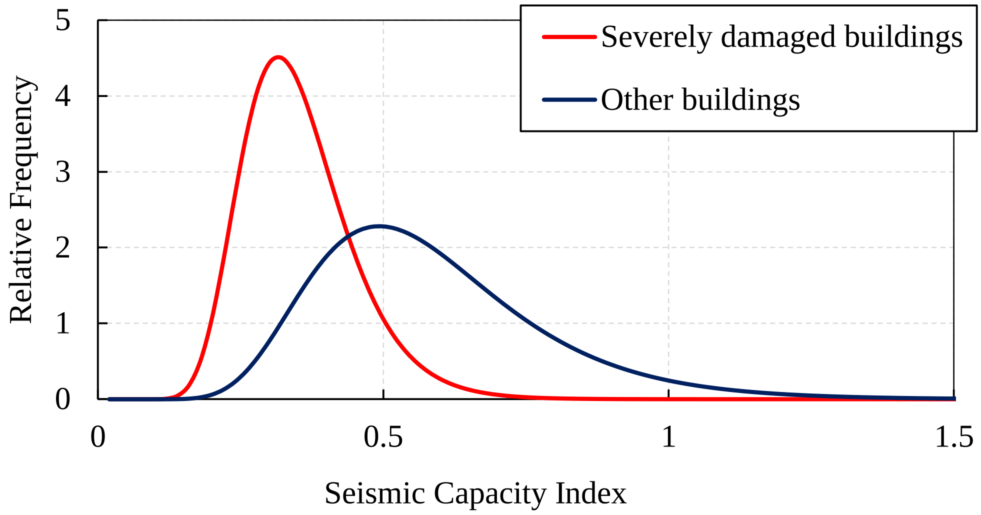


Figure 2.44 Distribution of seismic index for different damage level in Taiwan

Seismic capacity index of severely damaged building and all investigated building has been compared as shown in Figure 2.45. In this Figure, frequency distribution of severely damaged buildings is 22% which is also similar with the damage ratio of investigated buildings. The Figure 2.45 suggests that the seismic capacity index at 0.60 covers all the severely damaged buildings. Seismic capacity index at 0.60 has been assumed as the boundary for identification of most vulnerable buildings.

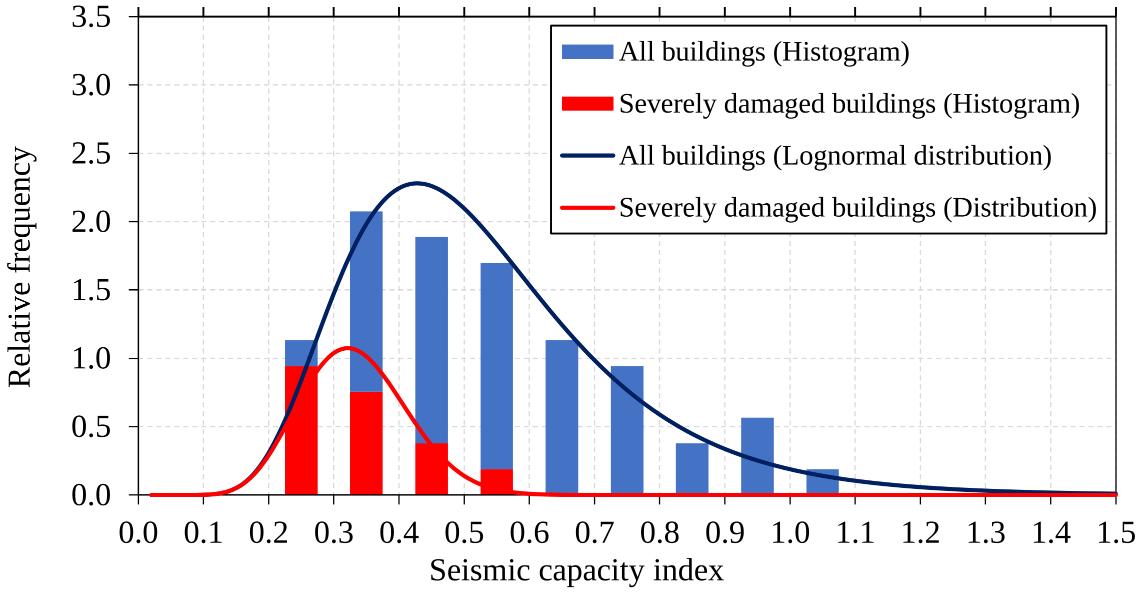


Figure 2.45 Distribution of seismic capacity index for total buildings and damaged buildings

2.6.3.2 Evaluation of relationship between seismic capacity index and damage probability

Damage probability with seismic capacity index has been evaluated based on the ratio of different damage level as shown in Figure 2.45. A correlation between seismic capacity index has been compared with damage ratio as shown in Figure 2.46. From this Figure, it has been seen that there are no severely damaged buildings at seismic capacity index is of 0.6. Therefore, seismic capacity index is of 0.6 can be used as judgement criteria for seismic capacity evaluation.

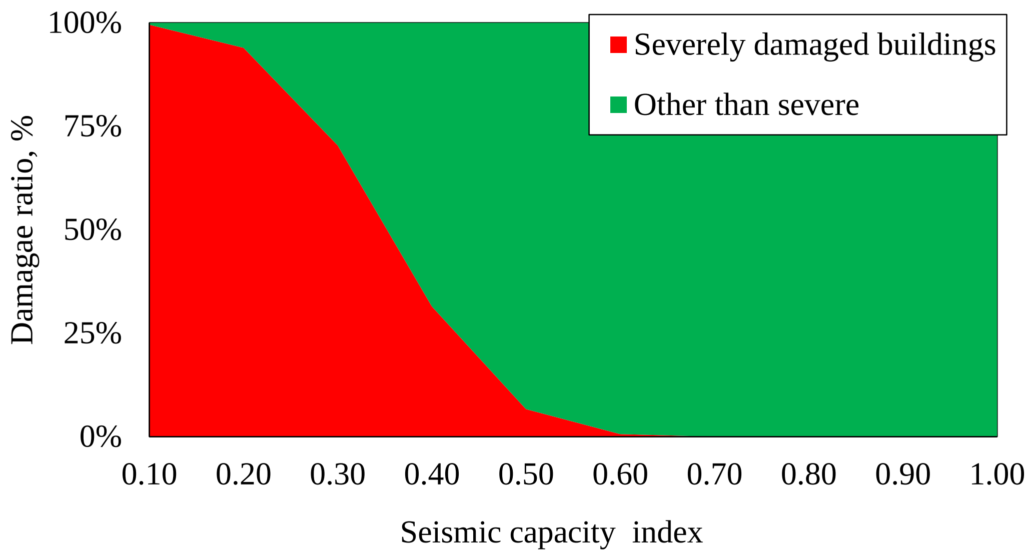


Figure 2.46 Correlation the seismic capacity with damage ratio based on investigated buildings

2.7 Summary of chapter 2

This chapter presents a study on three sets existing RC buildings database experienced past earthquakes in developing countries. First of all, the basic characteristics such as column area and infill wall area of these surveyed buildings have been investigated based on information found from the databases. A correlation has been developed between the basic characteristics (column area and infill area) and damage state of these investigated buildings. Afterward, seismic capacity has been evaluated of these buildings using these simple parameters.

In this chapter, a simple evaluation method has been discussed for seismic evaluation of existing RC buildings. The method is based on using the concept of Shiga Map as mentioned in earlier section, focusing on the cross-sectional areas of masonry infills and columns in existing infilled masonry-RC buildings. The proposed simplified evaluation procedure has been applied on these investigated buildings. First, the applicability of these parameters for seismic screening are verified comparing with seismic damage states. Secondly, seismic capacity index has been evaluated based on these simple parameters and a correlation of damage ratio with seismic capacity has been developed.

The following conclusions are made;

1. The vulnerability parameters such as column area ratio (I_c) and masonry infill wall area ratio (I_{inf}) showed good agreement with the damage state of surveyed building, based on past earthquake databases. The consistency between the observed damage distribution and boundaries supports the effectiveness of the proposed method.
2. These simple parameters are regarded as the most influencing parameters for identifying the seismic capacity of existing buildings in other seismic region.
3. A correlation between seismic capacity and damage ratio is useful information to identify the seismic vulnerability of existing RC buildings of those countries where past earthquake recorded building database are not available.

From the discussions above, the simplified evaluation method is a promising approach for identifying the most vulnerable buildings. However, the proposed method provides theoretical background for seismic evaluation to other developing counties, where damage databases are not available.

Chapter 3

Study on existing RC buildings in Bangladesh

3.1 Introduction

This chapter describes about seismic capacity of existing RC buildings in region where past earthquake record is not available. In order to assess the existing RC buildings, a set of existing RC buildings database has been collected and gathered. The main objective of this chapter is to understand the seismic capacity and probability of seismic damage of existing RC buildings in Bangladesh comparing with past earthquake damaged databases as mentioned in Chapter 2. First of all, existing RC buildings has been investigated to understand the basic characteristics of those buildings. Furthermore, seismic capacity has been evaluated and compared with past earthquake records to understand seismic vulnerability.

3.2 Study on existing RC buildings in Bangladesh

Over the past decades, urbanization has been rapidly taking place without proper regulations and guidance. As a result, many of the urban areas have been developed unplanned way due to lack of upgraded seismic code and its implementation. These urban centers are fast growing and influence the economic developments of the country. It is therefore, essential to have a realistic understanding on the nature, severity and consequences of likely damage/loss that a possible event of earthquake could cause.

Figure 3.1 Building scenario at Dhaka City, Bangladesh

A major earthquake affecting a major city such as Dhaka, Chittagong, or Sylhet may result a massive damages and destruction of infrastructures which is now major concern for the entire nation. In order to overcome the upcoming situation, it is necessary to study on seismic capacity and understand the vulnerability of existing RC buildings in Bangladesh.

3.2.1 Overview of buildings database

Considering the reality of the situation in Dhaka city, the Government of Bangladesh has been initiating several steps for earthquake risk reduction. Following the initiatives, one of the project named The Comprehensive Disaster Management Programme (CDMP) was implemented by Department of Disaster Management (DDM) under Ministry of Disaster Management and Relief (MoDMR). The CDMP was supported by United Nation Development Programme (UNDP), Department for International Development (DFID) and European Commission (EC). However, CDMP has been intended to strengthen the Disaster Management System and more specifically to develop a proactive risk reduction culture. The CDMP carried out three level building surveys. First level consists of 5260 RC buildings and second level consists of 875 number of RC buildings. Second level survey information consists of survey datasheet and pictures of the existing buildings. An example of survey datasheet has been shown in Figure 3.2.

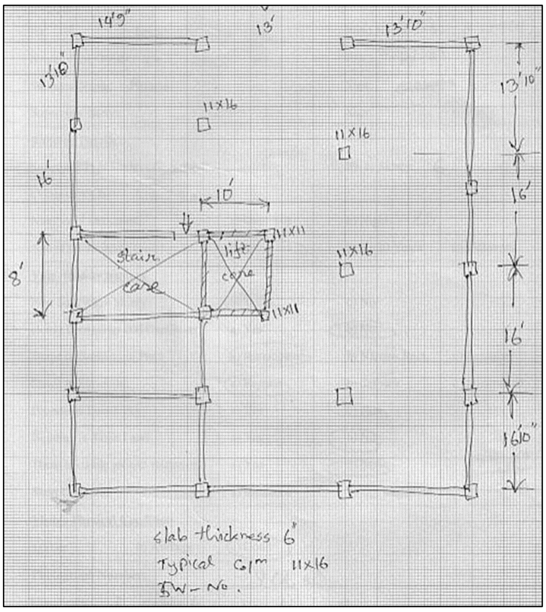
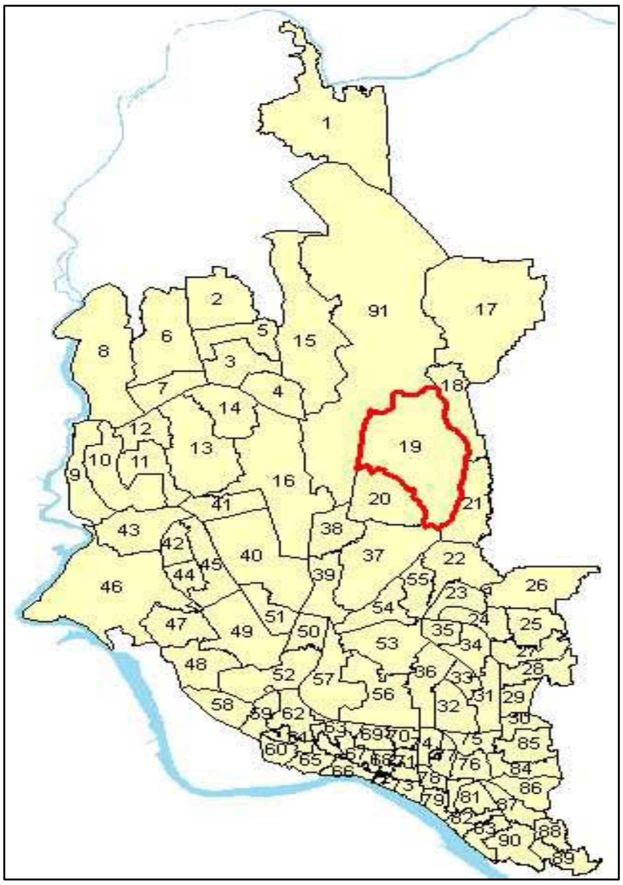


Figure 3.2 A typical As-built drawing for ground floor plan and photo of building (CDMP, 2009)

Those buildings database has been collected by SATREPS-TSUIB, a technical cooperation project between Ministry of housing and public works and Japan International Cooperation Agency (JICA). A total 583 number of investigated buildings from CDMP database have been studied. All buildings are Reinforced Concrete (RC) frame with masonry infill. The database contains of as-built floor plan and photos.

3.2.1.1 Location of buildings

As previously mentioned, all surveyed buildings are located at Dhaka city Corporation area. Dhaka city corporation area has been subdivided into 91 numbers of ward as shown in Figure 3.3. The investigated buildings are distributed for 1 to 90 ward. However, ward number 91 is under International airport and Dhaka cantonment. Due to restriction, ward number 91 is out of scope of the survey. Table 3.1 shows number of buildings investigated in ward 1 to 91 number. Ward number from 41 to 50 contains higher number of investigated buildings. Recent developments are carried out in this area.



Total number of ward: 90

Figure 3.3 Location of surveyed buildings (CDMP, 2009)

Table 3.1 Number of buildings in Ward basis (CDMP, 2009)

No. of ward	Ward No 1	Ward No 2-10	Ward No 11-20	Ward No 21-30	Ward No 31-40	Ward No 41-50	Ward No 51-60	Ward No 61-70	Ward No 71-80	Ward No 81-90
Bldg. number	54	47	86	61	80	108	68	22	33	24

3.2.1.2 Number of stories

Most of the surveyed buildings are three to six storied buildings. Now a day, the number of high rise buildings is increasing significantly due to accommodation of high volume of population. Figure 3.4 shows distribution according to number of story. It has been observed that about 40% of the surveyed buildings are six storied buildings. Thus, 6-storied building is commonly found in construction practices at Dhaka, Bangladesh.

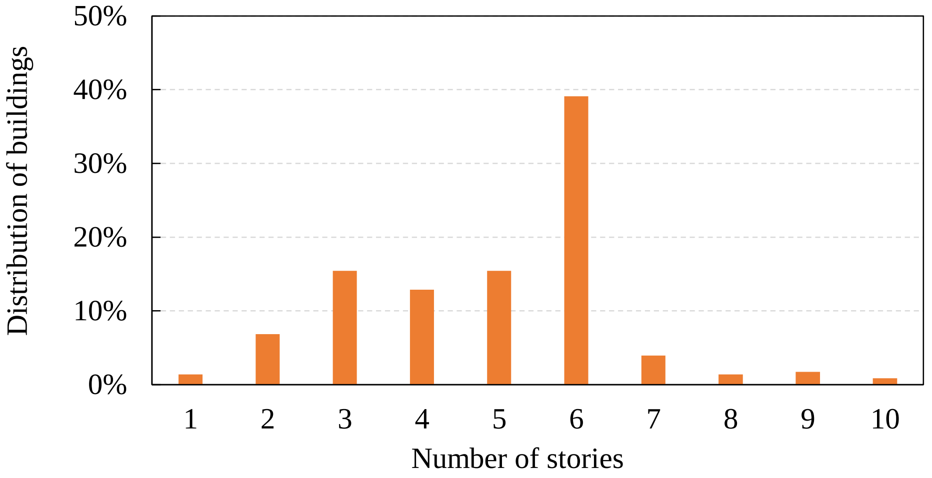


Figure 3.4 Distribution according to Number of stories

3.2.1.3 Occupancy category

Figure 3.5 shows occupancy categories for the investigated buildings. Investigation shows that three-quarter of investigated buildings are residential categories. Many buildings have combined-functions, with a ground floor are used for commercial purposes and upper floors are used for residential purposes. It should has observed that ground floor are open for parking space as well as for commercial purposes, which is common practice in Bangladesh.

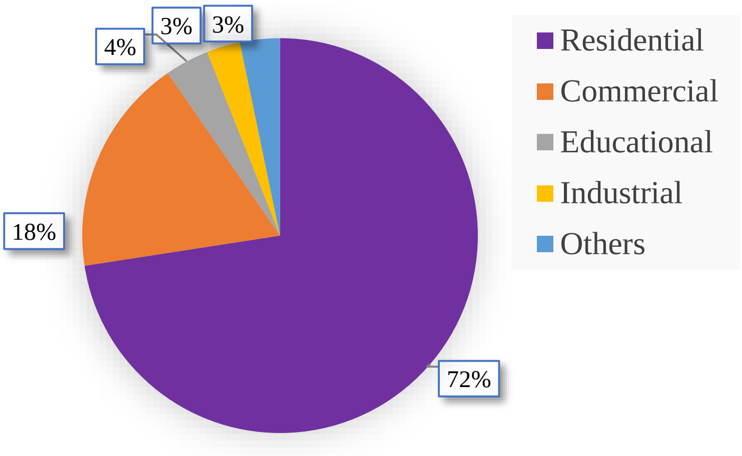


Figure 3.5 Occupancy categories of CDMP database

3.2.1.4 Types of structures

Structural system of these buildings are reinforced concrete (RC) moment resisting frame (MRF). Masonry wall is commonly used as partition wall in this structures. A few of them consists of RC wall used to control story drift.

3.2.2 Buildings characteristics

The surveyed buildings from CDMP database have been investigated to identify buildings characteristics, such as column size, thickness of masonry infill, building weight. These are describing in the following sections.

3.2.2.1 Column area ratio

Column area has been calculated using information found from the survey datasheet as shown in Figure 3.2. The cross-sectional area of column size ranging from 250 to 450mm as per investigated buildings. The usual practice for least dimension of typical column is 250 mm. Distribution according to column area ratio has been shown in Figure 3.6. In about 40% of total buildings, the column area ratio is under 0.2% because the cross-sectional area is smaller compared to the story number and total buildings area. The average value of column area ratio is about 0.29 with standard deviation 0.21.

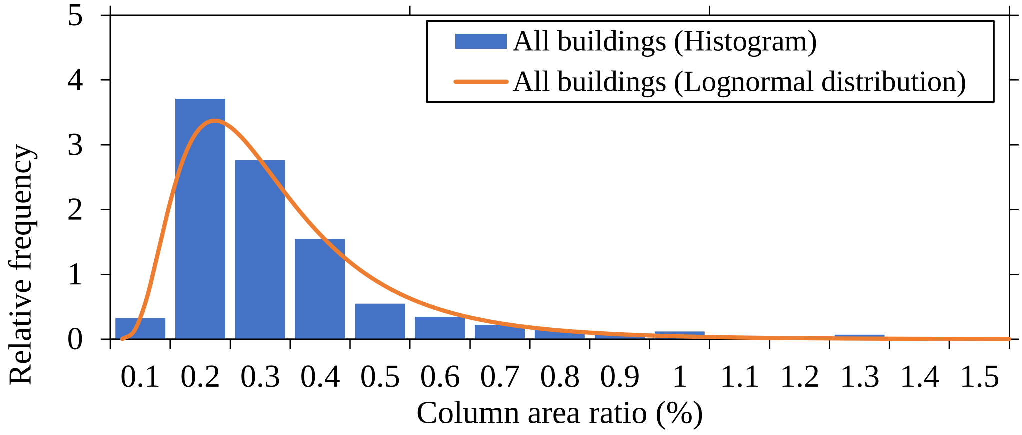


Figure 3.6 Column area ratio (%) of investigated buildings

3.2.2.2 Masonry infill wall area ratio

As previously mentioned, all buildings are RC with masonry infilled structures. The usual thicknesses of masonry infill are 250 mm and 150 mm for exterior and interior wall respectively. These masonry infill is using for partition wall. Both solid and partial infill due to door and window are considered for calculating the masonry infill area. However, in case of large opening, those which have opening larger than 40% of panel area, are not considered in this study for calculating masonry infill area. On the other hand, due to open space for parking and other shop for commercial purpose, about 55 % of these buildings have lower wall density, as shown in Figure 12. It is noted that upper floor contains more wall density than ground floor which are usually typical.

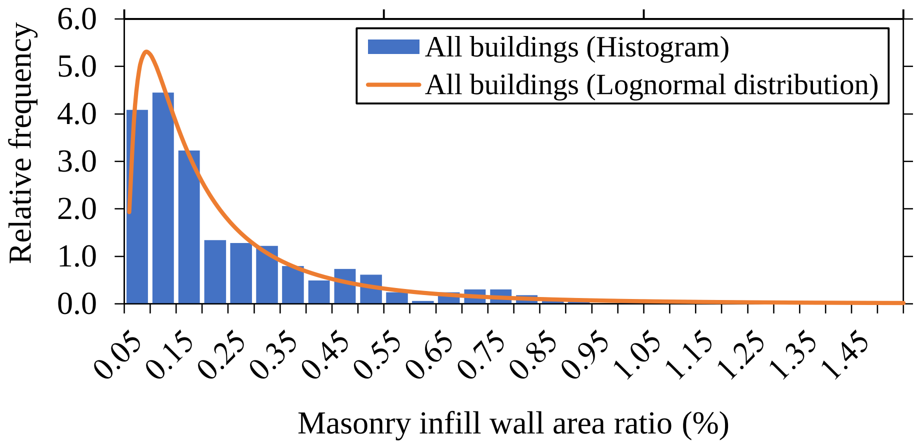


Figure 3.7 Masonry wall area ratio (%) of investigated buildings

3.3 Study on seismic capacity of existing RC buildings

As previously stated, total number of 583 RC buildings (as listed in Appendix A) are selected in this study in order to investigate their seismic vulnerability. Seismic capacity has been calculated based on information found from the CDMP database. Seismic capacity has been calculated by column area ratio and masonry infill wall area ratio, and average shear strength of column and masonry infill. It is noted that column and masonry wall are ratio are calculated by normalizing with total floor area at base as stated in previous sections.

As previously mentioned, for shear strength of masonry infill (τ_w), a unique value of 0.2 Mpa, is also adopted for Bangladesh as lower bound of the lateral shear strength (τ_w) of Masonry infill. The average shear strength of column (τ_c) is roughly assumed 1.0 Mpa which is also common in other countries.

Distribution of seismic capacity index has been shown in Figure 3.8. The seismic capacity index ranging from 0.1 to 1.3. However, it has been seen that most of the surveyed buildings has lower seismic capacity index. About half of the buildings shows 0.2 to 0.3 which indicates lower seismic capacity.

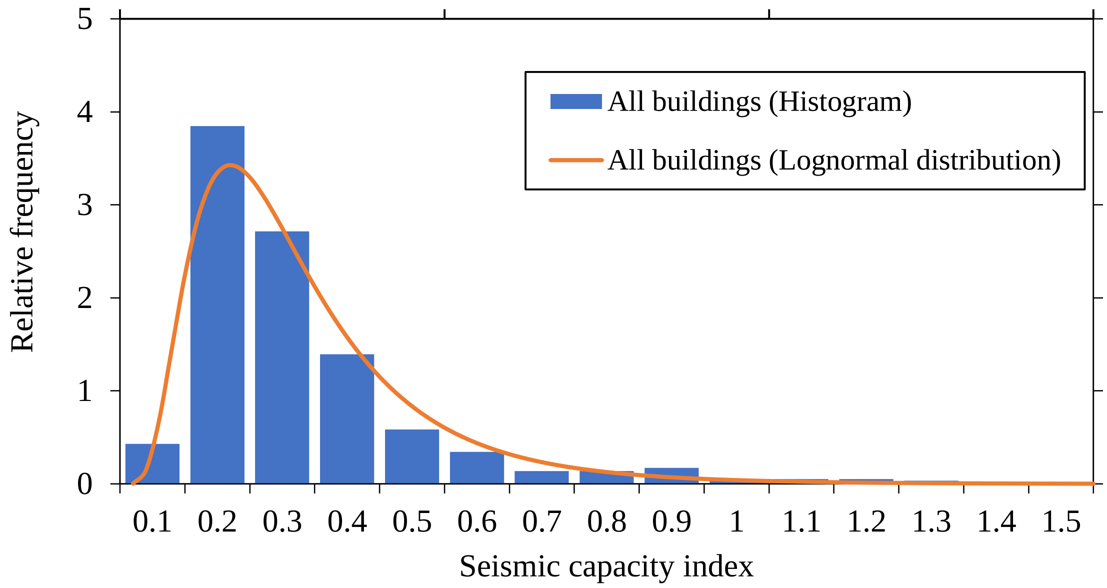


Figure 3.8 Distribution of seismic capacity index of investigated buildings

3.4 Comparison with past earthquake damage database from different seismic region

The aforementioned section describes the seismic capacity of existing buildings in Bangladesh. Generally, past earthquake record is one of the evidence for describing the level of seismicity and helpful for identification of lack of seismic capacity of existing buildings. However, in Bangladesh, there are no past earthquake record for judgement the level of seismic capacity of existing buildings. In this context, level of seismic capacity or seismic damage due to earthquake can be obtained by comparing the seismic capacity of damaged buildings in past earthquake in other countries. Therefore, seismic capacity of RC buildings has been compared with the past earthquake record in different countries. The following sections described in details the comparison with the other buildings database.

3.4.1 Compare with Nepal earthquake database

3.4.1.1 Column area ratio

Column area ratio of existing RC buildings has been compared with Nepal EQ database. Figure 3.9 shows the distribution of both investigated buildings database. It has been seen that column area ratio is lower than that of Nepal earthquake damage database.

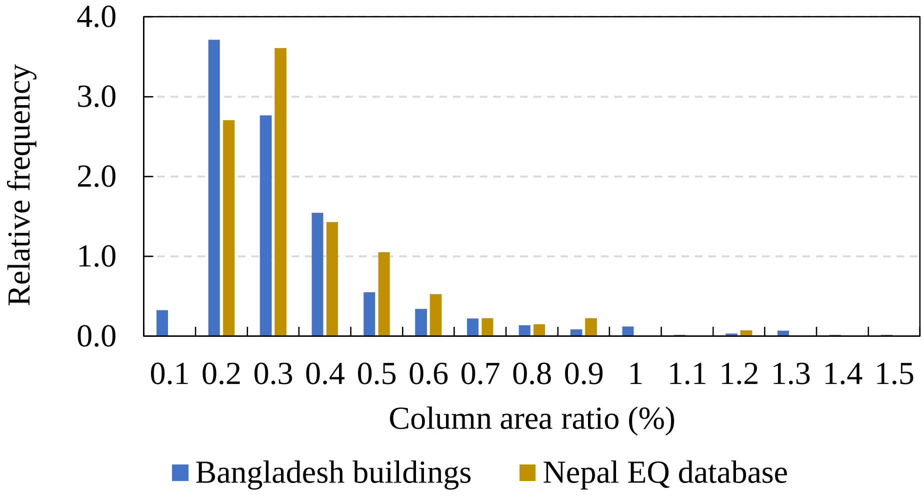


Figure 3.9 Column area ratio of Bangladesh and Nepal buildings

Generally, the seismic design and construction practices in these developing countries are almost similar. Thus, the cross-sectional areas are also similar. Study shows that most of the buildings are 2 to 4 storied. On the other hand, the similar cross-sectional areas are found but the number of stories are larger than Nepal buildings databases. As a result, the average values for column area ratio is of 0.32 which is little higher than that of Bangladesh buildings. Thus, seismic capacity is lower than Nepal buildings.

3.4.1.2 Masonry infill wall area ratio

Masonry infill wall area ratio has been compared with Nepal EQ database. Figure 3.10 shows distribution of masonry infill wall area ratio between Nepal and Bangladesh building database. As seen from the Figure 3.10, the average values of masonry infill area ratio are 0.48 and 0.21 for Nepal and Bangladesh database, respectively. It indicates that most of the surveyed buildings in Bangladesh, are found open ground floor due to car parking or commercial purposes.

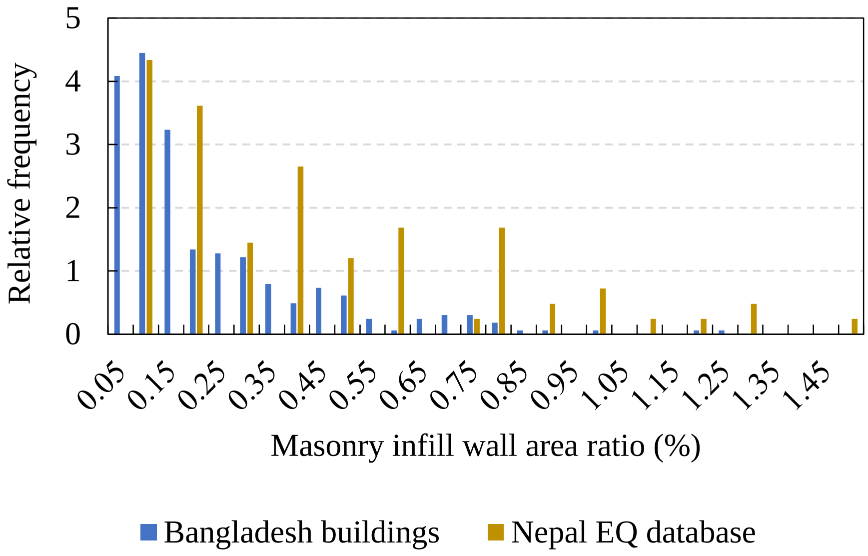


Figure 3.10 Masonry infill wall area ratio of Bangladesh and Nepal buildings

3.4.2 Compare with investigated buildings in Ecuador earthquake database

3.4.2.1 Column area ratio

Column area ratio has been compared with damage database of Ecuador earthquake. In Ecuador, column size is about 230mm size which is also similar to Bangladesh. However, all buildings are low-rise results higher column area ratio, despite the average column size are the same. Figure 3.11 shows the distribution of Bangladesh building database and Ecuador damage database. It has been observed that the average value of Ecuador EQ database about 0.42 which is 1.5 times of Bangladesh existing Buildings.

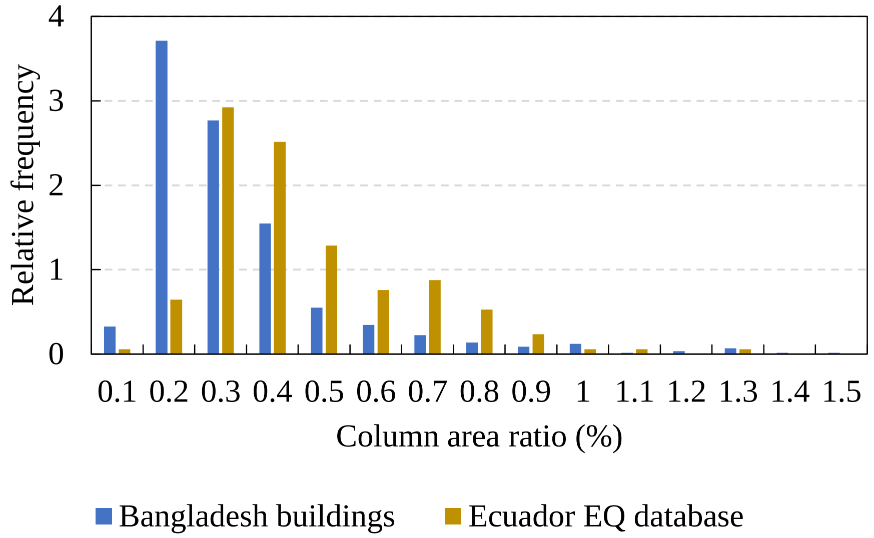


Figure 3.11 Column area ratio of Bangladesh and Ecuador buildings

3.4.2.2 Masonry infill wall are ratio

In Ecuador, concrete block, clayed bricks are commonly used as a construction material for infilled wall RC buildings. On the other hand, the construction practices in Bangladesh, clayed brick commonly is used in infill wall as a partition in infilled RC buildings. Figures 3.12 shows the differences in masonry infill area ratio between RC buildings in Ecuador and Bangladesh. It has been seen that the masonry infill ratio is also lower than Ecuador EQ database. In case Ecuador RC buildings, the average values of masonry infill area ratio are 0.35 which is slight higher than that of RC buildings in Bangladesh. Investigation shows that most of investigated building are low-rise resulting less floor area. However, for Bangladesh, the surveyed buildings are low to mid rise buildings, therefore, total floor area are higher than Ecuador buildings. Thus, the masonry infill area ratio is lower than RC buildings in Ecuador.

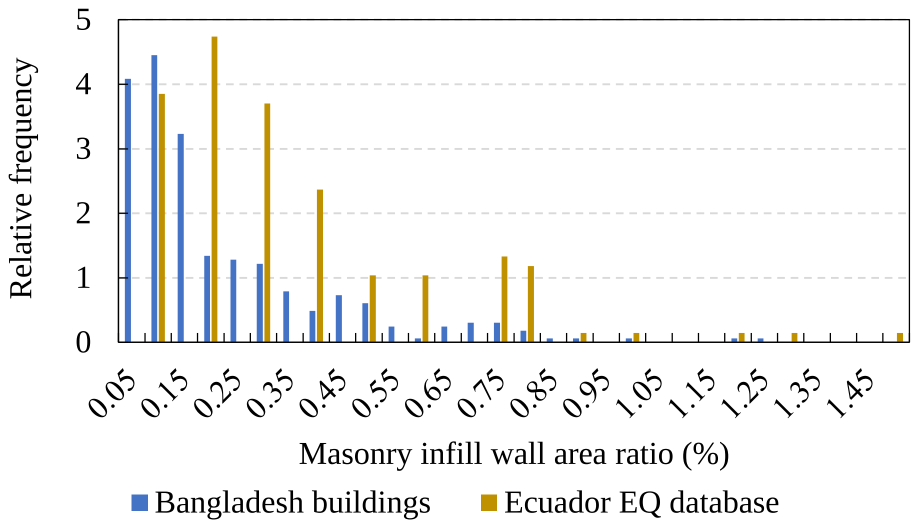


Figure 3.12 Masonry infill wall ratio of Bangladesh and Ecuador buildings

3.4.3 Compare with Taiwan earthquake database

3.4.3.1 Column area ratio

Column area ratio has been compared between Bangladesh and Taiwan EQ damage database. Figure 3.13 shows distribution of these two buildings databases. It has been seen that column area ratio of Bangladesh is much lower than that of Taiwan Buildings. Due to high seismic zone and updated building code and design practice in Taiwan results column area are higher compared with number of stories. In contrast, lack of updated building code and construction practices made the buildings lower column area ratio. From the Figure, it has been observed that the column arear ratio are almost double of compared with Bangladesh buildings database.

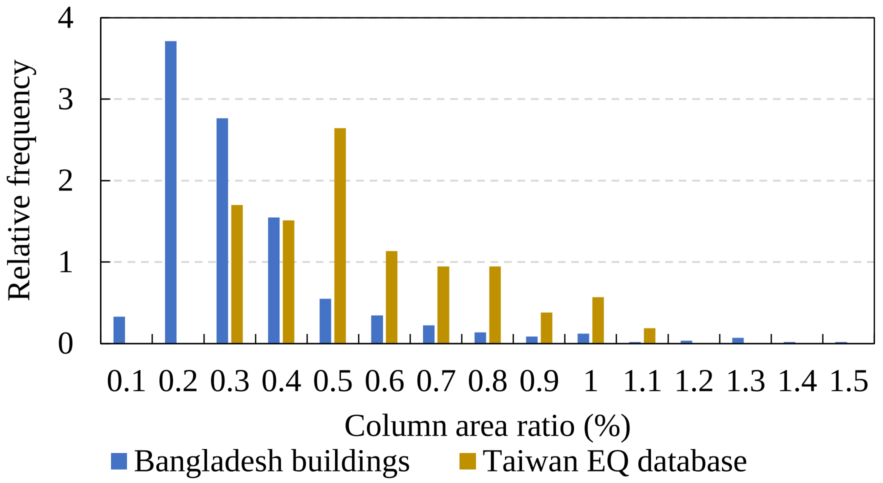


Figure 3.13 Column area ratio of Bangladesh and Taiwan buildings

3.4.3.2 Masonry infill wall area ratio

In Taiwan, generally, concrete block is used as construction material for infill wall in RC buildings. However, investigation shows that the average thickness of masonry infill is about 230mm, which is common in Taiwan buildings construction practice. On the other hand, masonry infill thickness in Bangladesh is 125 mm which is common practices. Figure 3.14 showing a comparison between Bangladesh buildings and Taiwan buildings database. It has been observed that the average values are of 0.46 which is almost similar to Nepal earthquake damage databases. Study shows that masonry infill ratio is lower than that of Bangladesh buildings.

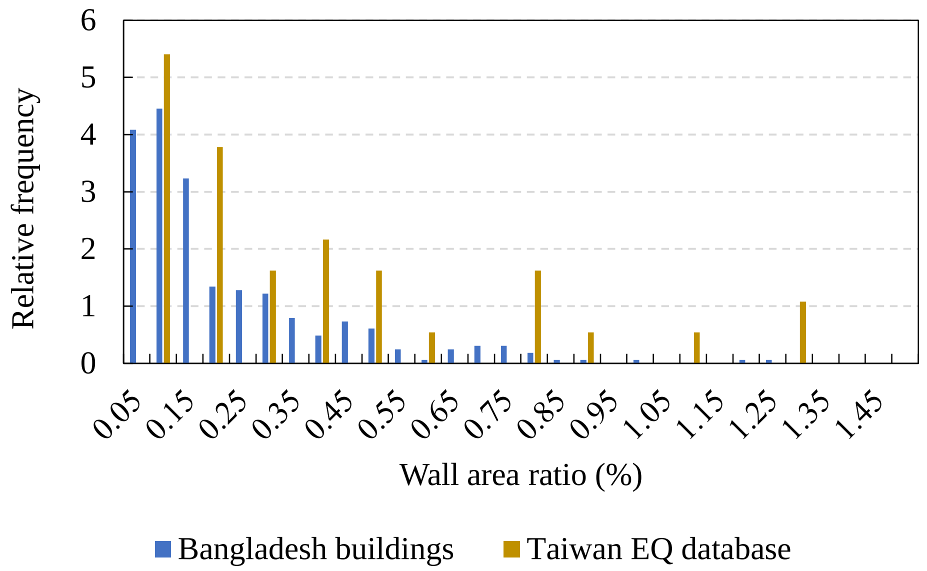


Figure 3.14 Masonry infill wall ratio of Bangladesh and Taiwan buildings

3.5 Comparison of the seismic capacity index with damaged buildings

Seismic capacity index, calculated for each EQ database, has been compared with the seismic capacity of Bangladesh buildings database. The following section describes about the comparison of seismic capacities.

3.5.1 Compare with Nepal earthquake buildings database

Seismic capacity of existing buildings in Bangladesh has been compared with Nepal earthquake damage database to understand the capacity of existing buildings. Figure 3.15

shows distribution of seismic capacity index of Nepal EQ database and Bangladesh buildings database. As seen from the Figure, the range of seismic capacity index of Bangladesh Buildings are from 0.2 to 0.3 of most of the investigated buildings. In addition, about 40% of investigated buildings contains the seismic capacity is about 0.2. On the other hand, the seismic capacity index is ranging from 0.2 to 0.4 for most of the buildings in Nepal building database. However, the average seismic capacity is of 0.38 for Nepal EQ database which is 1.3 times higher than that of RC buildings in Bangladesh. This is because of column area ratio and masonry infill area ratio of Nepal EQ database are higher comparing to Bangladesh buildings. It seems that higher column size and low-rise buildings results the higher seismic capacity index.

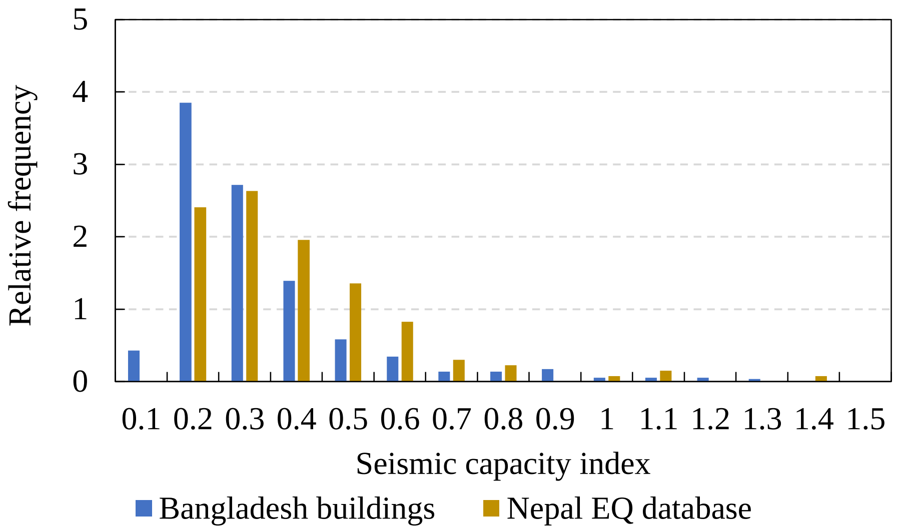


Figure 3.15 Seismic capacity index of Nepal buildings and Bangladesh buildings database

3.5.2 Compare with Ecuador earthquake buildings database

Seismic capacity of surveyed building in Bangladesh has also been compared with investigated buildings in Ecuador earthquake. Seismic capacity index of the investigated buildings has been calculated as shown in previous chapter. Figure 3.16 shows comparison between seismic capacity index of RC buildings in Bangladesh and Ecuador earthquake buildings database. In Ecuador, most of investigated buildings are low-rise that means number of story is lower. As a results, the buildings weight is lower results higher the seismic capacity. In contrast, for Bangladesh buildings, most of the buildings are higher resulting higher buildings weight. Thus, seismic capacity index is lower compare with Ecuador EQ damages databases. As shown in Figure 3.16, the average value of seismic capacity index of RC buildings in Bangladesh and Ecuador are of 0.46, 0.29, Respectively. It indicates that the seismic capacity index of RC buildings in Bangladesh is showing lower due to lower cross-sectional area and masonry infill wall area ratio compared with investigated RC buildings in Ecuador. Thus, the seismic capacity of Ecuador EQ database is 1.5 time higher than Bangladesh buildings.

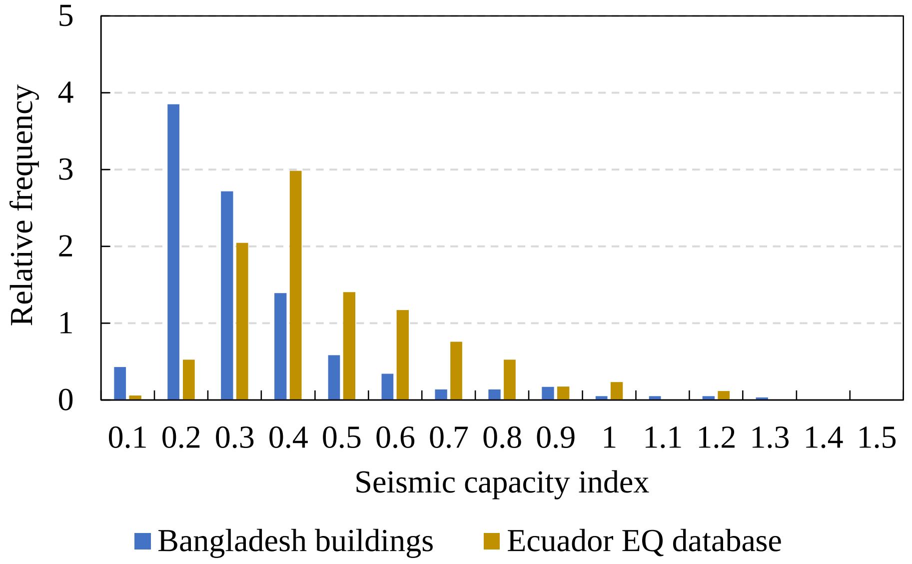


Figure 3.16 Seismic capacity index of Ecuador buildings and Bangladesh building database

3.5.3 Compare with Taiwan earthquake buildings database

Seismic capacity index of RC buildings in Bangladesh has been compared with seismic capacity of investigated buildings in Taiwan earthquake damage database. It has been found that the seismic capacity is much higher than RC buildings in Bangladesh. The design practices consider higher column area due to high seismic region. In addition, the buildings are school buildings contains higher masonry infill area ratio. Figure 3.17 showing the distribution of seismic capacity index of investigated RC buildings into two buildings databases. The average value of seismic capacity is of 0.53 which is twice of Bangladesh buildings database as 0.29. It indicates the Taiwanese buildings are much higher than existing buildings in Bangladesh.

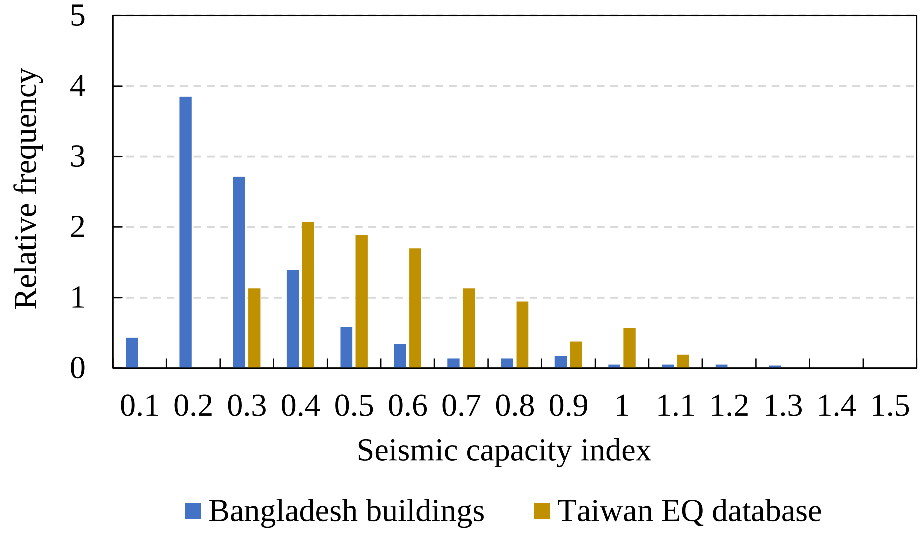


Figure 3.17 Seismic capacity index of Taiwan buildings and Bangladesh buildings database

3.6 Determination of extent of seismic damage of existing buildings in Bangladesh

In order to mitigate the earthquake disaster risk, it is essential to understand or predict the level of seismic vulnerability due to future probable earthquake. Generally, past earthquake record (i.e. buildings damage database) is a valuable evidence for helping in prediction of future vulnerability of existing buildings in any region. Based on past earthquake experience's, seismic design procedure has been revised by upgradation of building code, incorporation of safety provisions, and construction procedure in many high seismic region, such as Japan, Taiwan, New Zeeland. However, the other high seismic regions, where past earthquake data/record is not available or not archived, it is not easy to predict the extent of vulnerability due to future probable earthquake. The correlation of seismic capacity and experienced damage from other countries, is an alternative option for identifying the damage extent or vulnerability in a seismic region or countries. In this aspects, Okada and Nakano (1988) conducted reliability analysis on seismic capacity of existing RC buildings in Japan. Damage ratio can be predicted by comparing with the damaged buildings of recent earthquake damages databases and capacity of existing buildings (Okada and Nakano, 1988). The proposed concept has been used and applied in Bangladesh buildings, as a case study, the correlation with damage ratio and seismic capacity as well as seismic demand from other countries has been applied in existing RC buildings. The extent of damage based on study have been described in the following sections.

3.6.1 Probability of damage comparing with the Nepal earthquake database

As previously mentioned, a total of 133 RC buildings are recorded during investigating after the Nepal earthquake. Total 58 of the surveyed RC buildings has been documented as severely damaged based on investigation after the earthquake. Ratio of different level of damages have been discussed in chapter 2. Investigation depicts that about 44% of investigated buildings are listed as severely damaged and 55% of buildings are recorded as other than severe such as moderate, light and no damage buildings. Using the proportion of different levels of seismic damage, a correlation between seismic index and damage ratio has been developed and shown in previous chapter 2.

Figure 3.20 shows the distribution of seismic capacity of all buildings and severely damaged buildings using damage ratio of Nepal earthquake database. From the Figure, it has been found that the severely damaged buildings are about 55% of total buildings. Figure 3.20 (a) shows the probability of severely damaged buildings due to similar seismicity in Bangladesh, if happened.

3.6.1.1 Ground motion response acceleration

Ground motion time histories implies that ground motion acceleration of Nepal earthquake is higher than that of Bangladesh National Building Code seismicity. Figure 3.18 shows comparison between response acceleration of Nepal ground motion and BNBC response acceleration. It has been seen that for Nepal, the response acceleration is about 0.60 g which is 1.33 times larger than that of BNBC response acceleration in Bangladesh.

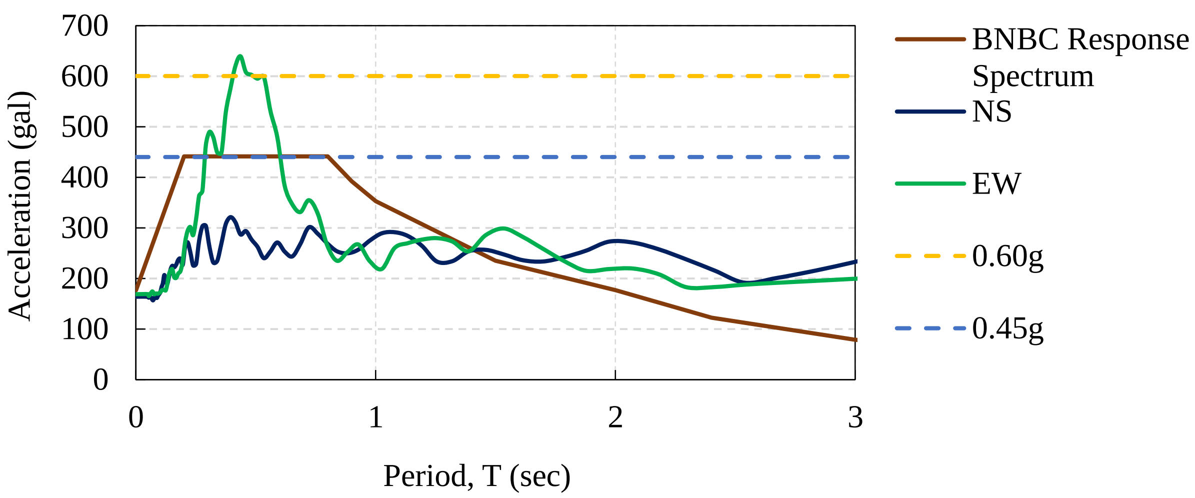


Figure 3.18 Comparison of different levels of response acceleration

3.6.1.2 Distribution of severely damaged buildings for different levels of seismicity

Distribution of severely damaged buildings for Bangladesh database has been calculated for both considering Nepal earthquake ground motion and Bangladesh local seismicity as per response acceleration mentioned in BNBC design code (BNBC 2015). Considering Nepal ground motion, distribution of severely damaged buildings has been calculated based on damage ratio and the mean values of severely damaged buildings as calculated for Nepal EQ database (please see Figure 2.37 in chapter 2). Figure 3.19 showing distribution of severely damaged buildings of CDMP database using similar damage ratio as found in Nepal earthquake damage database. It should be noted that the distribution of severely damaged buildings is based on Nepal ground motion where the acceleration response spectrum is about 0.6g (see Figure 3.18). Actually the seismicity of these two region are not the same. However, in case of Bangladesh, as mentioned in Nepal ground motion is 1.33 times higher than that of Bangladesh. In that case, distribution of severely damaged buildings has been calculated, where mean value of severely damaged buildings of Nepal by proportion of ground motion acceleration is of 0.80. Figure 3.19 showing the different distribution of severely damaged buildings between Nepal ground motion and BNBC code seismicity.

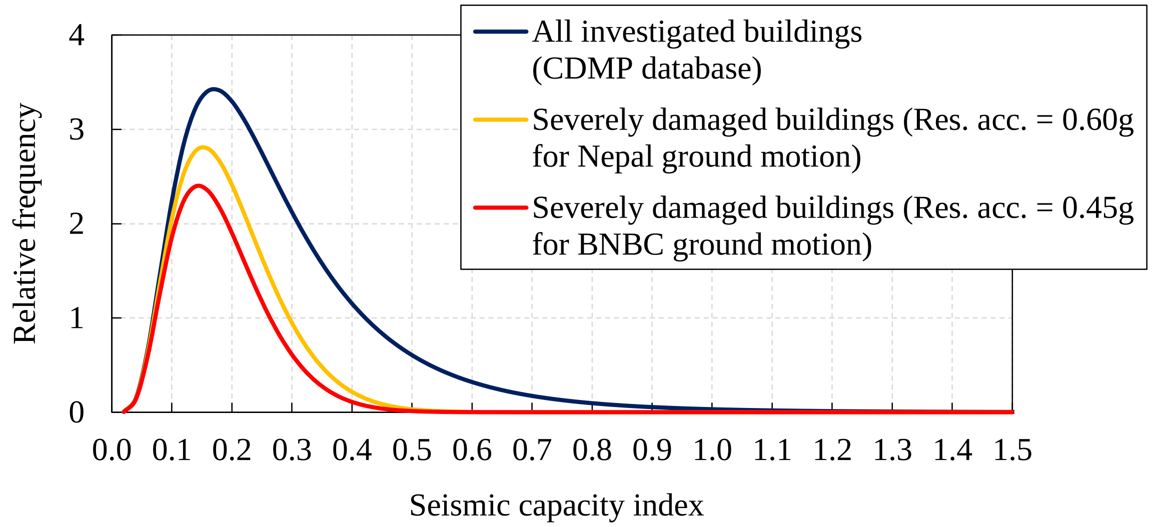
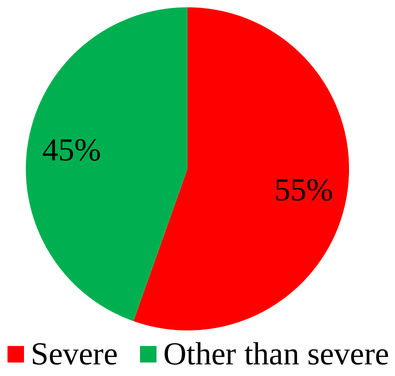


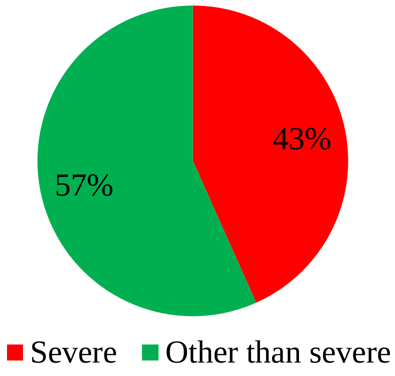
Figure 3.19 Distribution of seismic capacity index for severely damaged RC buildings

3.6.1.3 Ratio of severely damaged buildings for different levels of seismicity

Figure 3.20 showing the extent of damage probability considering Nepal and BNBC ground motions. It has been seen that, 55% of buildings will be severely damaged using similar damage ratio for Nepal earthquake database. Afterward, probability of seismic damage has been calculated considering the local seismicity as per BNBC ground motion as described in previous section. Figure 3.20 shows, in case of Bangladesh Buildings, the probability of severely damaged buildings is about 43% which is slight lower than Bangladesh.



(a) Res acc. = 0.6g for Nepal ground motion



(b) Res. Acc.= 0.46g for BNBC ground motion

Figure 3.20 Probability of seismic damage due to different levels of seismicity

3.6.2 Probability of damage comparing with the Taiwan earthquake database

For Taiwan EQ database, 63 number of RC buildings have been investigated. From all of these buildings, 12 numbers of buildings are reported as severely damaged. As previously mentioned, about 23% buildings are severely damaged and 77% buildings are moderate, light and none damage. Based on the proportioned of level of seismic damage, distribution of damage ratio has been developed. Probability of damage ratio estimated using damage ratio based on Taiwan earthquake database.

3.6.2.1 Ground motion response acceleration

Figure 3.21 shows comparison between ground motion of Taiwan EQ and BNBC response acceleration. As discussed in the previous chapter 2, all investigated buildings are located near ground motion station CHY62. Therefore, average response acceleration is assumed 0.9g for the recorded ground motion at Station CHY 62. However, the response acceleration as per BNBC code (BNBC 2015) is 0.46g which is half of the Taiwan ground motion as shown in Figure 3.21.

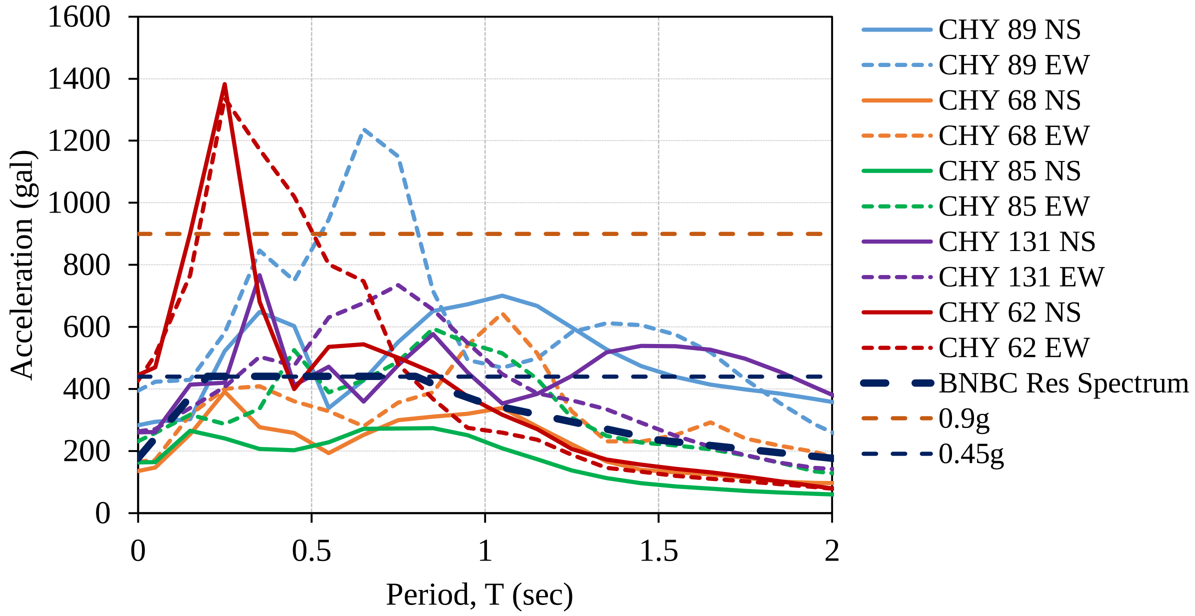


Figure 3.21 Comparison of different levels of response acceleration

3.6.2.2 Distribution of severely damaged buildings for different levels of seismicity

Distribution of severely damaged buildings has been also calculated considering Taiwan EQ ground motion and BNBC ground motion. First of all, distribution of severely damaged buildings has been determined as shown in Figure 3.22. However, the level of seismicity in Bangladesh is half of Taiwan EQ ground motion. Considering the proportions of seismicity level, the damage ratio has been calculated modifying the mean value of severely damaged buildings. The distribution of severely damaged buildings as shown in Figure 3.23 for BNBC seismicity.

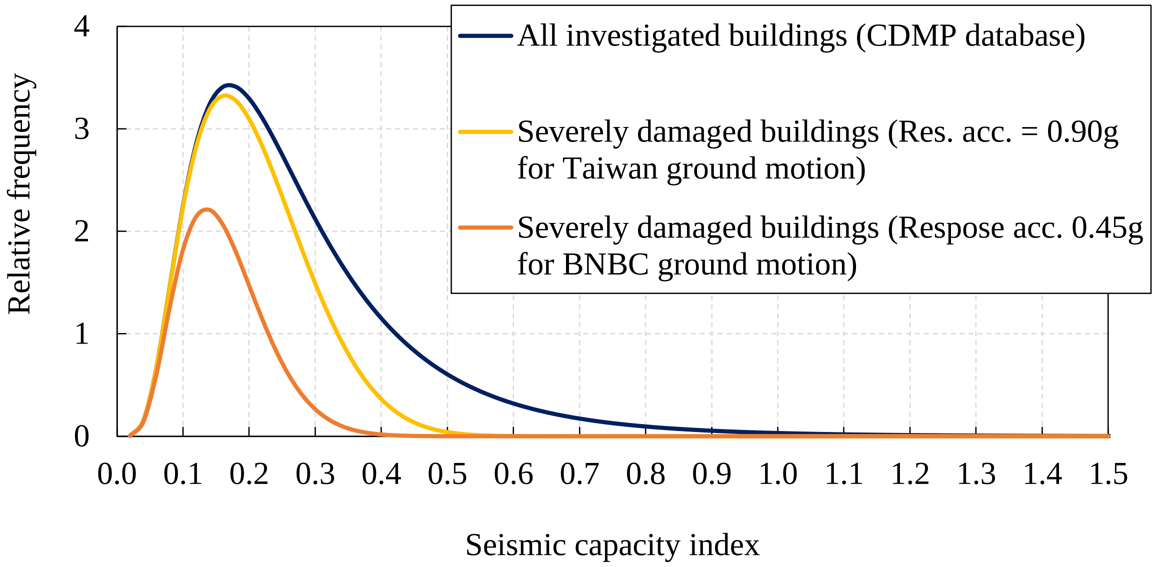
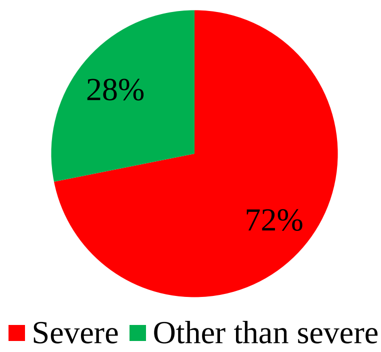


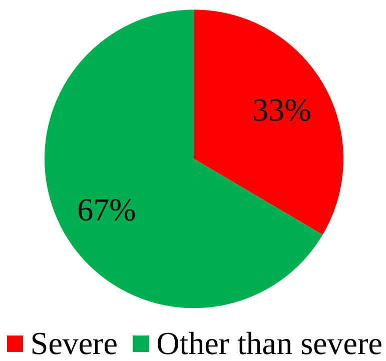
Figure 3.22 Distribution of seismic capacity index for severely damaged buildings

3.6.2.3 Ratio of severely damaged buildings for different levels of seismicity

Damage ratio has been calculated based on distribution showing in Figure 3.23. The damage ratio considering Taiwan EQ ground motion and BNBC ground motion are of 72% and 33%, respectively. It is evident that Taiwan located higher seismic zone and seismic capacity of existing buildings are much higher than that of Bangladesh buildings. As a result, the probability of damage ratio due to BNBC seismicity is almost half comparing with the Taiwan ground motion.



(a) Res acc. = 0.9g for Taiwan ground motion



(b) Res. Acc.= 0.46g for BNBC ground motion

Figure 3.23 Probability of seismic damage due to different levels of seismicity

3.6.3 Probability of damage comparing with the Ecuador earthquake database

As stated in previous section, Ecuador EQ database, 171 buildings have been investigated for understanding the damage ratio of Bangladesh buildings. A total 76 numbers of buildings have been severely damaged which is about 44% of total surveyed buildings. Other than severe, 55 % of total buildings are reported as moderate and light damage based on investigation. Damage ratio has been determined using the average value of severely damaged buildings. Probability of damage ratio calculated based on comparison between seismicity of Ecuador and BNBC ground motion.

3.6.3.1 Ground motion response acceleration of Ecuador EQ and BNBC response spectrum

Figure 3.24 shows the comparison of response acceleration of Ecuador ground motion and BNBC code ground motion. Like Taiwan ground motion, for Ecuador EQ also response acceleration is much higher compared with Bangladesh BNBC ground motion. Therefore, level of seismic damage also will be higher due to different level of seismicity. From recorded ground motion, it has been assumed that the average response acceleration is of 0.9g which is twice of BNBC ground motion as shown in Figure 3.24.

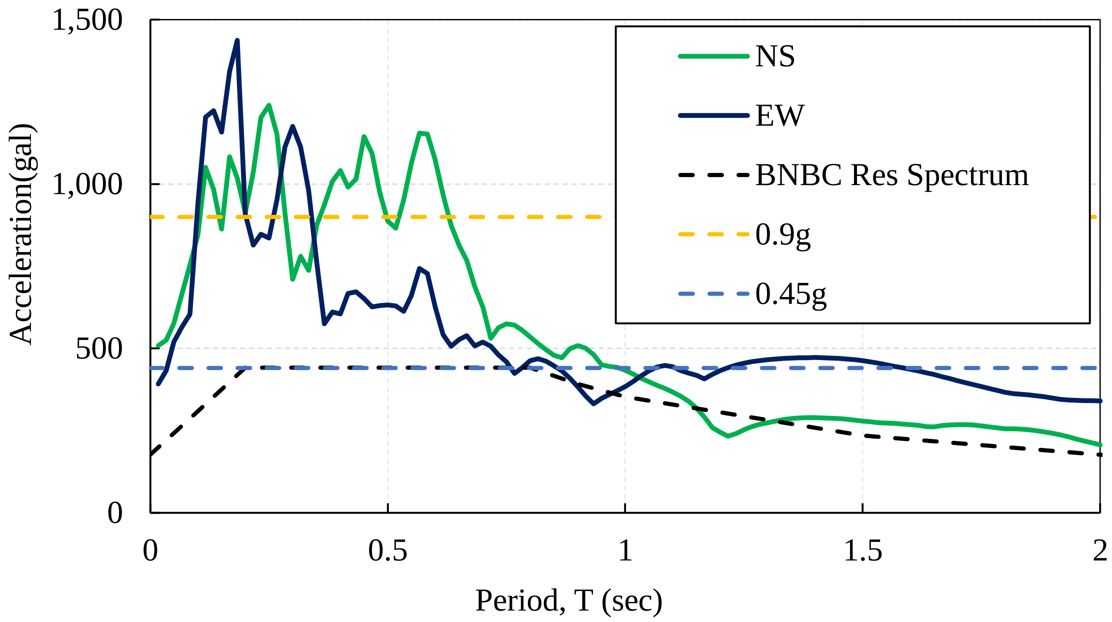


Figure 3.24 Comparison of different levels of response acceleration

3.6.2.2 Distribution of severely damaged buildings for different levels of seismicity

Distribution of severely damaged buildings for Bangladesh Buildings has been also calculated considering Ecuador EQ ground motion and BNBC ground motion in similar way of Nepal and Taiwan earthquake damage database. Distribution of severely damaged buildings has been determined for existing RC buildings in Bangladesh using the calculated damage ratio for Ecuador earthquake database. Figure 3.22 showing the distribution of severely damaged buildings corresponds to Ecuador ground motion. However, the seismicity of Bangladesh ground motion is half of Ecuador ground motion like Taiwan earthquake database. Hence, the probability of damage will not be same for Ecuador and Bangladesh ground motion. Therefore, distribution severely damaged buildings for Bangladesh database has been calculated corresponding to BNBC ground motion following similar concept as mentioned in Nepal and Taiwan ground motion. It is already mentioned, the proportion of response acceleration between Ecuador and Bangladesh is almost half of each other.

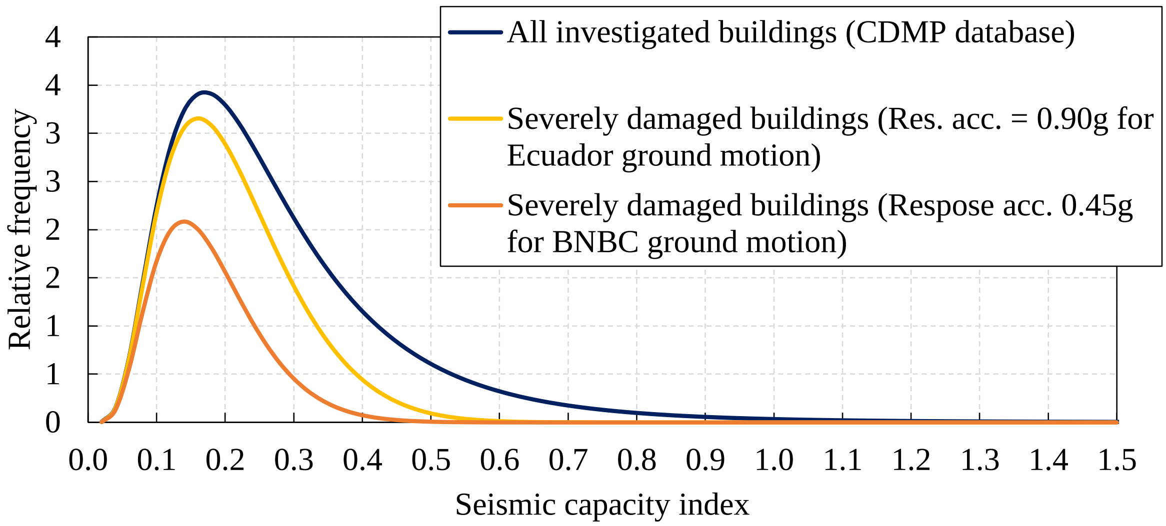
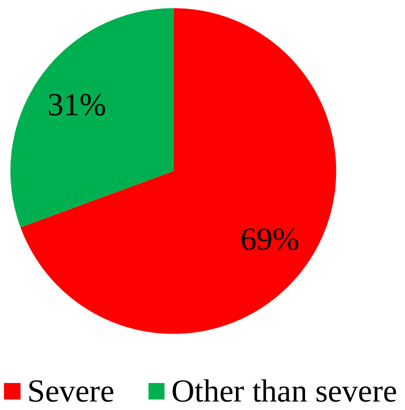


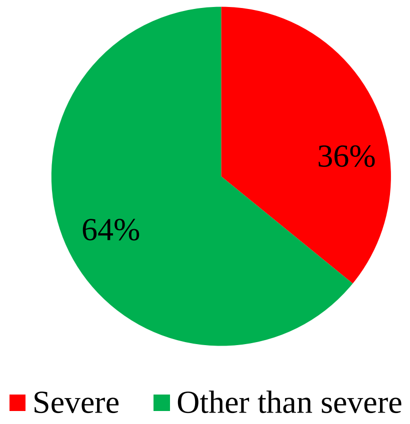
Figure 3.25 Distribution of seismic capacity index for severely damaged buildings

3.6.3.3 Ratio of severely damaged buildings for different levels of seismicity

Probability of damage ratio has been calculated using the distribution mentioned in Figure 3.25. The estimated damage ratio is shown in Figure 3.26. It has been observed that the probability of damage is about 69% using similar damage ratio based on recorded database. However, the probability of damage ratio is reducing to 36% considering BNBC seismicity. In this case, the damage ratio has been modified using the proportions of ground motion as discussed in previous sections. Therefore, the extent of seismic damage will be almost half in case of Bangladesh BNBC ground motion.



(a) Res. acc. = 0.9g for Ecuador ground motion



(b) Res. Acc.= 0.46g for BNBC ground motion

Figure 3.26 Probability of seismic damage due to different levels of seismicity

3.7 Summary of chapter 3

This chapter presented seismic evaluation of existing RC buildings in developing country where past earthquake damage database is not available. As a case study, existing RC buildings located in Bangladesh have been collected for seismic capacity evaluation. These exiting RC buildings database are originated from Comprehensive Disaster Management Program (CDMP) project, a national project of Government of Bangladesh. Seismic capacity has been evaluated based on information found from the database. Column area ratio and infill wall area ratio of those existing RC buildings are calculated and compared with those of other past earthquake damage databases as discussed in chapter 2. Afterward, seismic capacity has also been compared with the damaged RC buildings databases for identifying the extent of damage level of existing RC buildings.

The summary of this chapter are as follows:

1) Column area ratio and masonry infill wall area ratio are found lower (1.2 to 1.6 times less) than other buildings database from different developing countries such as Ecuador, Nepal and Taiwan earthquake damage database.
2) The lower masonry infill ratio (≈1.7 times less) comparing with other databases indicates most of the investigated buildings in Bangladesh ground floor are open.
3) Seismic capacity of Bangladesh buildings is found much lower (≈1.5 times less) than comparing with other past earthquake damage databases of Ecuador, Nepal and Taiwan.
4) Probability of damage ratio for Bangladesh buildings has been estimated comparing with seismic capacity and ground motion intensity of each ground motion. Study shows that probability of severely damaged building is approximated about 36%, 43%, and 33% comparing with Ecuador, Nepal, and Taiwan earthquake damage database, respectively.

Chapter 4

Study on existing rapid visual screening methods

4.1 Introduction

This chapter describes the study of existing rapid visual screening methods that are available in different countries. Main objectives of this chapter is to understand the applicability and effectiveness of existing rapid visual screening methods for identification of the most vulnerable buildings as well as priority settings for detail evaluation. First of all, existing rapid visual screening methods such as FEMA P154, Turkish RVS method and Indian RVS method have been studied. Afterward, those RVS methods have been applied on Taiwan earthquake damage database, as a case study to understand the applicability and effectiveness of these methods. Finally, seismic capacity of these investigated RC buildings has been compared with the results or RVS scores of each rapid visual screening method.

4.2 Background

Chapter 2 and Chapter 3 showed a simplified method and applied on surveyed EQ damaged RC buildings and non-damaged RC buildings in different countries. This simplified method is very effective for estimating the seismic capacity very rapidly and results shows good correlation with seismic damage. However, it is quite challenging to apply this method on existing buildings because of many of the existing RC buildings does not have architectural buildings. Therefore, screening thorough visual investigation is an alternative approach to identify the most vulnerable buildings.

Generally, rapid visual screening (RVS) is a simple and rapid seismic evaluation method for evaluation of a large building stock in order to set the priority for higher level or detail evaluation. The investigation procedures are based on visual survey within 15-30 minutes for each building and record the important components of seismic capacity. Those methods propose a scoring system to classify the buildings in different risk categories. However, the majority of visual screening methods consider wide ranges of screening procedures. In addition, the inclusion of few parameters results a variation in different RVS method. The following sections described about the existing Visual Screening method from different countries.

4.3 Review of existing rapid visual screening methods

Several rapid visual screening methods are available in different countries from US, Canada, New-Zealand, Turkey, India and so on. These are qualitative approach mainly based on expert's judgement and observation from earthquake reconnaissance report. The main concept is similar in these existing rapid visual screening method. However, some differences are found during consideration of modification parameters such as buildings type, age, geotechnical condition etc.

The National Research Council of Canada (NBC) developed a seismic screening procedure based on visually investigation. The proposed method calculated seismic priority index considering structural factors and non-structural factors. The main parameters are local seismicity, soil type, structural type, irregularities, importance categories and other non-structural elements. However, the score assigned to each factor is related to the year of construction of investigated buildings.

The New Zealand code suggests two-level screening process for the seismic evaluation of existing RC buildings (NZ code). The initial evaluation procedure (IEP) considers an initial assessment of the seismic performance of existing RC buildings against the standards required for a new RC building. For each existing building, the percentage of met requirements has been calculated regarding the standards for new building (% NBS). A % NBS of 33 or less indicates that the building has been considered as potentially earthquake prone and detailed evaluation is needed. The result of the rapid screening method is defined as a "*structural score*" which is based on about 14 (fourteen) numbers of structural criteria and which is also an indicator of potential damage. The total structural score has been divided into two parts. Firstly, a basic structural score which reveals the standard used for original design and earthquake damage potential of the respective building types and local seismicity such as high, moderate or low seismicity zones. Another part is that a modification to the basic structural score on account of different vulnerable parameters present in the building. The intent of these vulnerable parameters is to ensure that more detail seismic evaluation is required for the buildings with significant vulnerabilities. The structural irregularities, such as weak story and torsional effect, are considered in the evaluation method.

The Greek RVS method has been developed by OASP in 2000 has been based on the FEMA 154 handbook (the first edition) and defined as OASP-0. The proposed method is considered as a standard rapid visual screening procedure using both primary lateral load resisting system and buildings material of existing buildings. Buildings are classified into 18 structural types and initial hazard score has been calculated.

This initial hazard score is modified according to local seismicity and other vulnerable parameters such as soft story, short columns and regular arrangement of the masonry infill. Final score has been calculated by modifying with some modifiers related to observed performance characteristics. A final score of 2 or less indicates the buildings should proceed detail seismic evaluation. This method considers two approach one is OASP-0 and OASP-R. The first one is based on the OASP-0 method is based on first edition of FEMA and OASP-R is based on second edition of FEMA 154.

However, the well-known rapid visual screening (RVS) methods that have been used worldwide Such as FEMA P 145, Turkish RVS method and Indian RVS methods are commonly used in different countries. The basic criteria and development of these procedure are described in subsequent sections.

4.3.1 Federal Emergency Management Agency (FEMA P 154)

4.3.1.1 Introduction

The United States Federal Emergency Management Agency (FEMA) proposed a number of guidelines which are available for seismic risk assessment and rehabilitation of buildings. In 1989, FEMA 178 has been first published and later revised in 1992. Later, in 1998 another version of FEMA 310 has been established which is also based on FEMA 178 in 1992. In 1988, another guideline has been published FEMA 154 for rapid visual screening which is revised in 2002.

The FEMA 154 methodology initiated in 1988 with the publication of the FEMA 154 handbook report, *Rapid Visual Screening of Buildings for Potential Seismic Hazards: A Handbook* (FEMA, 1988a). Later on, the FEMA 154 has been updated and improved based on the data and information during in the first decade research and experiments. In this context, FEMA 154 has been updated with revised scoring system in 2002 incorporating the same framework and approach of the original procedure. The scoring system has been developed based on the criteria in FEMA 310 report and the damage and loss estimation methodology provided in the HAZUS Technical manual (FEMA 1999d). The third edition of FEMA 154 has been published in 2015, recognized as FEMA P 154, including major enhancements such as data collection form in level 1 and level 2.

FEMA P 154 (2015) method estimates a performance score which predicts the probability of collapse of existing buildings/structures. However, the FEMA final score is the summation of basic score and score modifiers due to other vulnerability parameters or seismic performance parameters as shown in Equation (4.1):

FEMA final score=Basic score + Score modifiers (4.1)

4.3.1.2 FEMA P 154 Basic score

FEMA proposes basic score for different types of structure i.e. lateral force resisting system of buildings and seismic zone or region. Table 4.1 defines different types of structural system considered by FEMA P 155.

In the Table 4.1, C1, C2, and C3 are the reinforced concrete structures. The masonry infilled RC structures are defined as C3 type as shown in the Table 4.1, which is common types of structural system in developing countries. Therefore, each building type contains individual scores based varying with different soil condition. The methodology for estimation of basic structural scores has been described in the third edition of FEMA P 155. Table 4.2 shows the basic scores considered for masonry infilled RC buildings type C3.

Table 4.1 FEMA P 154 buildings Types (based on ASCE/SEI 41-13)

Building type	Building description
W1	Light wood frame single- or multiple-family dwellings of one or more stories in height
W1A	Light wood frame multi-unit, multistory residential buildings with plan areas on each floor of greater than 3.000 square feet
W2	Wood frame commercial and industrial buildings with a floor area larger than 5,000 square feet
S1	Steel moment-resisting frame buildings
S2	Braced steel frame buildings
S3	Light metal buildings
S4	Steel frame buildings with concrete shear walls
S5	Steel frame buildings with unreinforced masonry infill walls
C1	Concrete moment-resisting frame buildings
C2	Concrete shear wall buildings
C3	Concrete frame buildings with unreinforced masonry infill walls
PC1	Tilt-up buildings
PC2	Precast concrete frame buildings
RM1	Reinforced masonry buildings with flexible floor and roof diaphragms
RM2	Reinforced masonry buildings with rigid floor and roof diaphragms
URM	Unreinforced masonry bearing wall buildings
MH	Manufactured housing

Table 4.2 Basic scores for masonry infilled RC buildings type C3 (FEMA P 154 2015)

Level of seismicity	Basic score
Low seismicity	3.5
Moderate seismicity	2.0
Moderately high seismicity	1.4
High seismicity	1.2
Very high seismicity	0.9

Five seismicity regions are used in FEMA described as Low, Moderate, Moderate High, High, and Very high as shown in Table 4.3. These seismic regions are subdivided according to ranges of spectral response acceleration parameters.

Table 4.3 Seismicity Region Determination from MCE_R Spectral Acceleration Response

Seismicity Region	Spectral Acceleration Response, S_S (short-period, or 0.2 seconds)	Spectral Acceleration Response, S_1 (long-period, or 1.0 second)
Low	$S_S < 0.250g$	$S_1 < 0.100g$
Moderate	$0.250g < S_S < 0.500g$	$0.100g < S_1 < 0.200g$
Moderately High	$0.500g < S_S < 1.000g$	$0.200g < S_1 < 0.400g$
Very High	$1.000g < S_S < 1.500g$	$0.400g < S_1 < 0.600g$
High	$S_S > 1.500g$	$S_1 > 0.600g$

Notes: g = acceleration of gravity in horizontal direction

The FEMA basic scores are also varied on different types of soil type located at foundation of the structures. Table 4.4 showing the type of soils considering different condition.

Table 4.4 Soil Type definitions

Soil Type/Site Class S	Shear Wave Velocity[1] , $V_S{}^{30}$	Standard Blow Count[1] , N	Undrained Shear Strength of the upper 100ft[1], s_u
A. Hard Rock	$V_S{}^{30} > 5000$ ft/s		
B. Rock	2500 ft/s < $V_S{}^{30}$ < 5000 ft/s		
C. Very Dense Soil and Soft Rock	1200 ft/s < $V_S{}^{30}$ < 2500 ft/s	N >50	s_u >2000 psf
D. Stiff Soil	600 ft/s < $V_S{}^{30}$ < 1200 ft/s	15 < N <50	1000 psf < s_u < 2000 psf
E. Soft Clay Soil	$V_S{}^{30} \leq 600$ ft/s	N < 15	s_u < 1000 psf
	More than 10 feet of soft soil with plasticity index PI > 20, water content w > 40%, and s_u < 500 psf		
F. Poor Soil	Soils requiring site-specific evaluations. • Soils vulnerable to potential failure or collapse under seismic loading, such as liquefiable soils, quick and highly-sensitive clays, collapsible weakly-cemented soils. • Thicker than 10 feet of peat or highly organic clay • Very high plasticity clays (25 feet with PI > 75). • More than 120 ft of soft or medium stiff clays.		

[1]Average values.

Generally, the most common soil type has been found as Soil Type C and Soil Type D. The average type of soil is referred as Soil Type CD. If there are difficulty to recognize the type of soil, Soil type D has been considered. It has been recommended that the buildings located on Soil Type F should be further evaluated by design professional engineer and geotechnical engineer experienced in seismic design.

4.3.1.2 Score modifiers

The *FEMA P 154* considers performance modifiers which are considered to take into account the effect of number of stories, buildings irregularities both such as plan and vertical, pre-code or post-benchmark code detailing, and type of soil as shown in Table 4.5.

Table 4.5 showing the listed performance modifiers

FEMA Building type	Low seismicity	Moderate seismicity	Moderately high seismicity	High seismicity	Very high seismicity
Severe Vertical Irregularity, *VL1*	-1.1	-1.0	-0.8	-0.7	-0.6
Moderate Vertical Irregularity, *VL1*	-0.6	-0.6	-0.5	-0.4	-0.3
Plan Irregularity, *PL1*	-0.9	-0.8	-0.6	-0.5	-0.3
Pre-code	NA	-0.3	-0.1	-0.1	0.0
Post-Benchmark	NA	NA	NA	NA	NA
Soil Type A or B	+1.2	+1.3	+0.7	+0.3	+0.1
Soil Type E (1-3 stories)	-1.6	-0.7	-0.4	-0.2	0.0
Soil Type E (> 3 stories)	-1.6	-0.8	-0.4	-0.3	-0.1

4.3.1.3 Data collection form

The FEMA uses a data collection form for each of five seismicity regions such as low, moderate, moderately high, very high, and high. However, the criteria for the boundaries of the low, moderate, moderately high, very high, and high are shown in Table 4.4. Figure 4.1 showing an example of data collection form for recording information from visual screening procedure.

Rapid Visual Screening of Buildings for Potential Seismic Hazards — **Level 1**

FEMA P-154 Data Collection Form — **MODERATELY HIGH Seismicity**

PHOTOGRAPH

Address: ______________________ **Zip:** ________

Other Identifiers: ______________________

Building Name: ______________________

Use: ______________________

Latitude: __________ **Longitude:** __________

S_S: __________ **S_1:** __________

Screener(s): __________ **Date/Time:** __________

No. Stories: Above Grade: ____ Below Grade: ____ **Year Built:** ____ ☐ EST

Total Floor Area (sq. ft.): __________ **Code Year:** ____

Additions: ☐ None ☐ Yes, Year(s) Built: ____

Occupancy: Assembly, Commercial, Emer. Services, ☐ Historic, ☐ Shelter, Industrial, Office, School, ☐ Government, Utility, Warehouse, Residential, # Units: ____

Soil Type: ☐A Hard Rock ☐B Avg Rock ☐C Dense Soil ☐D Stiff Soil ☐E Soft Soil ☐F Poor Soil **DNK** *If DNK, assume Type D.*

Geologic Hazards: Liquefaction: Yes/No/DNK Landslide: Yes/No/DNK Surf. Rupt.: Yes/No/DNK

Adjacency: ☐ Pounding ☐ Falling Hazards from Taller Adjacent Building

Irregularities: ☐ Vertical (type/severity) ____ ☐ Plan (type) ____

Exterior Falling Hazards: ☐ Unbraced Chimneys ☐ Heavy Cladding or Heavy Veneer ☐ Parapets ☐ Appendages ☐ Other: ____

COMMENTS:

SKETCH

☐ Additional sketches or comments on separate page

BASIC SCORE, MODIFIERS, AND FINAL LEVEL 1 SCORE, S_{L1}

FEMA BUILDING TYPE (Do Not Know)	W1	W1A	W2	S1 (MRF)	S2 (BR)	S3 (LM)	S4 (RC SW)	S5 (URM INF)	C1 (MRF)	C2 (SW)	C3 (URM INF)	PC1 (TU)	PC2	RM1 (FD)	RM2 (RD)	URM	MH
Basic Score	**4.1**	**3.7**	**3.2**	**2.3**	**2.2**	**2.9**	**2.2**	**2.0**	**1.7**	**2.1**	**1.4**	**1.8**	**1.5**	**1.8**	**1.8**	**1.2**	**2.2**
Severe Vertical Irregularity, V_{L1}	-1.3	-1.3	-1.3	-1.1	-1.0	-1.2	-1.0	-0.9	-1.0	-1.1	-0.8	-1.0	-0.9	-1.0	-1.0	-0.8	NA
Moderate Vertical Irregularity, V_{L1}	-0.8	-0.8	-0.8	-0.7	-0.6	-0.8	-0.6	-0.6	-0.6	-0.6	-0.5	-0.6	-0.6	-0.6	-0.6	-0.5	NA
Plan Irregularity, P_{L1}	-1.3	-1.2	-1.1	-0.9	-0.8	-1.0	-0.8	-0.7	-0.7	-0.9	-0.6	-0.8	-0.7	-0.7	-0.7	-0.5	NA
Pre-Code	-0.8	-0.9	-0.9	-0.5	-0.5	-0.7	-0.6	-0.2	-0.4	-0.7	-0.1	-0.4	-0.3	-0.5	-0.5	-0.1	-0.3
Post-Benchmark	1.5	1.9	2.3	1.4	1.4	1.0	1.9	NA	1.9	2.1	NA	2.1	2.4	2.1	2.1	NA	1.2
Soil Type A or B	0.3	0.6	0.9	0.6	0.9	0.3	0.9	0.9	0.6	0.8	0.7	0.9	0.7	0.8	0.8	0.6	0.9
Soil Type E (1-3 stories)	0.0	-0.1	-0.3	-0.4	-0.5	0.0	-0.4	-0.5	-0.2	-0.2	-0.4	-0.5	-0.3	-0.4	-0.4	-0.3	-0.5
Soil Type E (> 3 stories)	-0.5	-0.8	-1.2	-0.7	-0.7	NA	-0.7	-0.6	-0.6	-0.8	-0.4	NA	-0.5	-0.6	-0.7	-0.3	NA
Minimum Score, S_{MIN}	*1.6*	*1.2*	*0.8*	*0.5*	*0.5*	*0.9*	*0.5*	*0.5*	*0.3*	*0.3*	*0.3*	*0.3*	*0.2*	*0.3*	*0.3*	*0.2*	*1.4*

FINAL LEVEL 1 SCORE, $S_{L1} \geq S_{MIN}$:

EXTENT OF REVIEW

Exterior: ☐ Partial ☐ All Sides ☐ Aerial

Interior: ☐ None ☐ Visible ☐ Entered

Drawings Reviewed: ☐ Yes ☐ No

Soil Type Source: ____

Geologic Hazards Source: ____

Contact Person: ____

LEVEL 2 SCREENING PERFORMED?

☐ Yes, Final Level 2 Score, S_{L2} ____ ☐ No

Nonstructural hazards? ☐ Yes ☐ No

OTHER HAZARDS

Are There Hazards That Trigger A Detailed Structural Evaluation?

- ☐ Pounding potential (unless S_{L2} > cut-off, if known)
- ☐ Falling hazards from taller adjacent building
- ☐ Geologic hazards or Soil Type F
- ☐ Significant damage/deterioration to the structural system

ACTION REQUIRED

Detailed Structural Evaluation Required?

- ☐ Yes, unknown FEMA building type or other building
- ☐ Yes, score less than cut-off
- ☐ Yes, other hazards present
- ☐ No

Detailed Nonstructural Evaluation Recommended? *(check one)*

- ☐ Yes, nonstructural hazards identified that should be evaluated
- ☐ No, nonstructural hazards exist that may require mitigation, but a detailed evaluation is not necessary
- ☐ No, no nonstructural hazards identified ☐ DNK

Where information cannot be verified, screener shall note the following: EST = Estimated or unreliable data OR DNK = Do Not Know

Legend: MRF = Moment-resisting frame; BR = Braced frame; RC = Reinforced concrete; SW = Shear wall; URM INF = Unreinforced masonry infill; TU = Tilt up; MH = Manufactured Housing; LM = Light metal; FD = Flexible diaphragm; RD = Rigid diaphragm

Figure 4.1 RVS of buildings for potential seismic hazard for level 1 (high seismicity)

FEMA P154 (2015) also considers minimum scores for each building typology in order to avoid negative values of final scores. Table 4.6 shows minimum score for masonry infilled RC buildings type C3.

Table 4.6 Minimum scores for masonry infilled RC buildings type C3 (FEMA P 154 2015)

Level of seismicity	Basic score
Low seismicity	0.5
Moderate seismicity	0.3
Moderately high seismicity	0.3
High seismicity	0.3
Very high seismicity	0.3

4.3.2 Turkish rapid visual screening (RVS) method

Metropolitan Municipality of Istanbul (BU-ITU-METU-YTU 2003) has been developed an earthquake master plan by 4 (four) universities has been subdivided into two teams: (1) Middle Eastern Technical University (METU) and Istanbul Technical University (ITU), and (2) Bogazici University (BU) and Yildiz Technical University (YTU). Three stages of assessment have developed such as (a) level first based on rapid visual assessment; (b) level two, access is required to a building; and (c) level three based on detailed evaluation procedure. The rapid visual screening i.e. level one has been developed by BU and ITU for priority setting of buildings has been based on the ratio of displacement capacity to displacement demand at roof level determined for two level performance criteria such as life safety and collapse prevention.

Later on, Sucuoglu *et al.* 2007 proposed a screening procedure for seismic risk assessment based on investigation of past earthquake damage database and revised the original rapid visual screening method developed by Middle East Technical University (METU). The proposed method provides a performance score for determining the priority of buildings which have significant damage risk. However, this performance score is a combination of initial score, vulnerability score and score modifiers.

Performance score=Initial score+∑(vulnerability parameter)X (Vulnerability Score Modifiers)

4.3.2.1 Initial score

The initial score is given with respect to the number of stories and the seismic intensity as well as study on past earthquake. The RVS procedure, developed by Sucuogˇlu et al. (2007), proposes initial score based on study of 454 three to six storied RC-frame buildings investigated after the 1999 Düzce earthquake and classified in 4 (four) damage classes. The initial score varies depending on the number of stories (3 to 6) and the seismic region. The proposed method proposes initial score based on range of peak ground velocity (PGV) as shown in Table 4.7.

Table 4.7 Seismic performance score according to number of stories

Number of Stories	Peak ground velocity (PGV), cm/sec		
	60< PGV<80	40<PGV<60	20<PGV<40
3	80	107	138
4	73	91	115
5 and 6	64	76	92

4.3.2.2 Vulnerability parameters

The original METU method (BU-ITU-METU-YTU 2003) considered simple parameters such as short columns, pounding, and topographical effects. However, rapid visual screening proposed by Sucuoglu, 2007, did not include short column and pounding effect. The reason behind pounding effect has not observed in Duzce earthquake damage database. It is difficult to investigate short column from street survey. Due to uniform soil condition and flat topography in the surveyed area, these parameters also excluded from the original rapid visual screening method. The parameters chosen in updated version of RVS are number of stories, soft story, heavy overhangs, and apparent building quality. The values for corresponding parameters are shown in Table 4.8. Apparent quality is divided into three point of classification, such as good, moderate and poor, considering material and workmanship quality and level of maintenance of a building.

Table 4.8 Vulnerability parameters and corresponding coefficient

Number of Stories	Vulnerability scores		
	Soft story	Heavy Overhang	Apparent Quality
3	23	9	23
4	22	15	30
5 and 6	24	23	33

Table 4.9 shows vulnerability score modifier for concrete buildings proposed by Sucuoglu (2007). If this types of vulnerability exists, then the values are multiplied by '0' otherwise '1'. In case of apparent quality are classified into three divisions such as good, moderate and poor as shown in the Table 4.9.

Table 4.9 Vulnerability score modifiers

Vulnerability parameters	Score modifiers		
Soft story	Does not exist=0	Exists= -1	
Heavy Overhang	Does not exist=0	Exists= -1	
Apparent Quality	Good (1)	Moderate (0)	Poor (-1)

4.3.3 Indian rapid visual screening (RVS) method

There are several approaches have been considered for rapid visual screening method for vulnerability assessment of existing building in India. Sinha and Goel (2004) have proposed an approach for rapid visual screening of existing buildings which is almost similar to FEMA 154 (2002). These method considers ten different types of structures. However, structural type is based on construction materials. Therefore, the building having similar materials have same level of vulnerability. Besides, Agrawal and Chourasia (2007) applied a qualitative approach for potentially vulnerable buildings. The proposed method is based on ATC-21 (1988) and applied on Jabalpur earthquake damage survey database. This method considers quality construction, irregularity of buildings, soil condition and ground condition such as slope. Later on, some of them are dropped in the updated version of the rapid method. Furthermore, Jain et al. (2010) proposed a rapid visual screening method for India based on damage database of past earthquake. The proposed method is similar to Turkish method which considers local seismicity for basic score. Moreover, the expected performance score which is summation of basic score, vulnerability score, and vulnerability modifiers.

$$\text{Performance score} = BS + \sum[VSM \times VS]$$

where, BS is the basic scores, VSM describes the vulnerability score modifiers, and VS is the Vulnerability score, respectively. The following sections describes values of each parameter.

4.3.3.1 Basic score

In the proposed RVS method, basic score has been determined based on soil type and seismic zone. Basic score is shown in Table 4.10. However, soil type has been classified into four types of soil. The soil types are classified into four types of soil as shown in Table 4.11. According to Indian Code (IS 1893:2002 (Part 1)), India has been subdivided four seismic zones. The definition of each zone is described in Table 4.11.

Table 4.10 Proposed basic scores

Soil Type	Seismic Zone			
	Zone II	Zone III	Zone IV	Zone V
Soft	85	70	55	40
Medium	100	85	70	55
Rock	115	100	85	70

Table 4.11 Seismic Zoning division in India (IS 1893:2002 (Part 1))

Seismic zone	Description
Zone II	Low seismic hazard
Zone III	Moderate seismic hazard
Zone IV	High seismic hazard
Zone V	Very high seismic hazard

4.3.3.2 Vulnerability parameters

The proposed method uses seven vulnerability parameters: Number of stories, basement, short column, open story, re-entrant corner and non-residential. These values of these vulnerable parameters depending on soil types as shown in Table 4.12.

Table 4.12 Vulnerability scores (Jain et al. 2010)

Soil Type	Basement	Number of stories	Maintenance	Re-entrant corners	Open story	Short column	Non-residential Use
Soft	+10	+10	-5	-5	-10	-5	+5
Medium	+10	+10	-10	-10	-10	-5	+5
Rock	+10	+10	-10	-10	-10	-5	+5

Vulnerability score modifiers is used to get actual modifiers for modification of basic score. Table 4.13 showing the score modifiers of each vulnerability parameters. However, for maintenance, the score is categorised into three class: poor, moderate and good which is similar to Turkish RVS method.

Table 4.13 Vulnerability scores modifiers (Jain et al. 2010)

Vulnerability Parameters	Score modifiers		
Basement	Yes (1)	No (0)	
Number of stories	Yes (1)	No (0)	
Maintenance	Poor (1)	Moderate (0.5)	Good (0)
Re-entrant corners	Yes (1)	No (0)	
Open story	Yes (1)	No (0)	
Short column	Yes (1)	No (0)	
Nonresidential Use	Yes (1)	No (0)	

4.4 Application existing RC buildings

The existing rapid visual screening method described in previous sections have been applied in existing RC buildings. The aim is to investigate the effectiveness and limitation of the existing rapid visual screening methods. Therefore, these method has been applied in several damaged buildings from past earthquake damage database. In this study, Taiwan earthquake damaged database is considered and applied based on information found from surveyed database from datacenter hub. These RVS method has been applied based on survey information and photo as shown in Figure 4.2.

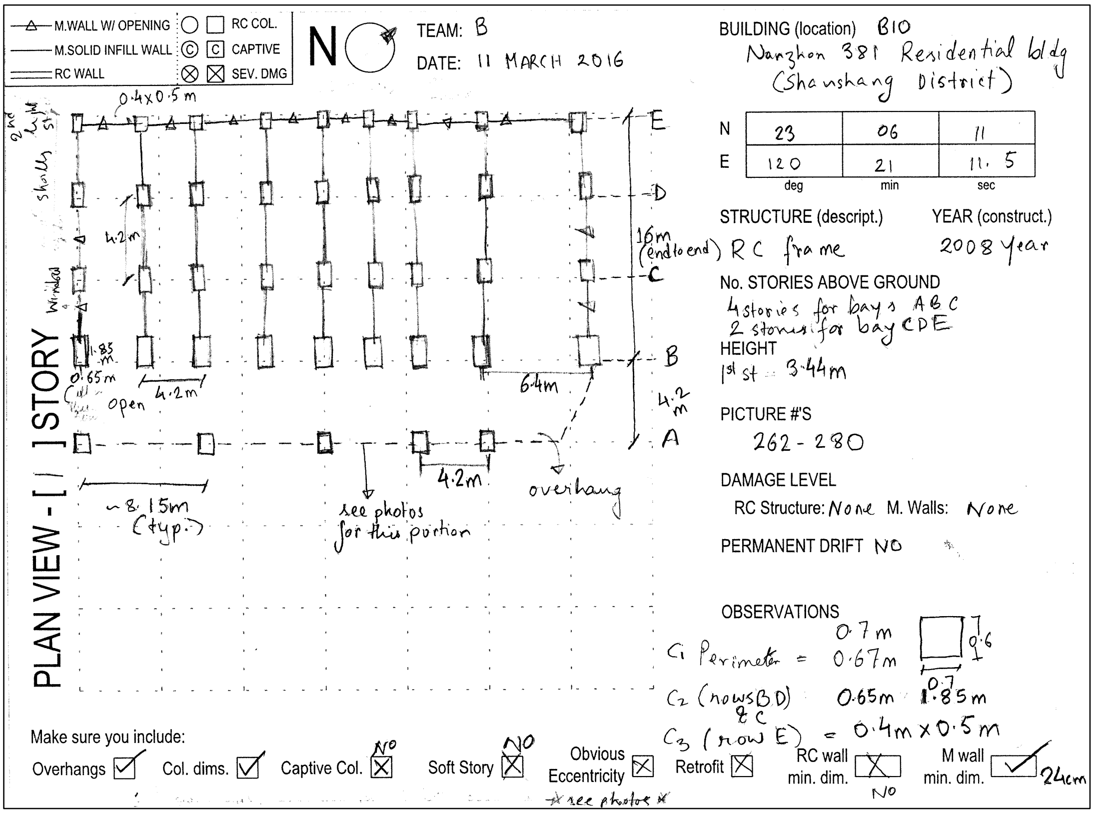


Figure 4.2 A typical survey datasheet for damaged buildings (www.datacenterhub.org)

4.4.1 Application of FEMA P154 method

4.4.1.1 Calculation of FEMA P 154 score

FEMA P154 method has been applied on the surveyed buildings. As previously mention, FEMA P154 method considers basic score based on structural system and region seismicity. FEMA building type has been mentioned in Table 4.1. It has been observed that all surveyed buildings are unreinforced masonry infilled RC buildings. Therefore, FEMA building type has been regarded as type C3 as shown in the Table 4.1. It has been noted that in case of seismic region, Taiwan has been assumed as moderately high seismic area based on considering spectral acceleration is about 1g for short period ground motion (Lee et al. 2017). Hence, the basic score is taken of 1.4 corresponding structural system type C3 and local seismicity. In addition, score modifier has been considered based on information found from the database and surveyed photos. However, plan and vertical irregularity are considered based on survey datasheet. Regarding soil classification, FEMA proposed soil type based on shear wave velocity as shown in Table 4.3. Figure 4.3 showing shear wave velocity proposed by Lee and Tsai (2008). The shear wave velocity of Tainan city ranging from 180m/s to 300m/s. Hence, in this study, soil type has been assumed as SD type considering from shear wave velocity. FEMA final score has been calculated based on score considered of each parameters as shown in Figures 4.3. It has been observed that the FEMA score ranges 0.3 to 1.3.

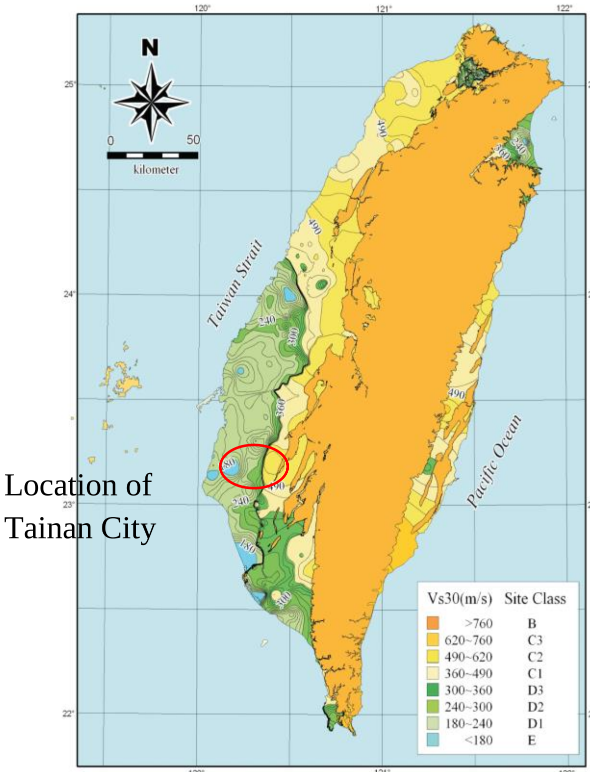


Figure 4.3 Shear wave velocity map in Taiwan (Lee et al. 2008)

4.4.1.2 Comparison between FEMA and seismic capacity index

Seismic capacity index has already calculated in previous chapter. FEMA score has been compared with previously calculated the seismic capacity index (minimum of two orthogonal directions) as shown in Figure 4.4. It has been observed that FEMA does not show correlation with seismic capacity index. Figure shows that most of severely damaged buildings contains lower seismic capacity index. As a result, seismic capacity has correlation with seismic damage. In case of FEMA score, few severely damaged buildings show higher FEMA score. Besides, several building are no damaged but FEMA score are showing lower. It indicates FEMA method provide score does not reflect seismic capacity. The main reason is that, FEMA score does not consider basic parameters such as column area and wall area etc.

FEMA considers seismic vulnerability based on structural system and provide overall seismic vulnerability.

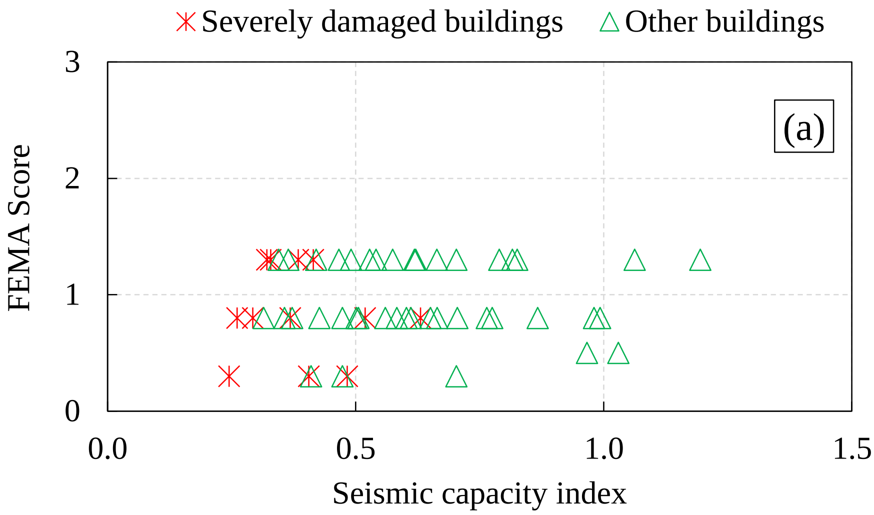


Figure 4.4 Seismic capacity index vs. the results of existing RVS method: FEMA P 154

4.4.2 Application of TURKISH RVS method

4.4.2.1 Calculation of performance score

TUKISH performance score has also calculated based information found from survey datasheet. As previously mentioned, TURKISH basic score depends on number of story and score is categorized by peak ground velocity at site (i.e., local seismicity). Number of story of investigated building are ranged 2 to 4 storied RC building. Regarding site condition and the buildings are located at Tainan city, therefore, peak ground velocity is assumed to be 20 to 40 cm/s for the ground motion (Lee et al. 2017). Actual score modifier is calculated using vulnerability parameters and modifiers. Score modifiers information is collected from survey datasheet mentioned in previous sections. It should be noted that score modifiers such as soft-story and overhang are considered in this study. In addition, apparent quality has been considered bad to be in conservative estimation.

4.4.2.2 Comparison between Turkish Score and seismic capacity index

Figure 4.3 showing the results of calculated of performance score based on Turkish RVS method. The calculated score has been compared with seismic capacity index. It has been observed that there is not clear correlation between performance score and seismic capacity. In addition, higher performance score for several severely damaged buildings indicates the correlation between damage state is lower. Therefore, similar to FEMA P 154, Turkish performance score does not consider column and infill area which is the main limitation of the proposed method.

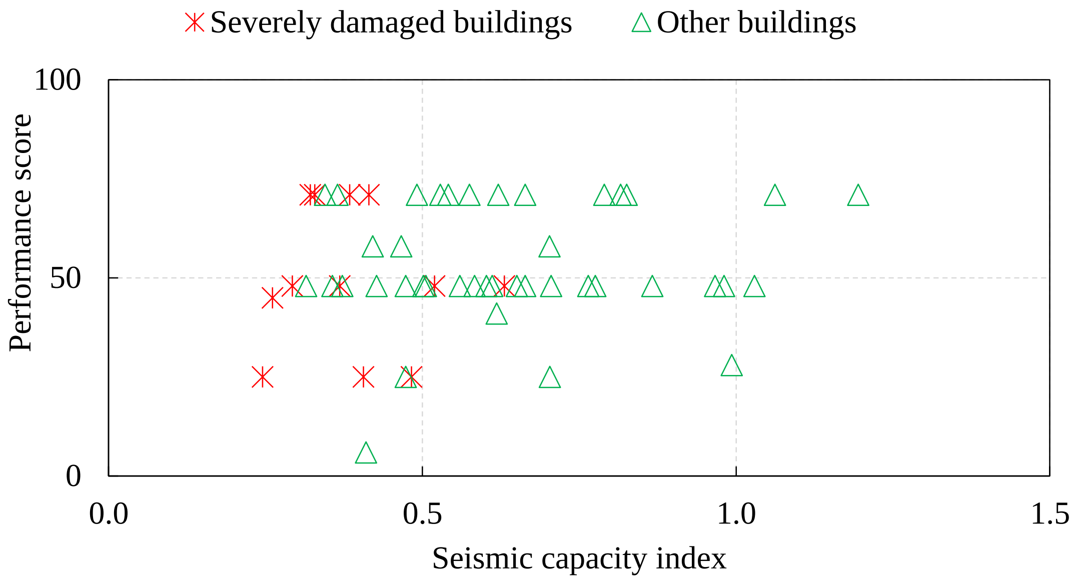


Figure 4.5 Seismic capacity index vs. the results of existing RVS method: Turkish method

4.4.3 Application of Indian RVS method

4.4.3.1 Calculation of performance score

The rapid visual screening method proposed by Jain (2010) has been applied in Taiwan earthquake damage database. As previously mentioned, the rapid visual screening basic score depends on soil type and seismic zone or level of seismicity. However, geotechnical condition has not been mentioned in the investigated building from the database. In this regard, Taiwan building code proposed three site classification according to shear wave velocity. As all investigated buildings are located at Tainan city, shear wave velocity is about 180 to 240 (Taiwan Building code). Hence, soil condition is assumed to be S2 (normal site) which is medium according to Indian RVS method. For seismic zone, Taiwan has been divided into two zone such as zone I and zone II. However, Tainan city is located at zone II as shown in Figure 4.6. Thus, in this study, seismic zone IV has been considered corresponding to moderate zone in Indian seismic zoning map as shown in Table 4.11. Therefore, the basic score of 70 is assigned on the basis of medium type soil and seismic zone IV as shown in Table 4.14. Vulnerability scores are also considered corresponding to medium type of soil. All investigated buildings do not have basement and occupancy category is school buildings. Therefore, vulnerability parameters such as basement and nonresidential use are not considered in this study. Maintenance are assumed as poor for all buildings to be conservative. All investigated buildings are rectangular shape in plan, therefore, re-entrant corner is not seen in these buildings.

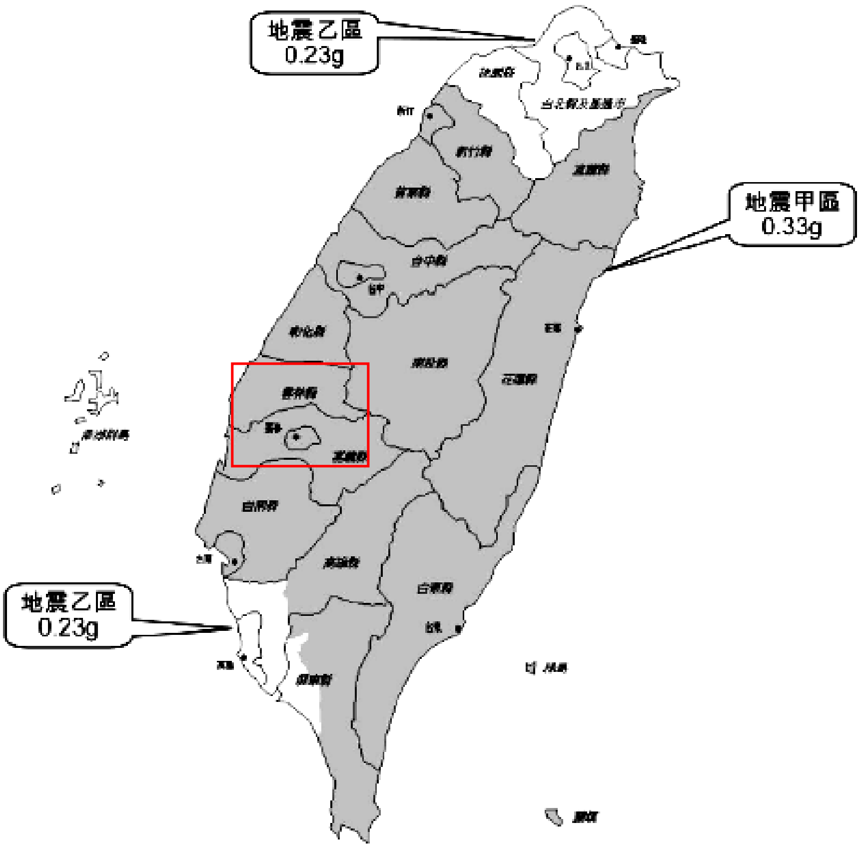


Figure 4.6 Seismic zones of Taiwan in 1999 Seismic Design Code.

Table 4.14 Site classification according to Taiwan building code

Site Class	V_{S30}-method (m/s)
S1:Hard site	V_{S30}>270
S2: Normal site	180≤ V_{S30}≤270
S3: Soft site	V_{S30}<180

4.4.3.2 Comparison between Indian RVS method and seismic capacity index

The performance score for the surveyed buildings has been calculated in previous section plotted in Figure 4.16. It has been seen that some of severely damaged buildings show higher performance score. It means that the seismic performance score does not reflect the seismic capacity of existing buildings. Figure 4.16 also shows the comparison between seismic capacity index in minimum direction and performance score. The variation of performance score is smaller than compared with seismic capacity. The reason is that the basic score depends only on soil type and seismic zone. Hence, there is not clear correlation between performance score and seismic capacity of existing building.

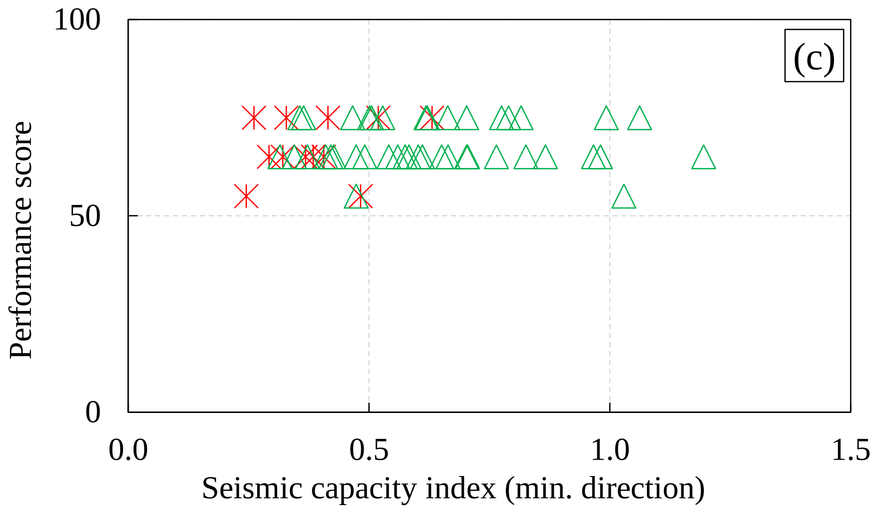


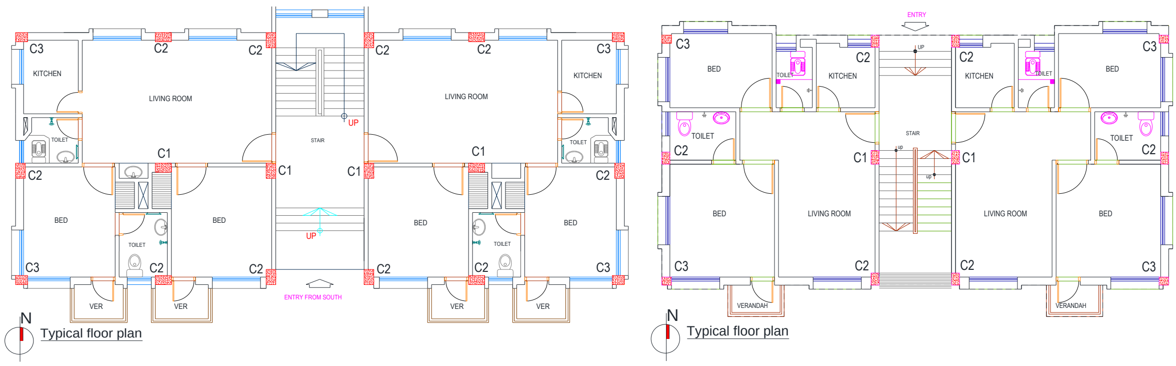
Figure 4.7 Seismic capacity index vs. the results of existing RVS method: Indian method

Furthermore, Indian rapid visual screening score indicates more conservative because there is no variation in RVS score for all surveyed buildings. However, for categorization of detailed evaluation, it is not easy to categorize of existing buildings which needs further detailed evaluation.

4.5 Limitation of existing rapid visual screening methods

Generally, the priority setting for detail or further evaluation is the main goal for any visual screening scheme or policy. However, the application of existing RVS methods implies that the stated method could not meet the general intention of building survey. The main reason behind the limitation is that those RVS methods consider parameters such as irregularities of buildings, local seismicity etc. Most of the cases do not consider the vertical elements (such as column, RC wall and masonry infills) which have been found the most fundamental parameters for seismic evaluation of existing buildings.

The limitation of the existing RVS method has been explained thorough example as described in this section. One of the RVS method such as FEMA P-154, has been applied on two model buildings located at Dhaka, Bangladesh. Figure 4.8 shows architectural floor plan of two buildings of six stories with different floor area, located at seismic zone of similar type (i.e. similar soil type). However, number of columns, cross-sectional area of columns and span lengths are not the same in these buildings as shown in Table 4.15.



(a) Building A (b) Building B

Figure 4.8 Floor plan of two model buildings

Table 4.15 Basic characteristics of two model buildings

Building ID	Number of story	Floor area	Number of columns	Size of column		
				C1	C2	C3
		m^2		mm × mm	mm × mm	mm × mm
A	6	160	18	300 × 500	300× 450	300 × 300
B	6	140	12	250 × 450	250 × 375	250 × 300

FEMA rapid visual screening (RVS) (FEMA P 154 2015) method has been applied on these buildings and the obtained FEMA final score is reported in Table 4.16. Both buildings have same final score because FEMA method considers structural system instead of column and wall area to determine final score. Other modifiers for vulnerability parameters of these buildings are also same. However, seismic capacity of these two buildings are not the same due to different cross-sectional areas of column and total floor area. The seismic capacity index of the model buildings has been estimated using the procedure in the previous chapter 2 and 3. The values are shown in Table 4.16. It has been seen that building A has much higher seismic capacity index of 0.25 (JBDPA 2001) which is almost twice of building B. Hence, buildings B needs more detail evaluation comparing with building A. On the other hand, Rapid Visual Screening method such FEMA provides similar results for both of the buildings. Using the exiting RVS method are not effective for periodization for further detail evaluation.

Table 4.16 Results of screening score of model buildings

Screening Method	Building A	Building B
FEMA P 154	2.0	2.0
Seismic Capacity Index	0.25	0.13

Likewise, FEMA method, other methods provides similar results due to the basic concepts are almost similar. From the above discussion, it has been concluded that there is large deviation between RVS results and seismic capacity. Therefore, consideration of vertical elements (such as column, wall) in rapid visual investigation, is very important to reduce the gap between seismic capacity prediction and RVS results. rapidly. However, there is no guideline and way to consider those parameters into visual screening method. Hence, this research is trying to find an easiest and simplest way for consideration of those vertical member's contribution during visual screening method which are the new point of this research.

4.6 Summary of chapter 4

This chapters presents three existing rapid visual screening (RVS) methods such as FEMA P154, Turkish method, and Indian RVS method. First of all, application procedure of the RVS methods have been discussed. These existing RVS methods have been applied on past earthquake damaged databases. In this study, Taiwan earthquake damage database has been chosen for application of the existing RVS method. Then each RVS score have been compared with the actual seismic capacity of investigated buildings.

The following conclusion have been made from this chapter:

1) (1) Study shows that the score computed from these methods do not have correlation with corresponding seismic capacity of buildings.
2) The main limitation of these existing RVS methods is that those methods do not consider the basic parameter such as column area, wall area which are regarded as most influential parameters for seismic capacity estimation.
3) Thus, existing rapid visual screening methods are not effective for identifying the vulnerable buildings.

However, it is urgent to include the seismic influencing parameters such as column area and infill wall area to overcome the limitation of existing RVS methods. Therefore, it is time to develop a visual screening method considering the effect of variation of vertical elements such as column area and masonry infill. As a result, this research work effort to develop a visual screening method using parameters such column area, infill wall area and floor area. The next chapter describes about new proposed method for visual investigation of existing RC buildings.

Chapter 5

Development of Visual Rating method

5.1 Introduction

This chapter describes a rapid seismic evaluation procedure thorough visual investigation of existing RC buildings. Chapter 2 and 3 showed a simplified seismic evaluation procedure using common parameters such as column area and masonry infill area. Those parameters are found to be most influencing parameter for seismic capacity evaluation. However, the existing visual screening method ignored those fundamental parameters as described in Chapter 4. Thus, this research aims to develop a visual screening method as herein referred as Visual Rating method using those basic parameters such as column area, infill area and material properties. This chapter describes the basic consideration and development procedure of the proposed Visual Rating method. First of all, theoretical background and development of visual rating method has been described. Furthermore, application procedure of proposed Visual Rating method has been also discussed in this chapter. The overall flow of this chapter is shown in Figure 5.1.

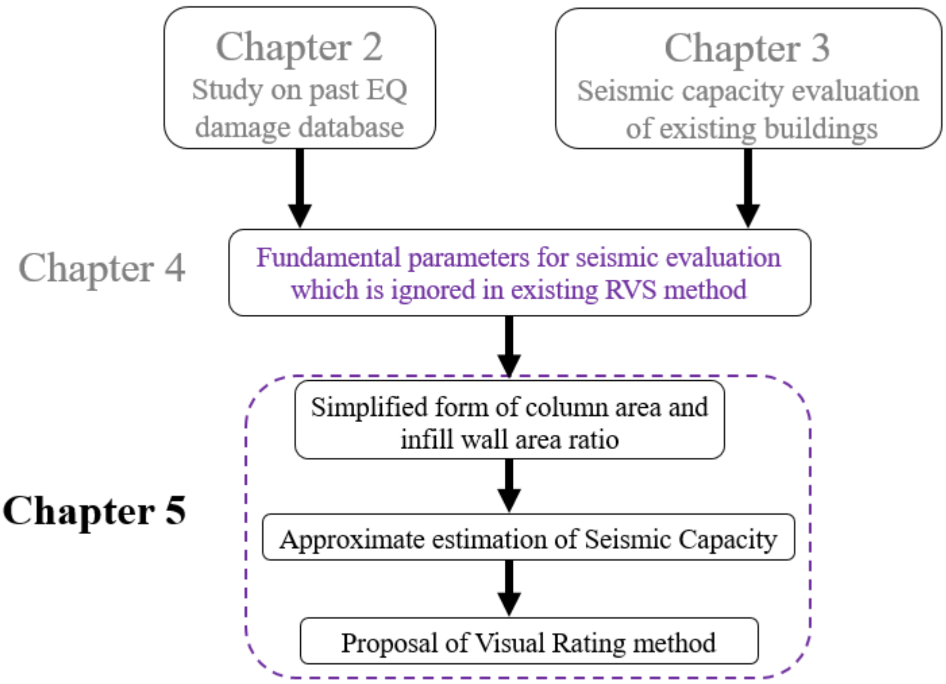


Figure 5.1 Flow of the chapter 5

5.2 Overview Visual Rating method

Visual Rating method is a simplified seismic estimation procedure which provides an approximate estimation of seismic capacity of existing RC buildings. As mentioned in previous chapter, screening large numbers of existing RC buildings, it is quite challenging to apply the seismic evaluation either detailed evaluation and even for preliminary seismic evaluation. This is because of it requires details architectural drawings for these seismic evaluation procedure. If architectural drawings are not available, as-built drawing preparation are necessary, which takes much time for seismic evaluation procedure. Therefore, the proposed Visual Rating method considers a simplified way for identification of column area ratio, masonry wall area ratio, and concrete wall area ratio. Simplified way considers visual inspection, collection of some parameters which provide approximate estimation of column area ratio, masonry infill area ratio and concrete wall area ratio.

5.3 Development of Visual Rating Index

5.3.1 Introduction

The main difference between proposed Visual Rating method from other existing rapid visual screening method is that the proposed Visual Rating method provide score which is approximated estimation of seismic capacity of existing buildings. This approximated seismic capacity is quantified by a score, hereafter reported as Visual Rating Index (I_{VR}). The Visual Rating Index (I_{VR}) is an indication of seismic vulnerability of existing buildings. It means that buildings with higher Visual Rating Index (I_{VR}) indicates the building will undergo less possibility vulnerable or not vulnerable. Conversely, the lower Visual Rating Index (I_{VR}) corresponds to most vulnerable building as identifies as most vulnerable buildings. The main purpose of the Visual Rating Index (I_{VR}) score or value is to set the priority of most vulnerable buildings for further detail evaluation. The following section describes about development and calculation procedure of Visual Rating Index (I_{VR}) accordingly.

5.3.2 Calculation procedure of Visual Rating Index (I_{VR})

As previously mentioned, Visual Rating method is a simplified way of estimation of seismic capacity of existing building by visual inspection. However, the concept of Visual Rating method came from the simplified seismic capacity index which is based on the concept of Shiga map (1968) as discussed in previous Chapter 2. The simplified seismic capacity index is calculated considering column area ratio, RC wall area ratio, masonry wall is ratio and their average shear strength. Since the proposed method is based on visual inspection, this Visual Rating method approximately estimates column area ratio, RC wall area ratio and masonry infill area ratio by more simplified way thorough visually investigation. Therefore, the simplified seismic capacity index of existing buildings is referred as Visual Rating Index (I_{VR}) which is expressed by following Equation (5.1).

$$I_{VR} = \frac{1}{n.w}\left[\tau_c.I_c + \tau_{\inf}.I_{\inf} + \tau_{cw}.I_{cw}\right] \tag{5.1}$$

where, I_c=column area ratio, $I_c = \frac{A_c}{A_f}$

I_{cw}=RC wall area ratio, $I_{cw} = \frac{A_{cw}}{A_f}$

I_{inf}=masonry infill wall area ratio, $I_{inf} = \frac{A_{inf}}{A_f}$

where, I_c, I_{inf}, and I_{cw} are expressed as column area ratio, masonry infill area ratio, and concrete wall area ratio respectively as mentioned in previous chapter. n is the number of stories and w is the unit weight of buildings. Those are the most influencing parameters to estimate the base shear capacity in seismic capacity evaluation. As previously mentioned, the proposed method is based on visual inspection within a short duration, it is not easy to measure all dimensions of all columns, masonry infill walls, and concrete walls, as well as total floor area. Therefore, a simplified way has been proposed for determining the column, masonry infill and concrete wall area ratio using visual inspection.

5.3.2.1 Simplified column area ratio (I_c)

Simplified column area ratio (I_c) is defined as approximate estimation of column area ratio of an existing buildings using simple way thorough visual survey. As previously mentioned, column area ratio consists of cross-sectional areas of all column and floor area. However, it is not easy to measure the cross-sectional areas of all columns and floor area within short time by visual investigation. Thus simplification of column area and floor are alternative approach for easy understanding of column area ratio. Sometimes, columns are surrounded by masonry infill which is common practice in Bangladesh. In that case, rigorous inspection is needed for preparation of as-built drawing which takes much time. Therefore, this method considers to investigate of these columns which are easy visible during building survey and inspection.

In this method, the cross-sectional area of column is simplified using average column size (b_c). The average column size (b_c) represents all column dimension of an investigated buildings. This proposed method proceeds the inspectors to enter inside the building and investigate columns by visual inspection of a building to be surveyed. Afterward, the average column size (b_c) has been chosen depending of inspector's engineering judgement. A typical floor plan has been shown in Figure 5.2. Inspectors, after entering inside the house, can easily investigate column size of interior column rather than exterior columns. In this regards, it has been suggested that surveyor investigate two or three interior column and make a decision of average columns size.

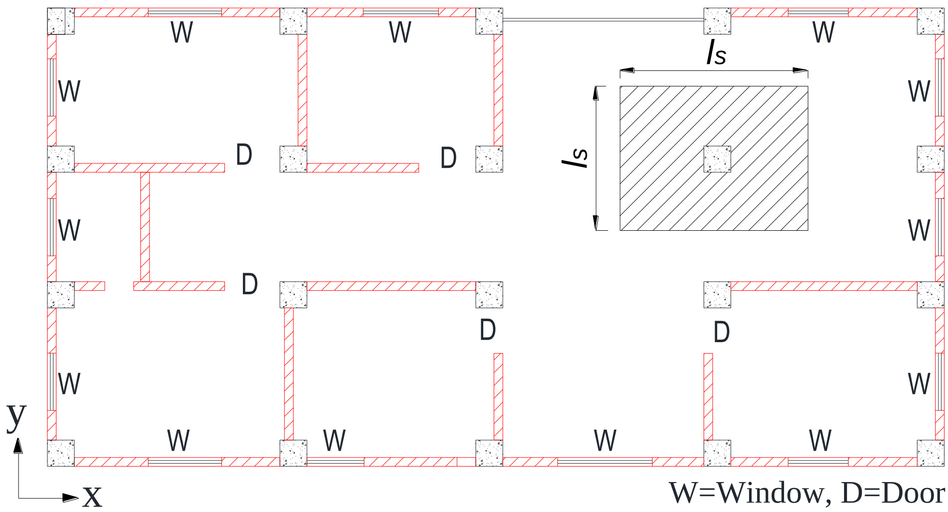


Figure 5.2 Schematic floor plan of a building with average span length

On the other hand, it is also difficult to measure floor area by visual inspection within short time. Because, it requires as-built drawing preparation if architectural drawings are not available which takes longer time for building survey. However, this method considers average span length (l_s) of building in both directions to overcome the limitation. The square of average span length (l_s) is a simplest way to approximately estimate the floor area of a buildings in a short time. Generally, the span length is not equal in each direction and also number of span are not the same. In this context, the investigator should check and measure one or two spans in both direction (longitudinal and transverses direction) of a building. Afterward, the appropriate value for average span length is chosen based on engineering judgement. Figure 5.1 shows an example of inspection procedure of average span length (l_s) of a surveyed building. Hence, simplified column area ratio is estimated by average column size (b_c) and average span length (l_s) using Equation (5.2) as follows:

$$I_c = \frac{A_c}{A_f} \approx \frac{b_c^2}{l_s^2} \tag{5.2}$$

5.3.2.2 Simplified masonry infill area ratio (I_{inf})

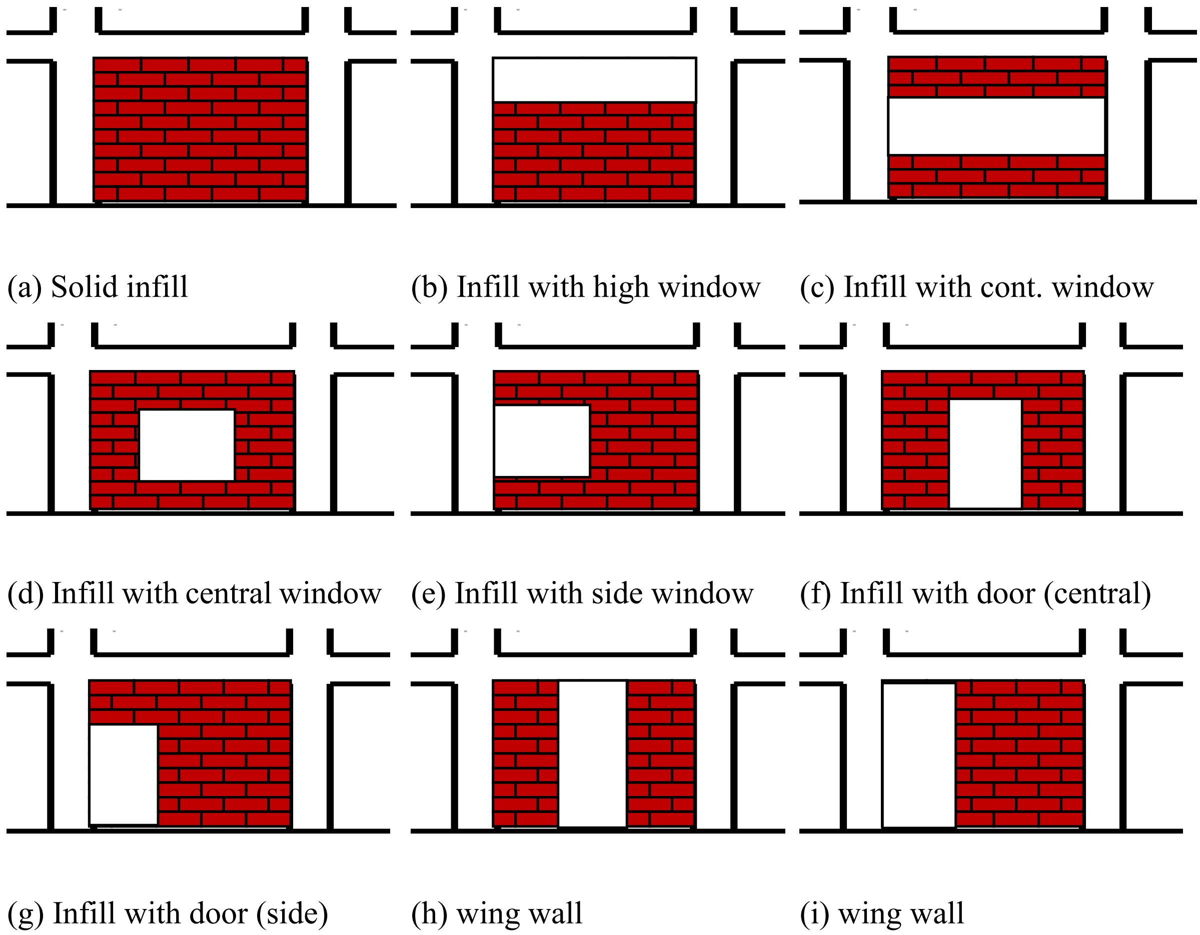
Simplified masonry infill area ratio is an approximate estimation of masonry infill area ratio of a building. The simplified masonry infill area is based on using simplified masonry infill area and floor area. However, floor area can be approximated using average span length (l_s) which is already explained in previous section. So, this section explains about the simplification procedure of masonry infill area based using simple parameter depending on visual inspection.

Generally, solid masonry infill i.e. without opening and with opening due to door, window and high window are common in RC buildings. Sometime, partial masonry infill are also found in existing buildings. It is difficult to measure length and width of each masonry infill either solid or with opening by visual inspection within short time. However, it is easy to count the number of masonry infill panel in each direction by visual inspection instead of measuring dimension of each masonry infill. Thus, masonry infill area can be easily estimated using number of infill panels, average span length (l_s) and thickness of masonry infill (t_{inf}) in each direction. Since the proposed method is based on visual inspection with limited time, it is should be noted that the partial infill or infill with opening due to door and window is not considered in this method. Therefore, only solid masonry infill is considered for estimation of masonry wall area to be in conservative. Hence, the masonry infill area ratio has been simplified by using masonry infill ratio (R_{inf}), thickness of masonry infill (t_{inf}) and average span length (l_s) as shown in Equation (5.3).

$$I_{\text{inf}} = \frac{A_{\text{inf}}}{A_f} \approx \frac{t_{\text{inf}}}{l_s}.R_{\text{inf}} \tag{5.3}$$

where, R_{inf} is the masonry infill ratio which indicates the quantity of masonry infill expressed as the ratio of the total number of solid masonry panel in a direction to the total number of spans for that direction. As previously mentioned, masonry infill with opening due to door and window are not considered in the proposed method. Figure 5.3 shows example of different types of opening. It should be noted that the solid infill outside the RC frame will not be considered. Therefore, Masonry infill area ratio (R_{inf}) is simplified as expressed by Equation (5.4).

$$R_{inf} = \frac{Number\ of\ masonry\ panel\ in\ a\ direction}{Total\ no\ of\ span\ in\ a\ direction} \tag{5.4}$$



(a) Solid infill (b) Infill with high window (c) Infill with cont. window

(d) Infill with central window (e) Infill with side window (f) Infill with door (central)

(g) Infill with door (side) (h) wing wall (i) wing wall

Figure 5.3 Masonry infill with different types of opening

Since the proposed method considers visual inspection, it has been suggested that the surveyor will count number solid masonry infill and number of span are also counted for both directions by visual inspection. Afterward, Masonry infill ratio, R_{inf} shall be calculated for both orthogonal directions. Finally, the minimum values of R_{inf} is considered to be in conservative

A typical floor plan is shown in Figure 5.4 as an example of calculation procedure of simplified masonry infill wall area ratio. As described in previous sections, masonry infill with opening is not considered in this method. Therefore, the number of solid masonry infill panels are 2 in X direction and 3 in Y direction as shown in Figure 5.3. On the other hand, the total number of spans are obtained as 16 and 15 in X and Y direction, respectively. Therefore, R_{inf} are to be found 2/16 and 3/15 for X-direction and Y-direction respectively. Here, minimum R_{inf} value 2/16 has been considered for capacity prediction.

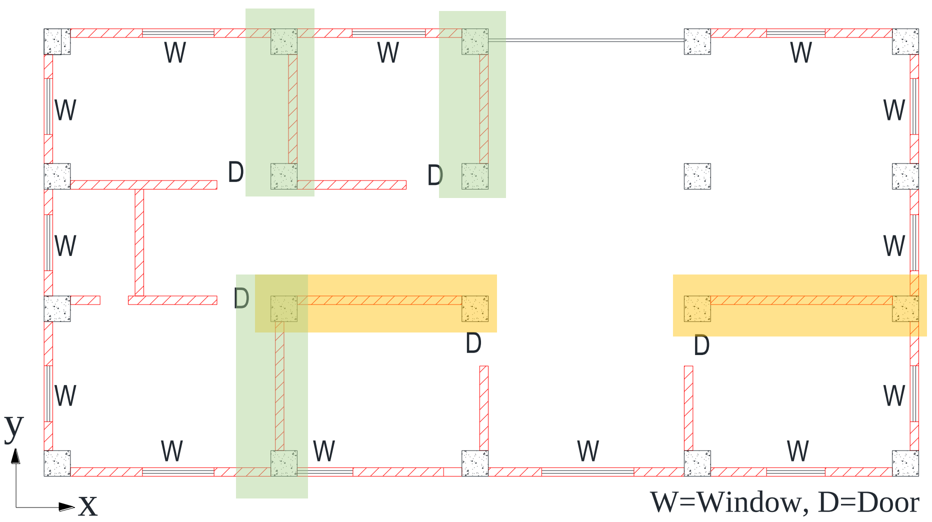


Figure 5.4 Typical floor plan showing location of masonry infill

5.3.2.3 Simplified concrete wall area ratio (I_{cw})

The concrete wall area ratio has been simplified by using similar way of masonry infill are ratio (I_{inf}) as discussed in the previous section. Therefore, it is simplified by concrete wall ratio (R_{cw}), thickness of concrete wall (t_{cw}) and average span length (l_s) as shown Equation (5.5).

$$I_{cw} = \frac{A_{cw}}{A_f} \approx \frac{t_{cw}}{l_s}.R_{cw} \tag{5.5}$$

where, concrete wall ratio (R_{cw}) indicates the quantity of concrete wall expressed as the ratio of the total number of solid concrete wall panel in a direction to the total number of spans for that direction as shown in Equation (5.6).

$$R_{cw} = \frac{Number\ of\ \text{concrete wall}\ in\ a\ direction}{Total\ no\ of\ span\ in\ a\ direction} \tag{5.6}$$

Concrete wall with opening due to door and window are not considered in this method. R_{cw} shall be calculated for both orthogonal directions and the minimum value is considered.

Considering simplified form of column area ratio (I_c), masonry infill area ratio (I_{inf}), and concrete wall area ratio (I_{cw}), the Visual Rating Index (I_{VR}), the Equation (5.1) can be re-written as follow as Equation (5.7):

$$I_{VR} = \frac{1}{n.w}\left[\tau_c\left(\frac{b_c^2}{l_s^2}\right) + \tau_{\inf}\left(\frac{t_{\inf}}{l_s}.R_{\inf}\right) + \tau_{cw}\left(\frac{t_{cw}}{l_s}.R_{cw}\right)\right] \tag{5.7}$$

5.3.2.4 Seismic capacity reduction factors

Many studies and post-earthquake observations exhibit that the seismic performance is amplified due to the buildings with irregularity in plan and elevation as well as by other vulnerable parameters such as deterioration and buildings age etc. In addition, different seismic evaluation method (Jain et al. 2010; Sucuoglu et al. 2007; Ozcebe et al. 2004) also focused on the importance of such parameters in seismic capacity evaluation based on past earthquake damaged database. In order to include the effect of these parameters into seismic capacity evaluation, a modification factor has been considered in this study. The modification factor is a reduction factor which takes into account the negative influence of these prevalent architectural features. Some common parameters such as horizontal imbalance or plan irregularity, aspect ratio, existence of soft story and quality of buildings that are reported to be found in most of damaged buildings. However, it is easy to investigate those parameters by visual inspection. Therefore, these parameters are employed for calculation of modification factor. After considering the influence of aforementioned parameters, the VR index in the Equation (5.8) can be expressed as:

$$I_{VR} = \frac{1}{n.w}\left[\tau_c\left(\frac{b_c^2}{l_s^2}\right) + \tau_{\inf}\left(\frac{t_{\inf}}{l_s}.R_{\inf}\right) + \tau_{cw}\left(\frac{t_{cw}}{l_s}.R_{cw}\right)\right]F_{IV}.F_{IH}.F_D.F_Y \tag{5.8}$$

where, F_{IV}, F_{IH}, F_D and F_Y are the modification factors for existence of vertical irregularity, horizontal irregularity, deterioration of concrete and year of construction respectively.

The basic assumptions about material properties and seismic capacity modification factors are described in the subsequent section.

5.4 Basic assumptions for Visual Rating Index (I_{VR})

This proposes method considers some basic assumptions for parameters such as material properties of vertical elements and seismic capacity modification factors. The material properties include average shear strength of column, masonry infill and RC wall, buildings unit weight, thickness of masonry infill and RC wall. On the other hand, seismic capacity modification factors include plan and vertical irregularity, deterioration and year of construction etc. However, these assumptions might vary based on construction practices with different material properties in different countries. The basic consideration of the assumptions is discussed in the subsequent sections:

5.4.1 Basic assumptions for material properties

The basic assumption for material properties are similar that considered for simplified seismic capacity index as mentioned in previous Chapter 2. The following assumptions are considered for the seismic capacity evaluations using in Equation (5.8):

5.4.1.1 Average shear strength of column (τ_c)

Generally, it is not easy to determine shear strength of column by visual investigation. Most of the cases, information regarding concrete strength is not available of existing RC buildings. However, many researchers and different seismic evaluation manual suggest some guideline consideration about material properties in absence of material properties information. From this point, Japanese seismic evaluation (JBDPA, 2001) suggests the range of shear strength is of 0.7N/mm^2~1.5N/mm^2 for preliminary seismic evaluation. Furthermore, Tsai et al. (2008) proposed the average ultimate shear strength of RC column is 15 kgf/cm^2 (1.47 MPa) for preliminary evaluation based on the detailed assessment results of school buildings after the 1999 Chi-Chi earthquake. Besides, a relationship between shear strength of column and

h_o/D ratio based on analysis of existing buildings located at Dhaka, Bangladesh (SATREPS 2015) as a case study of developing countries. From above discussion, the average shear stress for columns could be assumed as 1.0 MPa.

5.4.1.2 Average shear strength of masonry infill (τ_{inf})

The usual ranges of shear strength of masonry infill, τ_{inf}, is between 0.2N/mm^2~1N/mm^2 as discussed in previous chapter 3. The shear strength, τ_{inf}, commonly ranges $0.04f_m$~$0.1f_m$ depending on the relation between shear strength of masonry infill and masonry prism compressive strength, f_m as discussed in previously. However, this method also assumes a value for shear strength of masonry infill in absence of masonry prism compressive strength. In this regards, some guideline and researchers propose average shear strength based on past experimental studies. ASCE seismic evaluation guideline (ASCE/SEI 41-06 2007) prescribed 0.24 MPa for good masonry condition when masonry strength is not available. Besides, researchers from different counties also proposed the average lateral strength for masonry infill wall for preliminary seismic assessment. In this regard, the average shear strength is of 0.28 MPa for Nepal (Karmacharya, U. 2018 and Pradhan, 2009) and of 0.39 MPa for (Chiou et al. 2017) for Taiwan, proposed based on past experimental studies in Nepal. Since the proposed method is visual investigation, a lower boundary of average shear strength is considered in case of absence of data. In this study, a value of shear strength of masonry infill, τ_{inf}, is considered as 0.20 MPa, which is a conservative value for masonry infill strength.

5.4.1.3 Average shear strength of concrete wall (τ_{cw})

Likewise, JBDPA standard (2001) proposed average shear strength of concrete wall ranges from 1.0 N/mm^2~3.0 N/mm^2 considering without boundary column and with boundary column based on past damage investigation and experimental data. Hence, in this study, average shear strength of concrete wall (τ_{cw}) has been assumed 1.0 MPa for visual investigation.

5.4.1.4 Thickness of masonry infill (t_{inf})

In general, thickness of masonry infill is about 125 mm which is common practice in masonry infilled RC buildings in Bangladesh. Besides, the thickness of masonry infill varies within a range of 125 mm to 250 mm as found in the field survey in Bangladesh (SATREPS 2015). Sometimes for public building such as office building, the thickness of exterior wall and interior wall are of 250 mm and 125 mm. However, this study assumes the masonry infill thickness (t_{inf}) as 125 mm for single layer of infill panel.

5.4.1.5 Thickness of concrete wall (t_{cw})

The thickness of concrete wall ranges 200 mm ~300 mm as found in existing building in Bangladesh (SATREPS 2015) and Taiwan (Purdue University and NCREE 2016). In this study, the minimum thickness has been assumed as 200 mm considered as lower boundary conservatively.

5.4.1.6 Average unit weight per floor area (w)

In general, the unit floor weight of existing buildings is assumed of 10 to 12 kN/m^2 in structural design procedure. Similarly, the unit floor weight has also been found based on study of existing building in Bangladesh (SATREPS 2015). Furthermore, Japanese seismic evaluation guideline considers the building unit weight is about 12 kN/m^2. Therefore, in this study, the average unit weight per floor area, *w*, is set as 11.2 kN/m^2.

5.5 Basic assumptions for modification factors

The proposed method considers building irregularity, deterioration and buildings age as parameters for modification factor in calculation of Visual Rating Index. Buildings irregularity includes vertical irregularity and horizontal irregularity such as open ground floor, shape of floor plan and aspect ratio can easily have investigated during visual inspection. These parameters are discussed in subsequent sections:

5.5.1 Buildings Irregularity

The seismic behavior of RC buildings subjected to earthquake motions is influenced by the distribution of mass, stiffness, and strength of buildings in both horizontal and vertical planes. However, earthquake damages in such types of buildings generally starts from structural weak points located in lateral force resisting frame. Many seismic evaluation guidelines in different countries such as American Standard (ASCE/SEI 7-10), Japanese seismic evaluation guideline (JBDPA), New Zealand standard 2004 (NZS 1170.5), describe the irregularities of buildings into two categories. These are vertical and horizontal irregularities. Moreover, those seismic evaluation guidelines propose different approach for consideration of these influencing parameters during seismic capacity evaluation.

Past earthquake damage investigation helps to quantify the irregularities of existing RC buildings. However, the existing rapid visual screening method proposed some factors for seismic influencing parameters based on study of past earthquake damage databases, engineering justification and also individual perceptions.

Japan Building Disaster Prevention Association (JBDPA) (2001) proposed guideline for seismic capacity evaluation which does not cover masonry infilled RC buildings. In this study, JBDPA (2001) manual is extended to be used for the masonry infilled RC structures for modifying the Visual Rating Index, according to horizontal and vertical irregularity. Therefore, the proposed method assumes a modification factors following Japanese Seismic evaluation standard during estimation of Visual Rating Index. The following sections describes consideration of seismic capacity reduction factor due to vertical and plan irregularities:

5.5.1.1 Vertical irregularity factors (F_{IV})

It is generally thought that vertical irregularity significantly influences the seismic capacity of RC buildings more than that those has horizontal irregularity. Many researchers reported different types of the vertical irregularities such as story stiffness distribution along the height, the inconsistency between adjacent floor, ground floor parking, soft story etc. Usually, opening and soft story due to ground floor parking and commercial usage which are commonly found in most of RC buildings in developing countries. Many of buildings are found to be severely damaged due to this types of irregularities as shown in Figure 5.5 in Nepal Earthquake 2015 (datacenterhub.org).

Figure 5.5 Examples of buildings subjected to soft-story collapse during the Nepal earthquake (datacenterhub.org)

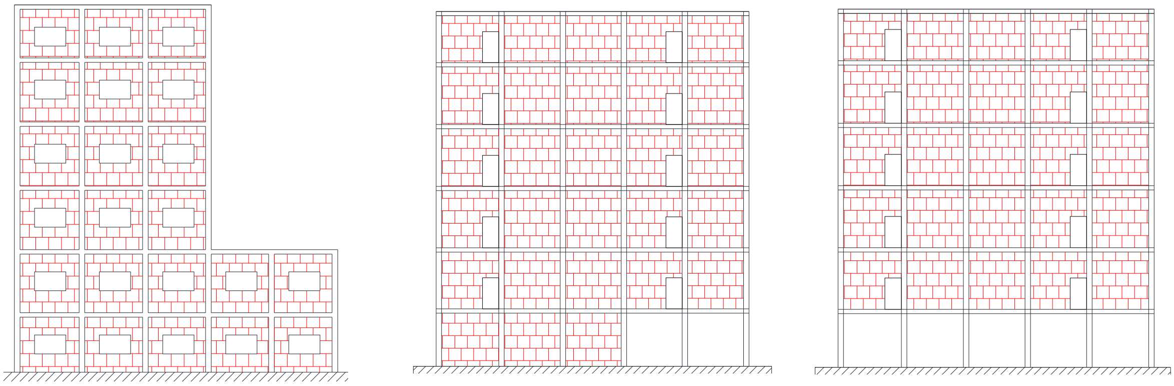
It is necessary to quantify the aforementioned vertical irregularities for taking into account in seismic evaluation procedure. However, it is not easy to investigate all types of vertical irregularities by visual inspection within very short time. Hence, this study considers full and partial opening at ground floor, setback etc. which can be visually observed during building survey and inspection. Therefore, this study classifies the vertical irregularities into three categories for easy understanding such as regular, nearly regular, irregular as shown in Figure 5.5.

A vertical irregularity factor *(F_{IV})* has been imposed in this study to quantify the vertical irregularity of existing buildings. In this context, many researchers and seismic evaluation code proposed some values for quantification of this types of irregularity in seismic evaluation procedure (JBDPA 2001; Sucuoglu et al. 2007; Ozcebe et al. 2004). Besides, Al-Nimry et al. (2015) proposed some reduction factors for irregularities of RC buildings according to building height. This study assumes modification factors which are based on Japanese seismic evaluation procedure. The reduction factors for different vertical irregularity criteria are shown in Table 1(JBDPA 2001) described as follows:

(a) Regular: The building has been considered as regular if there are no significant vertical irregularities. In this case, the value has been considered as unity.

(b) Nearly regular: Partial opening at ground floor and setback are exist in existing RC buildings (See Figure 5.6 b) which is also responsible for reduction of seismic capacity during earthquake.

(c) Irregular: Opening at ground floor due to car parking is very common for mid-rise buildings (See Figure 5.6 c) which is also common in RC building in developing countries.



(a) Setbacks (b) Some panels without infill at ground floor (c) soft or open story

Figure 5.6: Elevation view of some typical RC frame having vertical irregularities

Many guidelines and researchers propose values for reduction factors for open ground floor or soft story effect. However, Al-Nimry et al (2015) proposed reduction factors for soft story structures 0.85 and 0.75 for mid-rise and low-rise buildings respectively. It indicates about 15% to 25 % of reduction of actual seismic capacity. Similar observation also has found by other researcher such as Sucuoglu and Yazgan (2003), Gulkan and Yakut (1994), Magliulo *et al.* (2002) based on engineering judgement and field observations of actual earthquake damages. It has been concluded that the earthquake response magnifies about 13.5 % to 20% due to soft story compared with regular buildings. Furthermore, JBDPA (2001) propose reduction factor for soft story about 0.9 and eccentric soft story is of 0.8 for both first level and second level evaluation. As the proposed method is based on visual inspection within short time, this study assumes vertical irregularity factors is of 0.6 as a conservative for preliminary investigation as shown in Table 5.1. In case of partial opening or set back, a reduction factors is of 0.8 chosen as shown in Table 5.1.

Table 5.1 Factors for vertical irregularity (F_{IV})

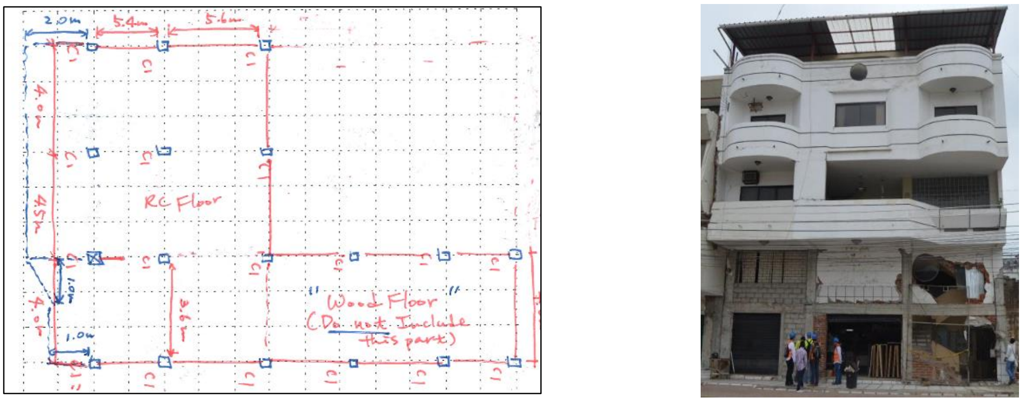
Items	Regular	Nearly Regular	Irregular
Criteria	Regular	Small opening at ground floor and setback	Soft story or open ground floor
F_{IV}	1	0.8	0.6

5.5.1.2 Horizontal irregularity factor (F_{IH})

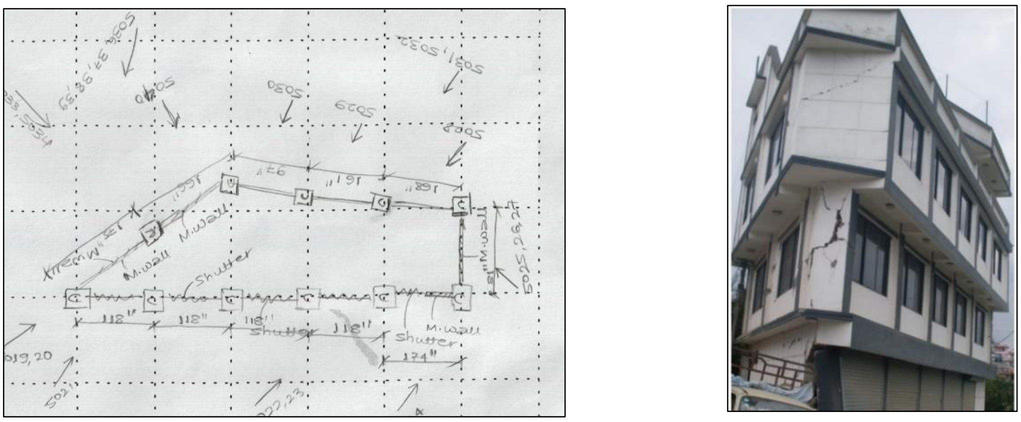
Buildings also suffers diverse of seismic damages due to different types of structural configurations such as L, U, and T shape of building. Sometimes, severely damaged occurs due to high aspect ratio of floor plan (here aspect ratio means ratio between longitudinal direction to transverse direction). Those types buildings have been reported as experienced severely damaged during past earthquake based on past earthquake damaged database. Figure 5.6 shows the buildings in irregular shaped RC buildings suffered severely damaged in Ecuador and Nepal earthquake. Figure 5.7(a) shows the building is L shaped floor plan. Since the perpendicular part is narrower than main part of the building, the center of mass is changed during the earthquake. As a result, there were a torsional effect during earthquake which turned into severely damaged. Figure 5.7 (b) showing a building with large aspect ratio have been affected severely damaged during Nepal earthquake. The investigated building is three storied and seismic capacities is not much lower to be severely damage. However, the building has been reported severely damaged due to plan irregularity with aspect ratio even though high seismic capacity.

The horizontal irregularity including different shape of buildings floor plan (such as L, T, U shaped floor plan), aspect ratio, re-entrant corner, extended floor plan etc. which are commonly observed in existing RC buildings. Since the propose method is based on visual inspection with limited time, all types of horizontal regularities are not considered during visual investigation. Hence, buildings shape and aspect ratio is considered and those parameters can be easily inspected during field survey.

Many of researcher's efforts to understand the behavior of RC buildings with plan irregularity. Many of seismic design code propose some guidelines to avoid torsional effect during earthquake. In addition, these guidelines are sometimes strict about selection of building shape in high seismicity region whenever design of new buildings. However, in seismic evaluation of existing RC buildings, it is necessary to quantify and consider a reduction factor associated with horizontal irregularities.



(a) Building with L shaped floor plan



(b) Floor plan with aspect ratio

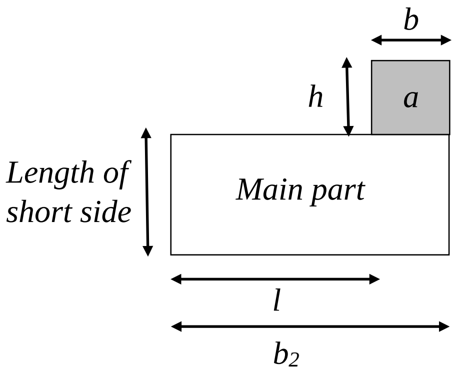
Figure 5.7 Damage due to horizontal irregularity of RC buildings in Nepal and Ecuador Earthquake

Most of researchers consider the horizontal irregularity factor as a qualitative approach. Some of them are trying to quantify the horizontal irregularity factors for seismic capacity evaluation. Al-Nimry et al. (2015) propose a reduction factors for horizontal irregularity is of 0.95 and 0.9 for low-rise and mid-rise buildings respectively based on different types of shape of buildings. However, JBDPA (2001) proposes guidelines for different criteria of plan irregularity and reduction factor for modifying the seismic capacity. The values have been considered as 1, 0.9, 0.8 for regular, nearly regular and irregular, respectively. The factors are considered depending on different possible shaped building plan (i.e. L, T or U-shaped). All types of horizontal irregularity are not easy to investigate during visual inspection. Therefore, only building configuration relates the shape of floor plan different possible shaped building plan (i.e. L, T or U-shaped) is considered in this study. JBDPA classified into three categories according to floor plan. The basic criteria for each parameter is described in JBDPA manual (2001), and the brief descriptions of plan regularity are shown in Figure 5.8. The following consideration are taken for plan irregularity:

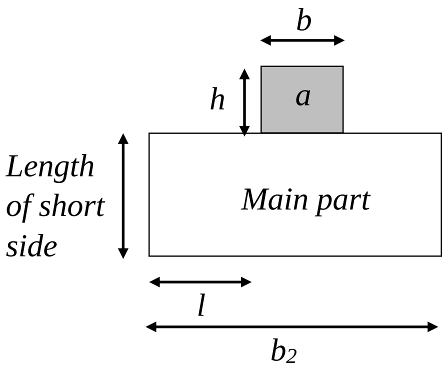
(i) Regular: Structural balance is good, and the area of a projection part (*a*) is not more than 10% of the floor area.

(ii) Nearly regular: Structural balance is worse than regular, or the area of a projection part (*a*) is not more than 30% of the floor area with L, T or U shaped plan.

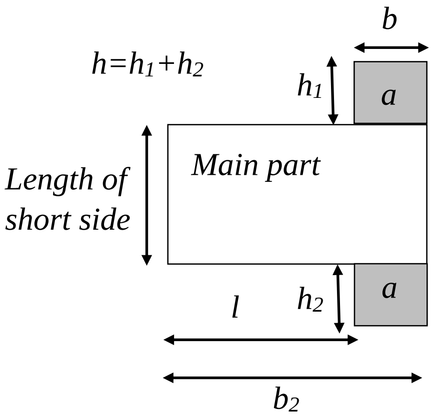
(iii) Irregular: Structural balance is worse than nearly regular, or the area of a projection part (*a*) is larger than 30% of the floor area with L, T or U shaped plan.



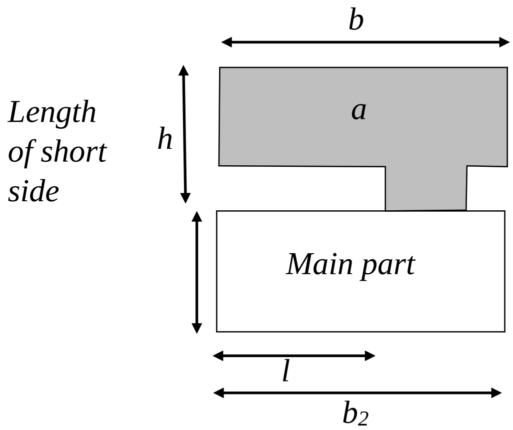
(a) L-shaped floor plan



(b) T shaped floor plan



(c) T shaped floor plan



(d) U shaped floor plan

Figure 5.8 Criteria for plan irregularity

Table 5.2 shows reduction factors for different horizontal irregularity factors based on Japanese seismic evaluation guideline (JBDPA 2001).

Table 5.2 Factors for horizontal irregularity (F_{IH})

Items	Regular	Nearly Regular	Irregular
Shape	Regular	L, T or U shaped plan.	L, T or U shaped plan
The projection area "a"	≤ 10 % of floor area	≤ 30% of floor area	> 30% of floor area
F_{IH}	1	0.9	0.8

5.5.2 Reduction Factors related deterioration and buildings age

Generally, seismic capacity of existing building is reduced for deterioration due to poor maintenance, quality of existing buildings and building's age. However, the proposed Visual Rating Index also considers those reduction parameters.

5.5.2.1 Deterioration factor (F_d)

Deterioration of concrete in structural elements indicates the actual state of seismic capacity of the building. Theoretically, presence of cracks as well as spalling in concrete are responsible toward the degradation of seismic capacity. This also refers a building might be possessed weak material and poor workmanship. Furthermore, the correlation between the building quality with different damage state has been observed based on study of past earthquake damage database (Sucuoglu et al. 2007). Figure 5.9 shows typical crack exists in RC structure which can be easily identified by visual inspection.

Table 5.3 shows the values of reduction coefficient due to presence of visible crack in the buildings according to JBDPA 2001.

Table 5.3 Deterioration factor (F_d)

Item	None	Minor	Severe
Criteria	No deterioration	Some cracks in structural element	Spalling in concrete
F_d	1	0.9	0.8

(a) Plaster crack (do not consider) (b) Crack through RC column (consider)

c) crack in wall (do not consider) d) plaster deterioration (do not consider)

Figure 5.9 Deterioration of Concrete due to cracking

5.5.2.2 Building year of construction factor (F_y)

Building year of construction refers to the age of building which reflects the quality of construction as well as the design procedure adopted for a particular building. Generally, old building cannot be expected to have a good performance during earthquake due to old construction practices ignoring seismic detailing in the recent building codes. For example, in Japan, poor seismic performance has been observed in old building, specially to those constructed before adopting new seismic design code 1981, in the 1995 Kobe earthquake. Hence, those buildings suffered severely damaged due to this devastating earthquake (Ohba et al. 2000). Therefore, building ages affects its overall seismic performance. Based on experience of past earthquake, JBDPA (2001) proposed a reduction factor in the seismic evaluation manual for building year of construction as shown in Table 5.4.

Table 5.4 Year of construction factor (F_y)

Item	New	Middle	Old
Criteria	Less than 15 years	15- 30 years	More than 30 years
F_y	1	0.95	0.9

The aforementioned assumed values for each parameter in Equation (5.8) could be adjusted later for each country based on suitable characteristics of buildings and materials strength properties in that region.

5.6 Summary of chapter 5

This chapter describes a proposal of rapid seismic evaluation method herein referred as Visual Rating (VR) method for screening of existing RC buildings. The proposed Visual Rating (VR) method considers fundamental parameters of a buildings dimensions such as column and infill wall area ratio and their shear strength. The Visual Rating (VR) method approximately estimates the seismic capacity of existing RC buildings in terms of Visual Rating Index (I_{VR}). The development and application procedure have been described in this chapter.

The following conclusions are discussed as follows:

1) The Visual Rating (VR) method considers the simplified column area ratio and the simplified infill wall area ratio, which estimates the seismic capacity of existing RC buildings.
2) The inclusion of those column and infill wall area ratio in Visual Rating (VR) method is the new concept that have not been considered in the existing visual screening methods.
3) The Visual Rating Index (I_{VR}) proposed in this chapter which approximates the seismic capacity of existing RC buildings.

However, the assumptions considered for column, masonry infill and concrete wall need further investigation for each countries according to local materials. Even though, this method is intended to buildings in Bangladesh, but could be easily adjusted to other countries by modifications for suitable characteristics of buildings and materials strength properties in the intended region.

Chapter 6

Survey of existing RC buildings in Bangladesh

6.1 Introduction

This chapter describes survey of existing RC buildings and application procedure of proposed Visual Rating method. The main objective of this chapter is to investigate the applicability and effectiveness of the proposed Visual Rating method. First of all, applicability of the proposed Visual Rating method has been verified by investigation of several existing RC buildings located at Dhaka, Bangladesh. Secondly, the obtained results from Visual Rating method have been compared with the seismic capacity from detail seismic evaluation to understand the effectiveness and accuracy. The flow of chapter has been shown in Figure 6.1.

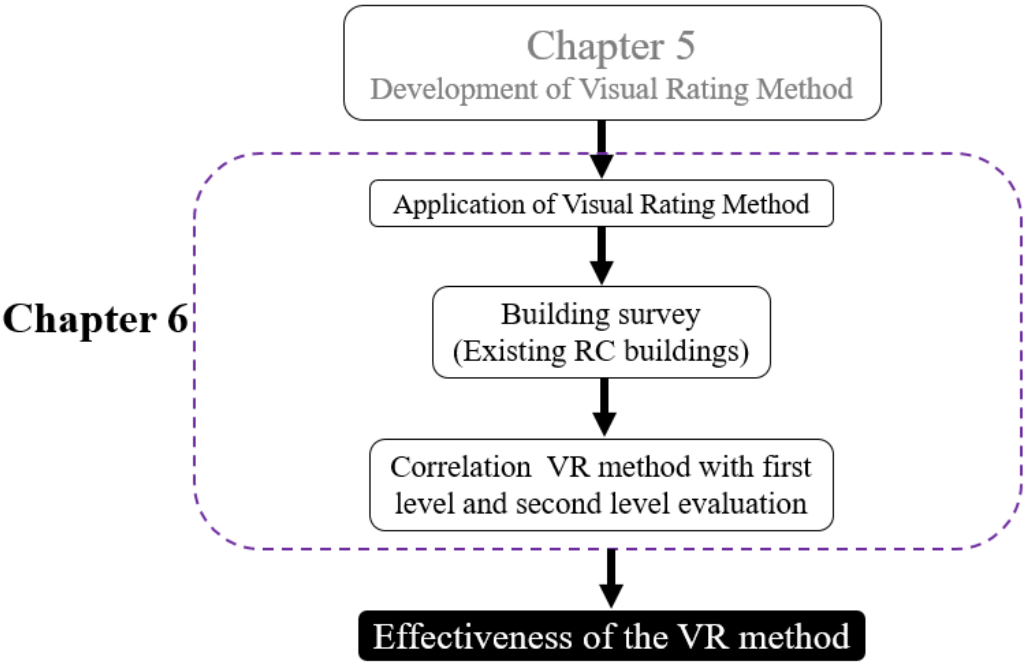


Figure 6.1 Flow of the chapter 6

6.2 Overview of surveyed RC buildings

This following section describes the general information and characteristics of surveyed existing RC buildings located in Dhaka, Bangladesh.

6.2.1 General information

Total of 22 existing RC buildings have been selected for building survey and application of Visual Rating method (see appendix B). The buildings survey has been done under a research project SATREPS-TSUIB which is a technical cooperation project between Government of Bangladesh and Japan International Cooperation Agency (JICA). These buildings are located at Dhaka, Bangladesh as shown in Figure 6.2. However, the structural system of those surveyed buildings are masonry infilled RC buildings which is common construction practice for mid to low rise buildings in Bangladesh as previously discussed in the previous Chapter 4.

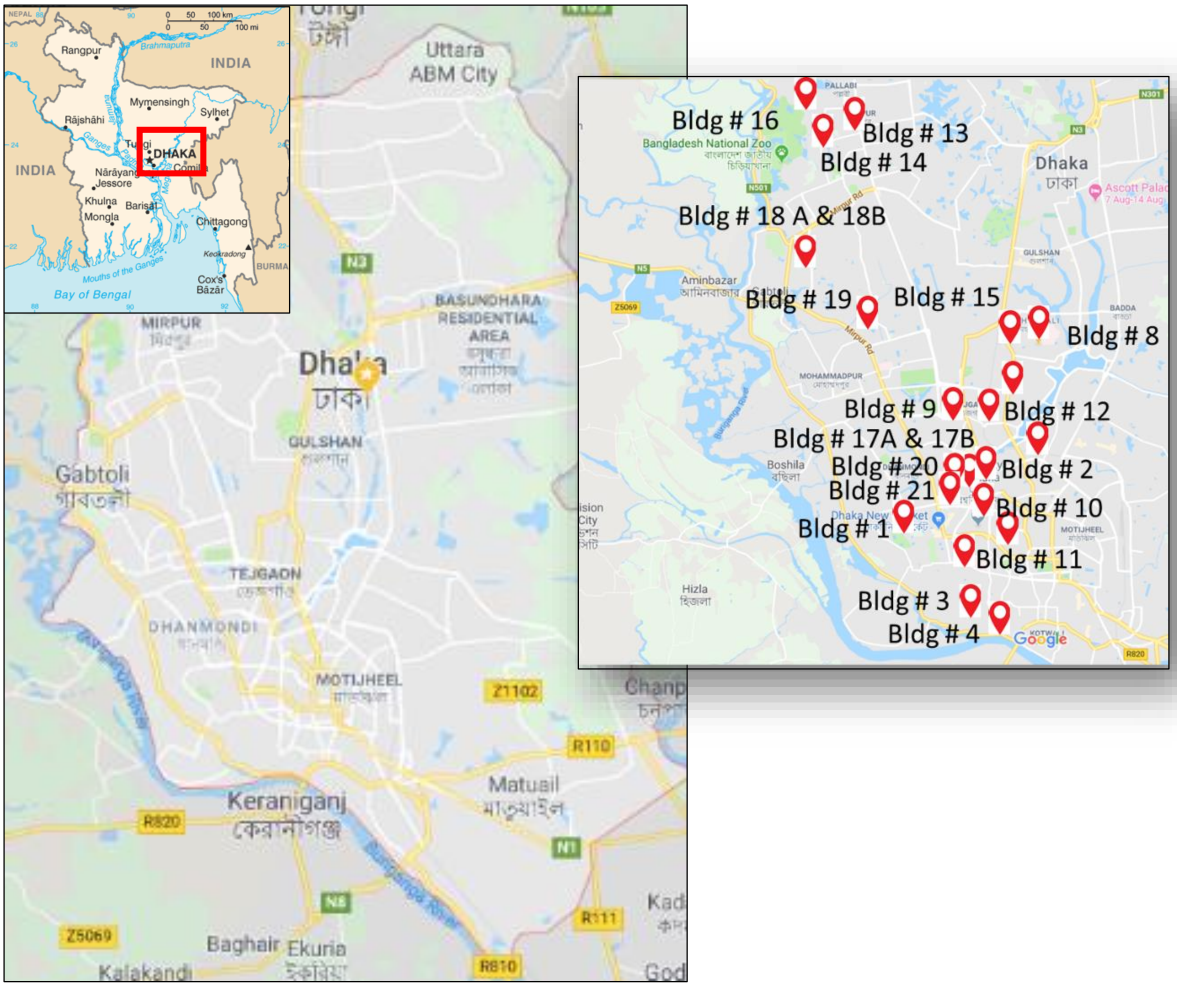


Figure 6.2 Location of Surveyed buildings at Dhaka, Bangladesh

It should be noted that those buildings are designed, constructed and maintained by Public Works Department (PWD), a governmental agency under ministry of housing and public works, who is responsible for design, construction and maintenance of public buildings all over in Bangladesh. The main difference of CDMP database (as discussed in Chapter 4) and PWD buildings database is that CDMP buildings database are the private buildings whereas, the PWD buildings are designed, constructed and maintained by Public Works Department (PWD). The main reason behind to select PWD buildings is that investigator are allowed to easy access inside the buildings for survey and investigation.

Figure 6.3 shows the distribution of surveyed buildings according to year of construction. It has been seen that most of the selected buildings are constructed within after 1993. Bangladesh National Building code has been first published in 1993. Afterward, the BNBC 1993 has been enacted as law in 2006. The revision of BNBC 1993 has been going on and first draft of revision is published in 2015.

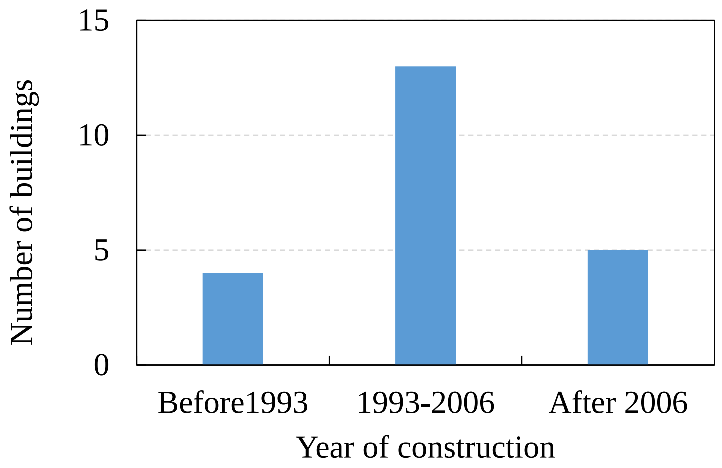


Figure 6.3 Distribution according to construction year

The number of stories are wide ranging in between 2 to 12 stories buildings. Figure 6.4 showing the distribution according to number of stories of surveyed buildings. Most of them are 6 storied buildings. Some of them are 2 to 5 storied buildings. 4 buildings are mid-rise buildings such as 10 to 12 storied buildings.

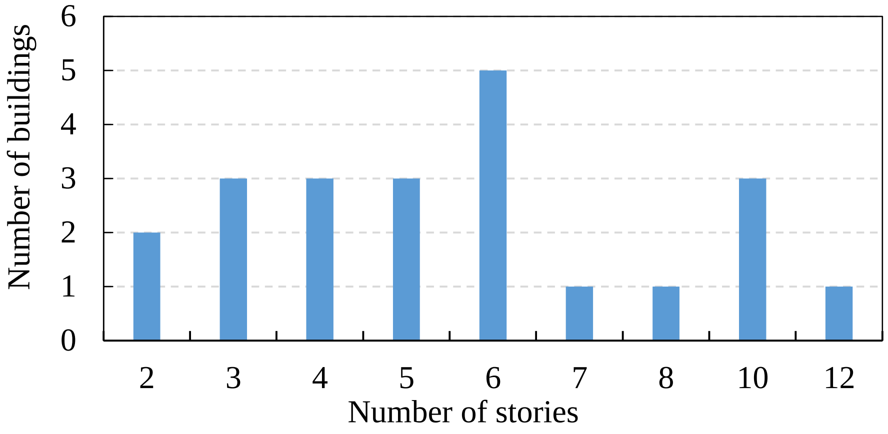


Figure 6.4 Distribution according to number of stories

Figure 6.5 shows occupancy categories higher than Larger numbers of buildings are 6 storied and the buildings constructed after 1993 is considered as and first seismic design code published Bangladesh national building code has been first published in 1993, It Generally, PWD buildings Therefore, some of them are official All those buildings are located surveyed in this study. All those buildings are located at Dhaka, Bangladesh.

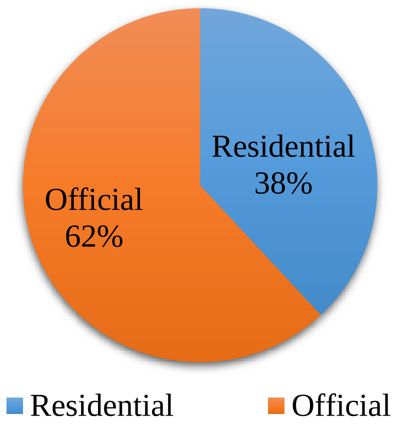


Figure 6.5 Distribution according to occupancy categories of surveyed building

Table 6.1 showing the list of surveyed buildings showing number of storied, year of construction, material properties and occupancy categories of each individual buildings. The year of construction ranging from 1968 to 2006 which covers old as well as new buildings. The material properties such as concrete compressive strength ranging from 13.75 MPa to 25 MPa. The reinforcement material strength ranging from 276 MPa to 400 MPa. The total floor area of the investigated buildings ranging from 105 m^2 to 1780 m^2 shows also large variation of the investigated building.

Table 6.1 List of RC buildings surveyed at Dhaka, Bangladesh

Building ID	Year of construction	Concrete strength (MPa)	No of story	Floor area (m^2)	Occupancy Categories
Bldg # 1	1998	17	2	176.94	Official
Bldg # 2	1968	11.5	5	402.60	Official
Bldg # 3	2006	25	6	174.24	Residential
Bldg # 5	2005	25	6	122.60	Residential
Bldg # 6	1990	20	4	513.09	Official
Bldg # 7	1978	13.75	3	261.72	Official
Bldg # 8	2008	25	5	157.32	Residential
Bldg # 9	2002	25	3	704.47	Official
Bldg # 10	2008	25	8	466.81	Official
Bldg # 11	2001	25	10	265.00	Official
Bldg #12	1999	25	6	442.00	Official
Bldg #13	2002	24	2	208.42	Official
Bldg #14	2009	24	6	179.70	Residential
Bldg #15	2006	24	5	136.98	Residential
Bldg #16	1993	17	3	324.50	Official
Bldg #17A	2002	24	4	355.80	Official
Bldg #17B	2002	24	4	434.81	Official
Bldg #18A	2002	24	10	105.66	Residential
Bldg #18B	2002	24	10	647.32	Residential
Bldg #19	1997	24	6	375.07	Official
Bldg #20	2001	24	7	608.55	Official
Bldg #21	1995	24	12	1780	Official
Note: Architectural drawing and structural drawings are not found for Bldg # 4, therefore, excluded from this analysis.					

6.3 Field survey of existing RC buildings

As previously mentioned, 22 number of existing RC buildings has been surveyed in this study. The survey procedure has been subdivided into two parts. First of visual rating method has been applied on these buildings. Afterward, as built architectural drawing preparation has been done because architectural drawings are not available for all surveyed buildings. Therefore, as-building drawing is prepared by onsite investigation. The following sections describe about the survey procedure in details.

6.3.1 Application of Visual Rating method in surveyed buildings

As previously mentioned, visual rating method has been applied on existing buildings to understand the applicability and effectiveness of the proposed visual screening method. Generally, this survey is based on visual inspection allowing inspectors to enter inside the building to be investigated. The estimated time requires for the survey is about 30 to 45 min for one buildings.

6.3.1.1 Visual Rating (VR) survey sheet

The proposed visual rating method considers a rapid building inspection for a short duration only to record the information using a common survey sheet as shown as shown in Figure 6.6. However, completion of survey data sheet is one of the major tasks for application of Visual Rating method. The visual survey datasheet contains basic parameters related to column area, floor and masonry infill area of a building. In addition, secondary parameters such as buildings irregularity, buildings deterioration and year of construction have been mentioned in the datasheet. The basic consideration and selection criteria for each items are explained in the previous chapter (see section 5.3).

The surveyor should take necessary action to ensure entry at all crucial locations for survey of the building. For this reason, he might ensure the schedule 2/3 days before the inspection. If due to restriction for entry some parameter cannot be determined, the surveyor will note other data, but not complete the survey. Irrational assumptions without confirmation are not encouraged.

The surveyor should be capable of understanding the whole picture of the ground floor as well as the frame system. If there is possibility for serious pounding effect, the surveyor might include it somewhere in the survey sheet.

Visual Rating (VR) Survey Sheet

Name of Building: Date:

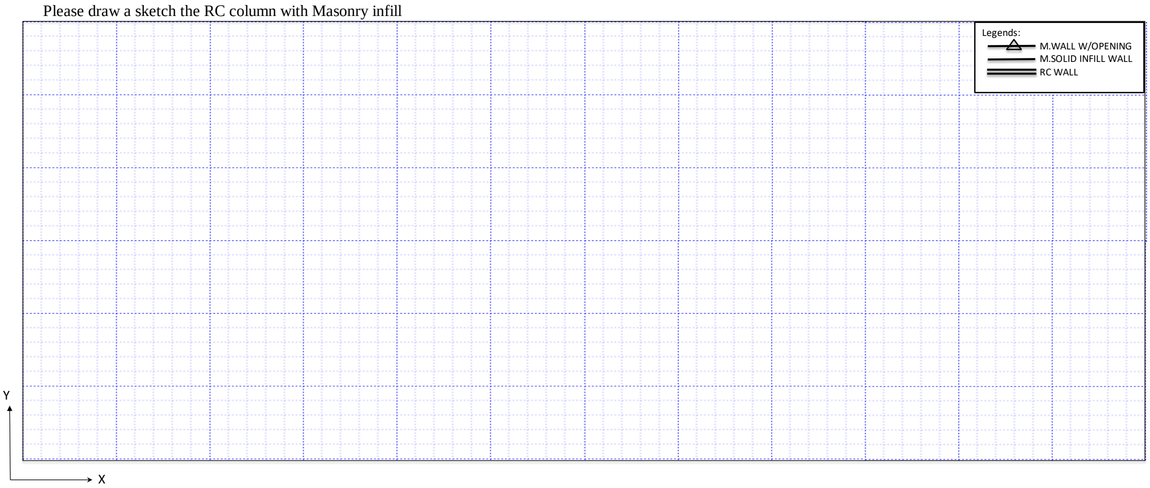
Address:

Please read carefully the selection criteria and put circle [○] in the appropriate items

No	Items	Selection Criteria		Categories								Please specify, If the value is found	Note
1	No of story (n)	Put story number											
2	Representative column size (b_c), (mm)	Please exclude the mortar/plaster thickness 50 mm		250 mm ~ 350 mm	350 mm ~ 450 mm	450 mm ~ 550 mm	550 mm ~ 650 mm	650 mm ~ 750 mm	750mm ~ 850 mm	850mm ~ 950 mm	950mm ~ larger	mm	
3	Average span length (l_s), (mm)	The size of equivalent square floor area carried by a single column		2500 mm ~ 3500 mm	3500 mm ~ 4500 mm	4500 mm ~ 5500 mm	5500 mm ~ 6500 mm	6500 mm ~ 7500 mm	7500 mm ~ 8500 mm	8500 mm ~ 9500 mm	9500 mm ~ larger	mm	
5	RC Shear wall ratio (R_{inf})	Option A	Shear wall ratio, R_{sw}: $= \frac{No\ of\ RC\ shear\ wall\ in\ x\ or\ y\ dir.}{Total\ no\ of\ span\ in\ x\ or\ y\ dir.}$	X- direction:				Y-direction:					
		Option B	Thickness (mm)										
			Length of shear wall (mm)	X-direction:				Y-direction:					
			Floor area of first floor (mm^2)										
5	Masonry infill ratio (R_{cw})	Option A	Masonry infill ratio, R_{inf}: $= \frac{No\ of\ infill\ panel\ in\ x\ or\ y\ dir.}{Total\ no\ of\ span\ in\ x\ or\ y\ dir.}$	X- direction:				Y-direction:					
		Option B	No of Masonry infill panel	X-direction:				Y-direction:					
			Floor area of first floor (mm^2)										
6	Vertical irregularity, F_{IV}	Regular= No irregularity Nearly Regular= Small opening at ground floor Irregular= Ground floor opening/parking		Regular (1)			Nearly regular (0.8)			Irregular (0.6)			
7	Horizontal irregularity, F_{IH}	Regular= No irregularity Nearly Regular= Small projection exists with irregular shape Irregular= large projection with irregular shape		Regular (1)			Nearly regular (0.8)			Irregular (0.6)			
8	Deterioration of concrete, F_D	None= No deterioration Minor= Some crack in structrual element Severe= Spalling of concrete and major Crack		None (1)			Minor (0.9)			Severe (0.8)			
9	Year of construction (F_y)	New= less than 15 years Middle=15~30 years Old= More than 30 years		New (1)			Middle (0.95)			Old (0.9)			

*numeral in parenthesis indicates corresponding weightage

Please draw a sketch the RC column with Masonry infill



Name of the Investigator:	

Figure 6.6 A typical survey datasheet used in the visual inspection.

6.3.1.2 Guidelines for filling up the survey data sheet

In this section, the procedure for filling up the survey datasheet will be discussed step by step.

Step 1: General Information:

a) Surveyor will input survey date, survey building name and building address at the top of survey data sheet as shown in Figure 6.6.
b) Surveyor will write his name in the place of Name of the Investigator located at the bottom of the sheet as shown in Figure 6.6.
c) If possible surveyor will collect structural/architectural drawing of the building. However, if drawing is not available, it will not affect the survey.

Visual Rating (VR) Survey Sheet

Name of Building: Residential building. Date: 7/6/2018

Address: National Institute of chest diseases, Mohakhali, Dhaka

Please read carefully the selection criteria and put circle [○] in the appropriate items

Figure 6.7 General information of survey datasheet

Table 3.6 Investigator's Name in survey datasheet

Name of the Investigator:	Mr. X

Figure 6.8 General information of survey datasheet

Step 2: Number of stories (n)

Surveyor will input the total story number as shown in Figure 6.9. If there is different story number in a building or set back in same building, surveyor will take the maximum story number. However, surveyor has to mark the part and story number in the rough sketch of VR survey Sheet accordingly.

Visual Rating (VR) Survey Sheet

Name of Building: Residential building (staff quarter) Date: 7/6/2018

Address: National Institute of Chest diseases, Mohakhali, Dhaka.

Please read carefully the selection critêria and put circle [○] in the appropriate items

No	Items	Selection Criteria	Categories	Please specify, If the value is found	Note
1	No of story (n)	Put story number	6 (Six)		

Figure 6.9 Total number of story

Step 3: Drawing Rough Sketch of the building

Firstly, it is suggested that surveyor should complete the rough sketch of the building. This shall be done by visually observing the building and noting its number of stories and shape. During completion of the form, double writing should be avoided. In this sketch, column location, location of the solid infill masonry walls and masonry walls with opening (for with window, door, ventilator etc.) shall be shown. Masonry wall with openings are not included in the calculation of Visual Rating Index. In the rough sketch, surveyor may also include column size, span size for later judgment. If necessary, a fresh sheet can be used to input the parameters. If any special case appears, the surveyor shall mention it on the right side of the sheet on the column as referred as named “Note”. An example of rough sketch of investigated building has been shown in Figure 6.10.

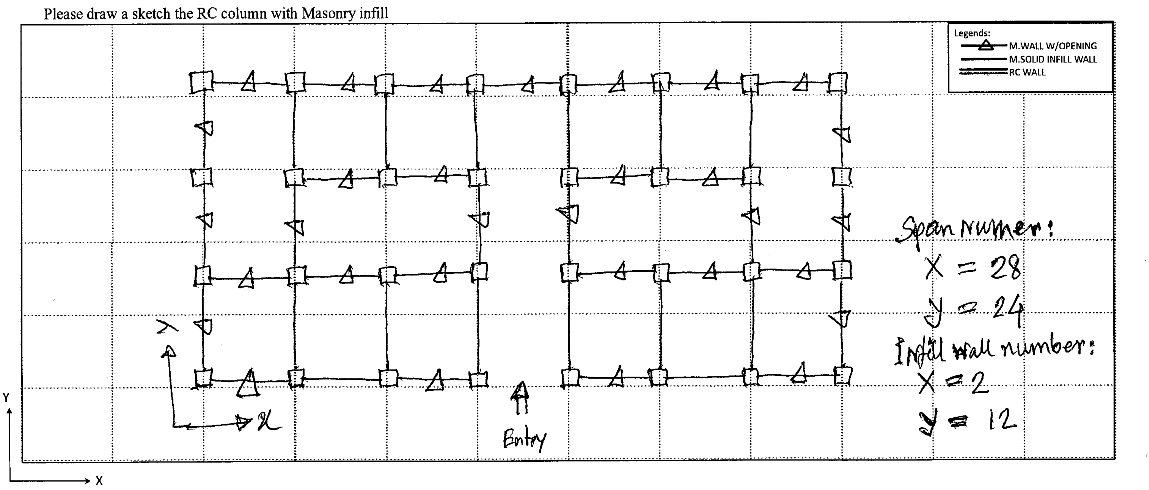


Figure 6.10 Rough sketch of the building showing Column layout and masonry infill walls with/without opening

Step 4: Average column size (${b_c}$)

For selecting representative column size surveyor shall follow section 5.3.2.1. In the following sketch, three interior columns have been chosen to determine average column size Inspectors, after entering inside the house, can easily investigate column size of interior column rather than exterior columns. In this regards, it has been suggested that surveyor investigate two or three interior column and make a decision of average columns size. The average column size (b_c) is considered excluding 50mm which is assumed to be the concrete cover.

As there is a range provided for average column size, precise calculation is not always required. In case the column dimension is fall in a range, it is suggested that surveyor put circle to corresponding range. If possible he will write the column dimension in the box as shown in Figure 6.11. Surveyor will fill up No.2 item in the survey datasheet accordingly.

No	Items	Selection Criteria		Categories								Please specify, If the value is found	Note
1	No of story (n)	Put story number		6 (Six)									
2	Representative column size (b_c), (mm)	Please exclude the mortar/plaster thickness 50 mm		250 mm ~ 350 mm	350 mm ~ 450 mm	450 mm ~ 550 mm	550 mm ~ 650 mm	650 mm ~ 750 mm	750mm ~ 850 mm	850mm ~ 950 mm	950mm ~ larger	350 mm	
3	Average span length (l_s), (mm)	The size of equivalent square floor area carried by a single column		2500 mm ~ 3500 mm	3500 mm ~ 4500 mm	4500 mm ~ 5500 mm	5500 mm ~ 6500 mm	6500 mm ~ 7500 mm	7500 mm ~ 8500 mm	8500 mm ~ 9500 mm	9500 mm ~ larger	3000 mm	
5	RC Shear wall ratio (R_{inf})	Option A	Shear wall ratio, R_{sw}: $= \frac{No\ of\ RC\ shear\ wall\ in\ x\ or\ y\ dir.}{Total\ no\ of\ span\ in\ x\ or\ y\ dir.}$	X- direction: $\frac{0}{28}$				Y-direction: $\frac{0}{24}$					No RC Wall
		Option B	Thickness (mm)										
			Length of shear wall (mm)	X-direction:				Y-direction:					
			Floor area of first floor (mm^2)										
5	Masonry infill ratio (R_{cw})	Option A	Masonry infill ratio, R_{inf}: $= \frac{No\ of\ infill\ panel\ in\ x\ or\ y\ dir.}{Total\ no\ of\ span\ in\ x\ or\ y\ dir.}$	X- direction: $\frac{2}{28}$				Y-direction: $\frac{12}{24}$					
		Option B	No of Masonry infill panel	X-direction:				Y-direction:					
			Floor area of first floor (mm^2)										

Figure 6.11Datasheet showing representative column size

Step 5: Average span length (l_s)

Average span length (l_s) of building in both directions can be estimated in different way. The square of average span length (l_s) is a simplest way to approximately estimate the floor area of a building in a short time. Generally, the span length is not equal in each direction and also numbers of spans are not the same. In this context, the investigator should check and measure one or two spans in both direction (longitudinal and transverses direction) of a building. For selecting Average span length surveyor shall follow section 5.3.2.1. In the sketch, three spans have been chosen to determine average span length. Afterward, the appropriate value for average span length is chosen based on engineering judgment. Surveyor will fill up No.3 item in the sheet accordingly as shown in Figure 6.12.

No	Items	Selection Criteria	Categories									Please specify, If the value is found	Note
1	No of story (n)	Put story number	6 (Six)										
2	Representative column size (b_c), (mm)	Please exclude the mortar/plaster thickness 50 mm	250 mm ~ 350 mm	350 mm ~ 450 mm	450 mm ~ 550 mm	550 mm ~ 650 mm	650 mm ~ 750 mm	750mm ~ 850 mm	850mm ~ 950 mm	950mm ~ larger		350 mm	
3	Average span length (l_s), (mm)	The size of equivalent square floor area carried by a single column	2500 mm ~ 3500 mm	3500 mm ~ 4500 mm	4500 mm ~ 5500 mm	5500 mm ~ 6500 mm	6500 mm ~ 7500 mm	7500 mm ~ 8500 mm	8500 mm ~ 9500 mm	9500 mm ~ larger		3000 mm	
5	RC Shear wall ratio (R_{inf})	Option A: Shear wall ratio, R_{sw}: $= \frac{No\ of\ RC\ shear\ wall\ in\ x\ or\ y\ dir.}{Total\ no\ of\ span\ in\ x\ or\ y\ dir.}$	X- direction: 0/28					Y-direction: 0/24					No RC Wall
		Option B: Thickness (mm)											
		Option B: Length of shear wall (mm)	X-direction:					Y-direction:					
		Option B: Floor area of first floor (mm^2)											
5	Masonry infill ratio (R_{cw})	Option A: Masonry infill ratio, R_{inf}: $= \frac{No\ of\ infill\ panel\ in\ x\ or\ y\ dir.}{Total\ no\ of\ span\ in\ x\ or\ y\ dir.}$	X- direction: 2/28					Y-direction: 12/24					
		Option B: No of Masonry infill panel	X-direction:					Y-direction:					
		Option B: Floor area of first floor (mm^2)											

Figure 6.12 Average span length in the survey datasheet

Step 6: Masonry infill ratio (R_{inf})

Masonry infill ratio indicates the quantity of masonry infill expressed as the ratio of total number of masonry infill panel to the total number of span for each direction of building. Masonry infill panel with opening due to door and window are not considered during calculation of R_{inf}. As previously mentioned in previous chapter 5, masonry infill with opening due to door and window are not considered in the proposed method.

For example, in Figure 6.15, total number of spans in x direction is 28 and number of solid infill is 2. Therefore, masonry infill ratio in x direction will be $\frac{2}{28}$. Similarly, total number of spans in y direction is 24 and number of solid infill masonry wall is 12. Hence, masonry infill ratio in y direction will be $\frac{12}{24}$ excluding the wall with opening. Figure 6.13 showing he procedure of filling the masonry infill section in the survey datasheet.

No	Items	Option	Selection Criteria	Categories								Please specify, If the value is found	Note
1	No of story (n)		Put story number	6 (Six)									
2	Representative column size (b_c), (mm)		Please exclude the mortar/plaster thickness 50 mm	250 mm ~ 350 mm	350 mm ~ 450 mm	450 mm ~ 550 mm	550 mm ~ 650 mm	650 mm ~ 750 mm	750mm ~ 850 mm	850mm ~ 950 mm	950mm ~ larger	350 mm	
3	Average span length (l_s), (mm)		The size of equivalent square floor area carried by a single column	2500 mm ~ 3500 mm	3500 mm ~ 4500 mm	4500 mm ~ 5500 mm	5500 mm ~ 6500 mm	6500 mm ~ 7500 mm	7500 mm ~ 8500 mm	8500 mm ~ 9500 mm	9500 mm ~ larger	3000 mm	
5	RC Shear wall ratio (R_{inf})	Option A	Shear wall ratio, R_{sw}: $= \frac{No\ of\ RC\ shear\ wall\ in\ x\ or\ y\ dir.}{Total\ no\ of\ span\ in\ x\ or\ y\ dir.}$	X- direction: $\frac{0}{28}$				Y-direction: $\frac{0}{24}$					No RC Wall
		Option B	Thickness (mm)										
			Length of shear wall (mm)	X-direction:				Y-direction:					
			Floor area of first floor (mm^2)										
5	Masonry infill ratio (R_{cw})	Option A	Masonry infill ratio, R_{inf}: $= \frac{No\ of\ infill\ panel\ in\ x\ or\ y\ dir.}{Total\ no\ of\ span\ in\ x\ or\ y\ dir.}$	X- direction: $\frac{2}{28}$				Y-direction: $\frac{12}{24}$					
		Option B	No of Masonry infill panel	X-direction:				Y-direction:					
			Floor area of first floor (mm^2)										

Figure 6.13 Average span length in the survey datasheet

Step 7: RC wall ratio (R_{CW})

Likewise, Masonry infill ratio, for calculating RC Shear wall ratio, R_{CW}, number of concrete wall in the frame in each direction shall be counted and divide it by the total number of span of that respective direction. It should be noted that, concrete wall connected between frames shall be counted only. Walls with opening like doors and windows shall not be included. However, there is not RC wall in this building in both directions. Hence, the value of number of RC wall ratio is 0.

Step 8: Vertical Irregularity

Surveyor has been suggested to follow section 5.5.1.1 to determine if there is any vertical irregularity in the building. If the surveyor cannot determine vertical irregularity on his own, he shall draw rough sketch of the building showing necessary elevations of the building so that higher supervising authority can judge the building frame system. In the survey datasheet reduction factor for vertical irregularity are mentioned for various cases. Surveyor should encircle the case which fits the building.

Step 9: Horizontal Irregularity

Surveyor has been suggested to follow section 5.5.1.2 to determine if there is any horizontal irregularity in the building. In the survey datasheet reduction factor for horizontal irregularity are mentioned for various cases. Surveyor should encircle the case which fits the investigated building.

Step 10: Deterioration and Year of Construction

Judgment of deterioration is sometimes very crucial. It takes extensive knowledge and vast experience to understand whether the deterioration is structural or non-structural. Surveyor may identify some common type of deterioration as mentioned in section 3.3.8. For any confusion, surveyor shall take photos of damaged location for better understanding of his supervising authority.

Similarly, for year of construction surveyor shall look up for the drawing and construction time. If the drawing is not available, surveyor may take information from the owner. However, precise year of construction is not a must as the range is of 15 years. In the survey datasheet, item number 6 to 9 represents the modification factor of the buildings as shown Figure 6.14.

6	Vertical irregularity, F_{IV}	Regular= No irregularity Nearly Regular= Small opening at ground floor Irregular= Ground floor opening/parking	Regular (1)	Nearly regular (0.8)	Irregular (0.6)	
7	Horizontal irregularity, F_{IH}	Regular= No irregularity Nearly Regular= Small projection exists with irregular shape Irregular= large projection with irregular shape	Regular (1)	Nearly regular (0.8)	Irregular (0.6)	
8	Deterioration of concrete, F_D	None= No deterioration Minor= Some crack in structrual element Severe= Spalling of concrete and major Crack	None (1)	Minor (0.9)	Severe (0.8)	
9	Year of construction (F_y)	New= less than 15 years Middle=15~30 years Old= More than 30 years	New (1)	Middle (0.95)	Old (0.9)	

*numeral in parenthesis indicates corresponding weightage

Figure 6.14 Modification factors of surveyed building

Visual Rating (VR) Survey Sheet

Name of Building: Residential building (staff quarter) Date: 7/6/2018

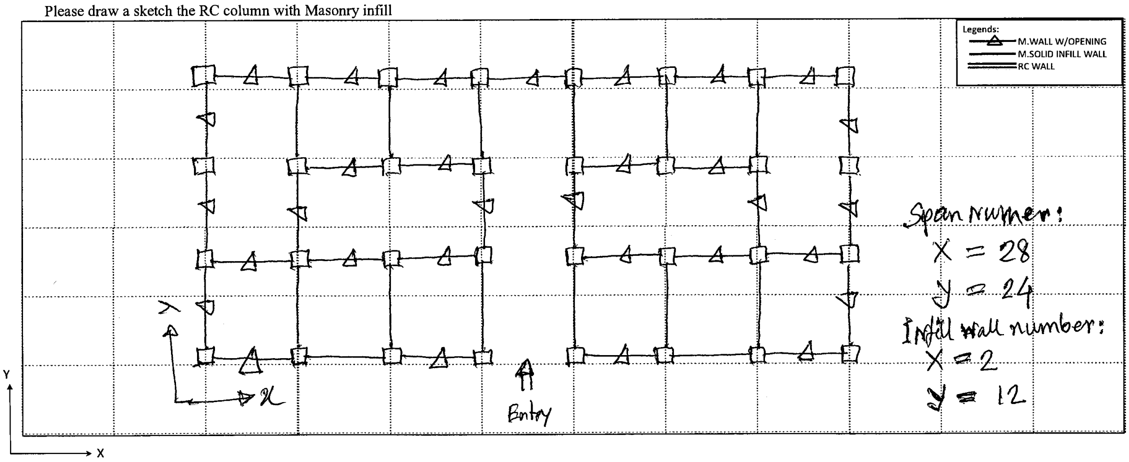
Address: National Institute of Chest diseases, Mohakhali, Dhaka.

Please read carefully the selection criteria and put circle [○] in the appropriate items

No	Items	Selection Criteria	Categories								Please specify, If the value is found	Note
1	No of story (n)	Put story number	6 (Six)									
2	Representative column size (b_c), (mm)	Please exclude the mortar/plaster thickness 50 mm	250 mm ~ 350 mm	350 mm ~ 450 mm	450 mm ~ 550 mm	550 mm ~ 650 mm	650 mm ~ 750 mm	750mm ~ 850 mm	850mm ~ 950 mm	950mm ~ larger	350 mm	
3	Average span length (l_s), (mm)	The size of equivalent square floor area carried by a single column	2500 mm ~ 3500 mm	3500 mm ~ 4500 mm	4500 mm ~ 5500 mm	5500 mm ~ 6500 mm	6500 mm ~ 7500 mm	7500 mm ~ 8500 mm	8500 mm ~ 9500 mm	9500 mm ~ larger	3000 mm	
5	RC Shear wall ratio (R_{inf})	Option A: Shear wall ratio, R_{sw}: $= \frac{No\ of\ RC\ shear\ wall\ in\ x\ or\ y\ dir.}{Total\ no\ of\ span\ in\ x\ or\ y\ dir.}$	X- direction: 0/28				Y-direction: 0/24					No RC Wall
		Option B: Thickness (mm)										
		Option B: Length of shear wall (mm)	X-direction:				Y-direction:					
		Option B: Floor area of first floor (mm²)										
5	Masonry infill ratio (R_{cw})	Option A: Masonry infill ratio, R_{inf}: $= \frac{No\ of\ infill\ panel\ in\ x\ or\ y\ dir.}{Total\ no\ of\ span\ in\ x\ or\ y\ dir.}$	X- direction: 2/28				Y-direction: 12/24					
		Option B: No of Masonry infill panel	X-direction:				Y-direction:					
		Option B: Floor area of first floor (mm²)										
6	Vertical irregularity, F_{IV}	Regular= No irregularity; Nearly Regular= Small opening at ground floor; Irregular= Ground floor opening/parking	(Regular (1))	Nearly regular (0.8)	Irregular (0.6)							
7	Horizontal irregularity, F_{IH}	Regular= No irregularity; Nearly Regular= Small projection exists with irregular shape; Irregular= large projection with irregular shape	(Regular (1))	Nearly regular (0.8)	Irregular (0.6)							
8	Deterioration of concrete, F_D	None= No deterioration; Minor= Some crack in structrual element; Severe= Spalling of concrete and major Crack	(None (1))	Minor (0.9)	Severe (0.8)							
9	Year of construction (F_y)	New= less than 15 years; Middle=15~30 years; Old= More than 30 years	(New (1))	Middle (0.95)	Old (0.9)							

*numeral in parenthesis indicates corresponding weightage

Please draw a sketch the RC column with Masonry infill



Name of the Investigator: [signature]

Figure 6.15 An example of filling the Visual Rating datasheet

6.3.2 Analysis after application of Visual Rating method

6.3.2.1 Simplified column area ratio

Simplified column area ratio has been calculated from information found from the investigation using the visual rating datasheet (See Figure 6.15). Simplified column area ratio is based on average column size and average span length of an investigated buildings. Here, simplified column area ratio has been calculated using Equation 5.6 in the previous chapter 5. The selection criteria and procedure of average column size is already described in the previous chapter 5. The average column size and average span length is based on engineering judgement of the investigator during field survey. Table 6.2 showing the simplified column area ratio of the investigated building.

6.3.2.2 Simplified masonry infill wall area ratio

Simplified masonry infill wall area ratio has been estimated using masonry infill ratio, thickness of masonry infill and average span length. The masonry infill ratio, as described in the previous chapter 5, is calculated using number of masonry infill panel and total number of span in the direction to be calculated. In this method, the minimum value should be taken for conservative estimation. The thickness of masonry infill has been assumed is of 125 mm as common construction practices in Bangladesh. It should be noted that the average span length should be same as considered for simplified column area ratio. Table 6.3 shows the simplified masonry infill wall area ratio of investigated buildings using visual rating method.

6.3.2.3 Simplified RC wall area ratio

The main structural system is masonry infill with RC frame. However, some of buildings contains RC wall as per structural design requirement. From the list of buildings, a few of them are consist of RC wall. The procedure for simplified RC wall area ratio is the similar to simplified masonry wall area ratio. Table 6.3 showing the simplified RC wall area ratio of the investigated buildings.

Table 6.2 Simplified column area ratio of surveyed buildings.

Building ID	Number of story (n)	Average column Size (mm)	Average span length (mm)	Simplified column area ratio (%)
Bldg # 1	2	450	4000	0.63
Bldg # 2	5	350	5000	0.10
Bldg # 3	6	350	3000	0.23
Bldg # 5	6	350	3000	0.23
Bldg # 6	4	500	5000	0.25
Bldg # 7	3	400	3000	0.59
Bldg # 8	5	350	3000	0.27
Bldg # 9	3	450	4500	0.33
Bldg # 10	8	550	5000	0.15
Bldg # 11	10	450	3500	0.17
Bldg #12	6	350	4000	0.13
Bldg #13	2	450	4000	0.63
Bldg #14	6	350	3000	0.23
Bldg #15	5	350	3000	0.27
Bldg #16	3	350	4000	0.26
Bldg#17A	4	400	4000	0.25
Bldg#17B	4	400	4000	0.25
Bldg#18A	10	550	3500	0.25
Bldg#18B	10	550	3500	0.25
Bldg #19	6	300	3000	0.17
Bldg #20	7	600	5000	0.21
Bldg #21	12	800	6000	0.15

Table 6.3 Simplified masonry infill wall area ratio

Building ID	Number of story	Average span length (mm)	Thickness of masonry infill (t_{inf}), (mm)	Masonry infill wall ratio (R_{inf}) in minimum direction			Simplified masonry infill wall area ratio (%)
				Number of masonry infill	Number of span	Masonry infill ratio (R_{inf})	
Bldg # 1	2	4000	125	3	14	0.21	0.33
Bldg # 2	5	5000	125	4	24	0.17	0.08
Bldg # 3	6	3000	125	2	18	0.11	0.08
Bldg # 5	6	3000	125	0	15	0.00	0.00
Bldg # 6	4	5000	125	2	24	0.08	0.05
Bldg # 7	3	3000	125	2	26	0.08	0.11
Bldg # 8	5	3000	125	2	17	0.12	0.10
Bldg # 9	3	4500	125	0	30	0.00	0.00
Bldg # 10	8	5000	125	6	26	0.23	0.07
Bldg # 11	10	3500	125	3	29	0.10	0.04
Bldg #12	6	4000	125	11	39	0.28	0.15
Bldg #13	2	4000	125	1	19	0.05	0.08
Bldg #14	6	3000	125	2	28	0.07	0.05
Bldg #15	5	3000	125	0	21	0.00	0.00
Bldg #16	3	4000	125	2	29	0.07	0.07
Bldg#17A	4	4000	125	1	25	0.04	0.03
Bldg#17B	4	4000	125	1	28	0.04	0.03
Bldg#18A	10	3500	125	0	29	0.00	0.00
Bldg#18B	10	3500	125	6	58	0.10	0.04
Bldg #19	6	3000	125	6	29	0.21	0.14
Bldg #20	7	5000	125	4	39	0.10	0.04
Bldg #21	12	6000	125	1	51	0.02	0.00

6.3.2.4 Modification factors

Modification factors relate the reduction of seismic capcity due to buildings irregularities, deterioration in concrete member and year of construction. This study considers the reduction factors as discussed in previous chapter 5 for inclusion of effect of these parameters. However, it has been observed that most of the buildings are regular in both vertical and horizontal irregularity. Therefore, reduction factors have been assumed as shown in Table 6.4. Similarly, deterioration factor also considered and showed in Table 6.4. Furthermore, reduction factors are considered based on construction year of the investigated buildings. It has been noted that the year of construction has been decided on information found from structural drawings. Table 6.4 mentioning the reduction factors for year of construction of investigated buildings.

6.3.2.5 **Visual Rating Index of surveyed buildings**

Visual Rating Index has been estimated for all surveyed buildings using information found from visual inspection. In this study, visual rating index is estimated using obtained simplified column area ratio, simplified masonry infill wall area ratio and simplified RC wall area ratio using Equation 5.8. The modification factors as shown in Table 6.4 have been considered for calculating the Visual rating index. However, the material properties for visual rating index have been discussed in Chapter 5. Table 6.4 shows the estimated visual rating index of all surveyed buildings.

Table 6.4 Reduction factors for modification of visual rating index (I_{VR})

Building ID	Vertical Irregularity factor, (F_{IV})	Horizontal Irregularity factor, (F_{IH})	Deterioration Factor (F_D)	Year of construction factor, (F_Y)	Reduction factors
Bldg # 1	1.00	1.00	0.90	0.90	0.81
Bldg # 2	1.00	0.80	0.90	0.90	0.81
Bldg # 3	1.00	1.00	0.90	1.00	0.90
Bldg # 5	1.00	1.00	1.00	1.00	1.00
Bldg # 6	1.00	1.00	1.00	1.00	1.00
Bldg # 7	0.80	0.80	0.80	0.90	0.72
Bldg # 8	1.00	0.80	0.90	1.00	0.90
Bldg # 9	0.80	0.80	1.00	1.00	1.00
Bldg # 10	1.00	1.00	0.90	0.95	0.86
Bldg # 11	1.00	0.60	1.00	1.00	1.00
Bldg #12	0.60	0.80	1.00	0.95	0.95
Bldg #13	0.80	0.60	1.00	0.95	0.95
Bldg #14	1.00	1.00	1.00	1.00	1.00
Bldg #15	0.80	0.60	1.00	0.95	0.95
Bldg #16	0.80	0.80	1.00	0.95	0.95
Bldg#17A	0.80	1.00	1.00	0.95	0.95
Bldg#17B	0.80	1.00	1.00	0.95	0.95
Bldg#18A	1.00	1.00	1.00	1.00	1.00
Bldg#18B	1.00	1.00	1.00	1.00	1.00
Bldg #19	1.00	0.60	0.95	0.95	0.90
Bldg #20	0.80	0.80	1.00	0.95	0.95
Bldg #21	0.60	1.00	1.00	0.95	0.95

Table 6.5 Visual Rating Index (I_{VR}) for investigated buildings

Building ID	Number of story	Simplified column area ratio (%)	Simplified masonry infill wall area ratio (%)	Simplified RC wall area ratio (%)	Reduction factors	Visual Rating Index (I_{VR})
Bldg # 1	2	0.63	0.33	-	0.81	0.51
Bldg # 2	5	0.10	0.08	-	0.81	0.07
Bldg # 3	6	0.23	0.08	-	0.90	0.19
Bldg # 5	6	0.23	0.00	-	1.00	0.20
Bldg # 6	4	0.25	0.05	-	1.00	0.23
Bldg # 7	3	0.59	0.11	-	0.72	0.25
Bldg # 8	5	0.27	0.10	-	0.90	0.19
Bldg # 9	3	0.33	0.00	-	1.00	0.19
Bldg # 10	8	0.15	0.07	-	0.86	0.13
Bldg # 11	10	0.17	0.04	0.14	1.00	0.17
Bldg #12	6	0.13	0.15	-	0.95	0.06
Bldg #13	2	0.63	0.08	-	0.95	0.26
Bldg #14	6	0.23	0.05	-	1.00	0.21
Bldg #15	5	0.27	0.00	-	0.95	0.11
Bldg #16	3	0.26	0.07	-	0.95	0.15
Bldg#17A	4	0.25	0.03	-	0.95	0.17
Bldg#17B	4	0.25	0.03	-	0.95	0.17
Bldg#18A	10	0.25	0.00	-	1.00	0.22
Bldg#18B	10	0.25	0.04	-	1.00	0.23
Bldg #19	6	0.17	0.14	-	0.90	0.09
Bldg #20	7	0.21	0.04	0.02	0.95	0.13
Bldg #21	12	0.15	0.00	0.01	0.95	0.08

In order to understand the effectiveness and accuracy of the proposed visual rating method, the estimated Visual Rating Index (I_{VR}) has been compared with seismic index of detail seismic evaluation of these investigated buildings. However, all of these investigated buildings do not have architectural drawing such as floor plan and sectional elevation showing location of RC columns, masonry infill and other important features that are needed for detail seismic evaluation. Therefore, as-built drawing preparation is done for all these building. The as-built drawing preparation are mentioned is described in subsequent section.

6.4 Preparation of as-built drawings of surveyed buildings

As previously mentioned, all building does not have architectural drawings, therefore, as-built drawings has been prepared for all investigated buildings. As-built drawing preparation involves drawing floor plan and sectional elevation of investigated buildings. Some photos are also taken for recording more detail information. The as-built floor plan includes the investigation of span length in between columns, dimension and location of column, masonry infill and RC wall. Sectional elevation has been drawn for location of doors and windows in masonry infill panel, floor height etc. Figure 6.17 showing some photos describing the preparation of as-built drawing of the building survey.

Figure 6.16 Photos of preparation of as-built drawing

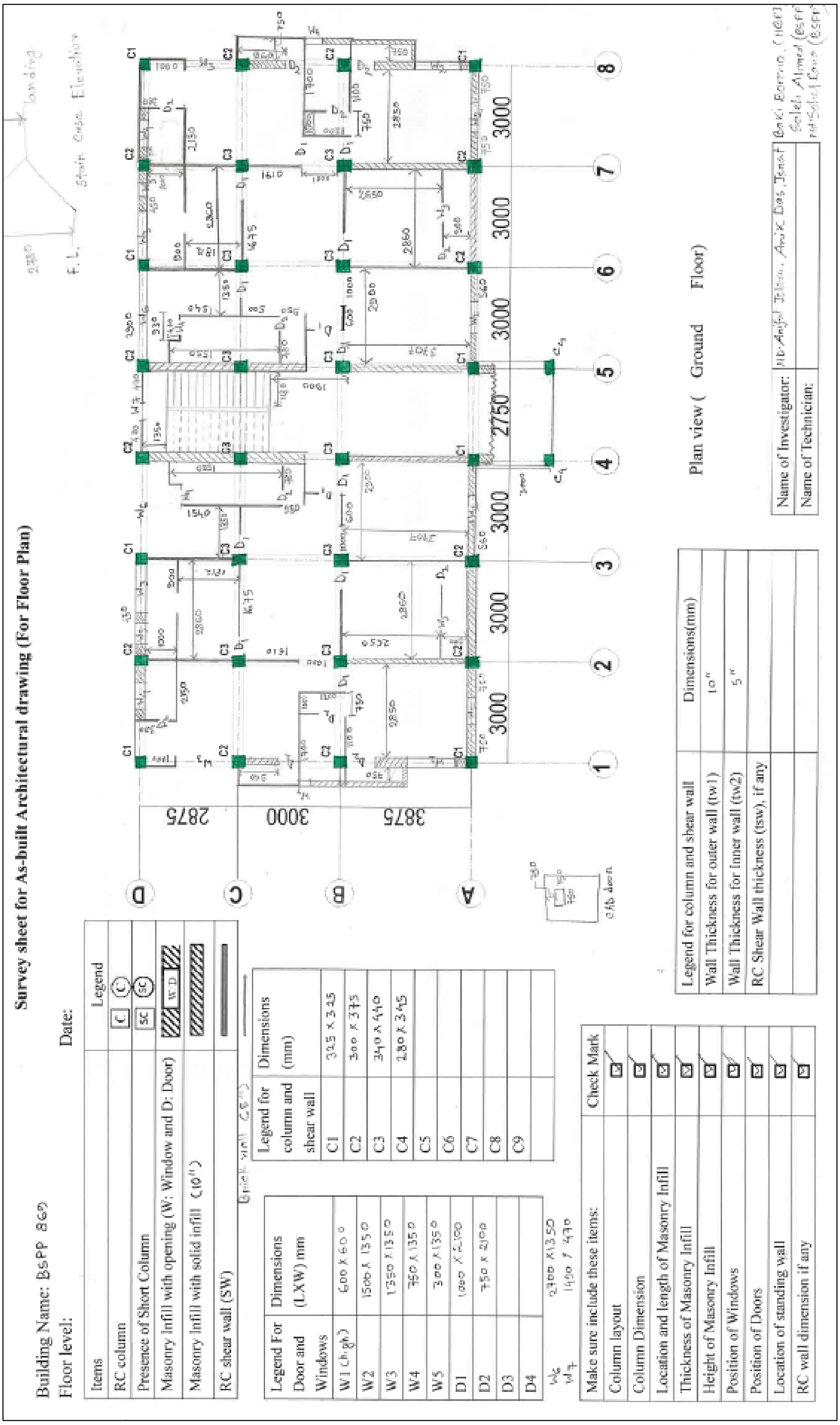


Figure 6.17 An example of as-built drawing of ground floor plan

6.5 Column area and masonry infill wall area ratio of surveyed buildings

Column area is calculated from structural drawing. However, masonry infill area has been calculated from prepared as-built drawings. The following sections discussed about the column and masonry infill wall area ratio of the investigated buildings.

6.5.1 Column area ratio

Column area has been calculated using information found from structural drawings. Column area ratio has been estimated and plotted in Figure 6.18. These buildings are designed and constructed by Public Works Department (PWD). Generally, PWD follows Bangladesh National Building Code (BNBC) and other buildings regulation during structural design (especially seismic design) and construction stage. Therefore, PWD maintain the size and material quality of buildings. As a result, the column area ratio is much higher than that of other building such as CDMP buildings database. The most of buildings column area ratio within 0.3 to 0.4 %. The average values of PWD buildings database is about 0.31%.

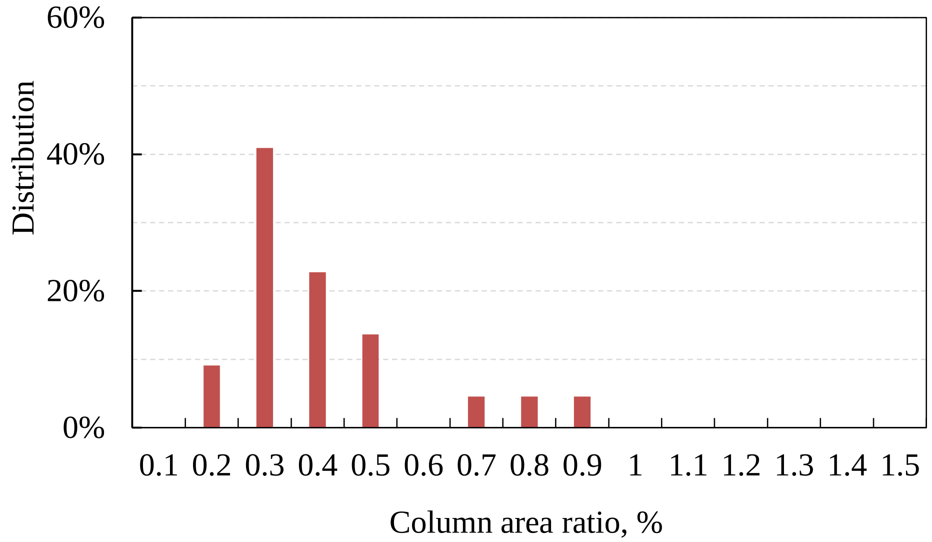


Figure 6.18 Distribution according to column area ratio (%)

6.5.2 Masonry infill wall area ratio

Masonry infill wall area has been calculated based on as-built architectural drawing after investigation of each building. Thickness of masonry infill differs from other buildings. In general, thickness of outer wall is of 250mm and interior wall is of 125 mm which is the common practice for government buildings. Masonry infill cross-sectional area has been calculated for both directions (i.e. transverse and longitudinal direction) of building considering both solid and partial infill panel. It should be noted that the masonry infill walls with large opening is not considered in cross-sectional area of masonry infill. Masonry infill wall consists of opening area is higher than 40% of panel area is not considered in this study. Masonry infill wall area ratio has been calculated using cross-sectional area and total floor area of building. Figure 6.19 shows distribution of masonry infill according to masonry infill wall area ratio. Masonry infill wall area ratio are similar to other CDMP database. The reason behind, most of exterior wall contains large opening. It has been seen that most of the building, the wall area ratio ranging from 0.1 to 0.3%.

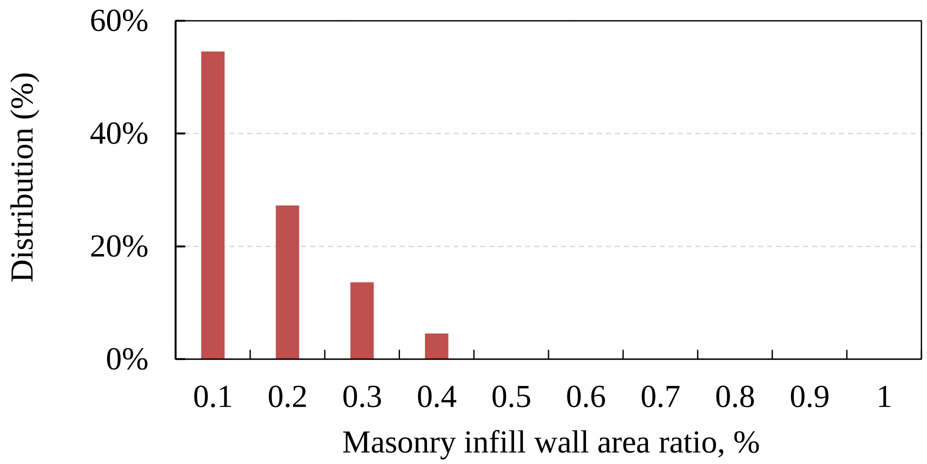


Figure 6.19 Distribution according to masonry wall area ratio (%)

6.6 Investigation of seismic capacity of the surveyed buildings

In this study, detail seismic evaluation has been done for all investigated buildings located in Bangladesh. Detail seismic evaluation has been done for all surveyed buildings. Two level evaluation has been done for detail evaluation such as first level evaluation and second level evaluation. In this regard, detail evaluation has been conducted using Japanese seismic evaluation standard (JBDPA, 2001) and CNCRP seismic evaluation standard (CNCRP, 2015) considering masonry infill proposed by Al-Washali (2018). The following section describes in detail seismic evaluation procedure. In this study, seismic evaluation is performed at ground floor.

6.6.1 First level evaluation procedure

In this study, first level evaluation is based using the JBDPA standard. However, JBDPA does not consider the effect of masonry infill. Therefore, the effect of masonry infill is considered along with Japanese seismic evaluation.

6.6.1.1 Methodology

The seismic index of structure, I_s in first level evaluation procedure is expressed by

$$I_s = E_0 . S_D . T \quad (6.1)$$

Where, E_0= Basic seismic index of structure = φ. C. F

C = Strength Index (See Figure 6.20)

F = Ductility Index,

S_D = Irregularity index,

T = Time index,

Φ= story-shear modification factor=$\frac{n+1}{n+i}$

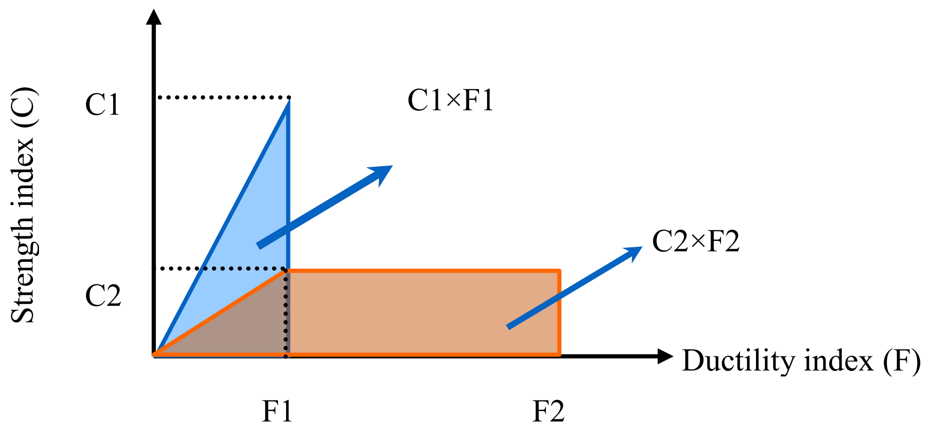


Figure 6.20 Force and displacement relationship

Strength Index (C) is based on strength index of RC column (Cc), masonry infill (C_{inf}) and RC wall (C_{cw}).

Strength Index for RC column (C_c):

$$Column\ (C_c) = \tau_c .\ \frac{A_c}{A_f . w}$$

Strength Index for masonry infill (C_{inf}):

$$Masonry\ infill\ wall\ \left(C_{inf}\right) = \tau_{inf} . \frac{A_{inf}}{A_f . w}$$

Strength Index for RC wall (C_{cw}):

$$RC\ wall\ (C_{cw}) = \tau_{cw} .\ \frac{A_{cw}}{A_f . w}$$

In the above Equation,

A_c, A_{inf} and A_{cw} are the cross-sectional area of RC column, masonry infill and RC wall, respectively.

τ_c, τ_{inf} and τ_{cw} are the average shear stress of RC column, masonry infill and RC wall, respectively.

A_f is total floor area of the structure.

w is unit weight of building.

6.6.1.1 Basic assumptions

The basic assumption has been taken as mentioned in Japanese seismic evaluation standard (JBDPA 2001). These are as follows:

***For RC column**,*

Average Shear Stress at the ultimate state of columns,

$$\tau_c = 1.0\ Mpa, in\ case\ of\ \frac{h_0}{D} \leq 6$$
$$= 0.7\ Mpa, in\ case\ of\ \frac{h_0}{D} > 6$$

Where, h_0 is the clear height of RC column and D is the column dimension in the direction of evaluation.

For RC shear wall,

Average shear stress at ultimate state of RC wall

$$\tau_{cw} = 1.0\ MPa\ without\ boundary\ column$$

$$\tau_{cw} = 2.0\ MPa\ with\ one\ boundary\ column$$

$$\tau_{cw} = 3.0\ MPa\ with\ two\ boundary\ column$$

For masonry infill,

Average shear stress for masonry infill, τ_{inf}, is also considered as of 0.2 MPa which is similar values as considered in the previous chapter.

Unit weight of building is also assumed as of 11.2kN/m^2

α=Strength modification factor=1

6.6.1.2 Result and discussion

Seismic index (I_S) of first level evaluation has been calculated following the aforementioned procedure for all buildings. Frist of all, strength index for RC column, RC wall and masonry infill has been calculated as shown in Table 6.6. Although all the surveyed buildings are masonry infill, a few of them contain RC wall due to structural design purpose.

Figure 6.21 showing the seismic index (I_S) for all investigated buildings considering masonry infills. It has been observed that the lower value is of 0.10 and higher values is about 0.65. It should be noted that the values of seismic index are lower in x-direction compared with seismic index of y-direction. The reason is that most of columns orientation long side in y-direction because of architectural requirement. However, the quantity masonry infill walls are also higher in y-direction compared with x-direction.

Table 6.6 Strength index of RC column, masonry infill and RC wall for first level evaluation

Building ID	Strength index of RC column, C_C		Strength index of masonry infill, C_{inf}		Strength index of concrete wall, C_{CW}	
	x-direction	y-direction	x-direction	y-direction	x-direction	y-direction
Bldg # 1	0.43	0.56	0.04	0.11	-	-
Bldg # 2	0.07	0.08	0.07	0.03	-	-
Bldg # 3	0.17	0.19	0.03	0.08	-	-
Bldg # 5	0.23	0.33	0.00	0.11	-	-
Bldg # 6	0.28	0.30	0.03	0.03	-	-
Bldg # 7	0.31	0.43	0.18	0.21	-	-
Bldg # 8	0.21	0.21	0.04	0.05	-	-
Bldg # 9	0.31	0.41	0.01	0.07	-	-
Bldg # 10	0.24	0.24	0.03	0.01	-	-
Bldg # 11	0.19	0.17	0.02	0.01	0.16	0.22
Bldg #12	0.14	0.20	0.06	0.07	-	-
Bldg #13	0.45	0.55	0.05	0.18	-	-
Bldg #14	0.22	0.22	0.05	0.14	-	-
Bldg #15	0.31	0.44	0.00	0.05	-	-
Bldg #16	0.19	0.25	0.01	0.11	-	-
Bldg #17A	0.26	0.17	0.01	0.05	-	-
Bldg #17B	0.25	0.15	0.06	0.07	-	-
Bldg #18A	0.19	0.22	0.00	0.05	-	-
Bldg #18B	0.18	0.21	0.00	0.03	0.00	0.03
Bldg #19	0.18	0.18	0.03	0.05		
Bldg #20	0.19	0.15	0.01	0.02	0.06	0.12
Bldg #21	0.19	0.19	0.00	0.00	0.02	0.03

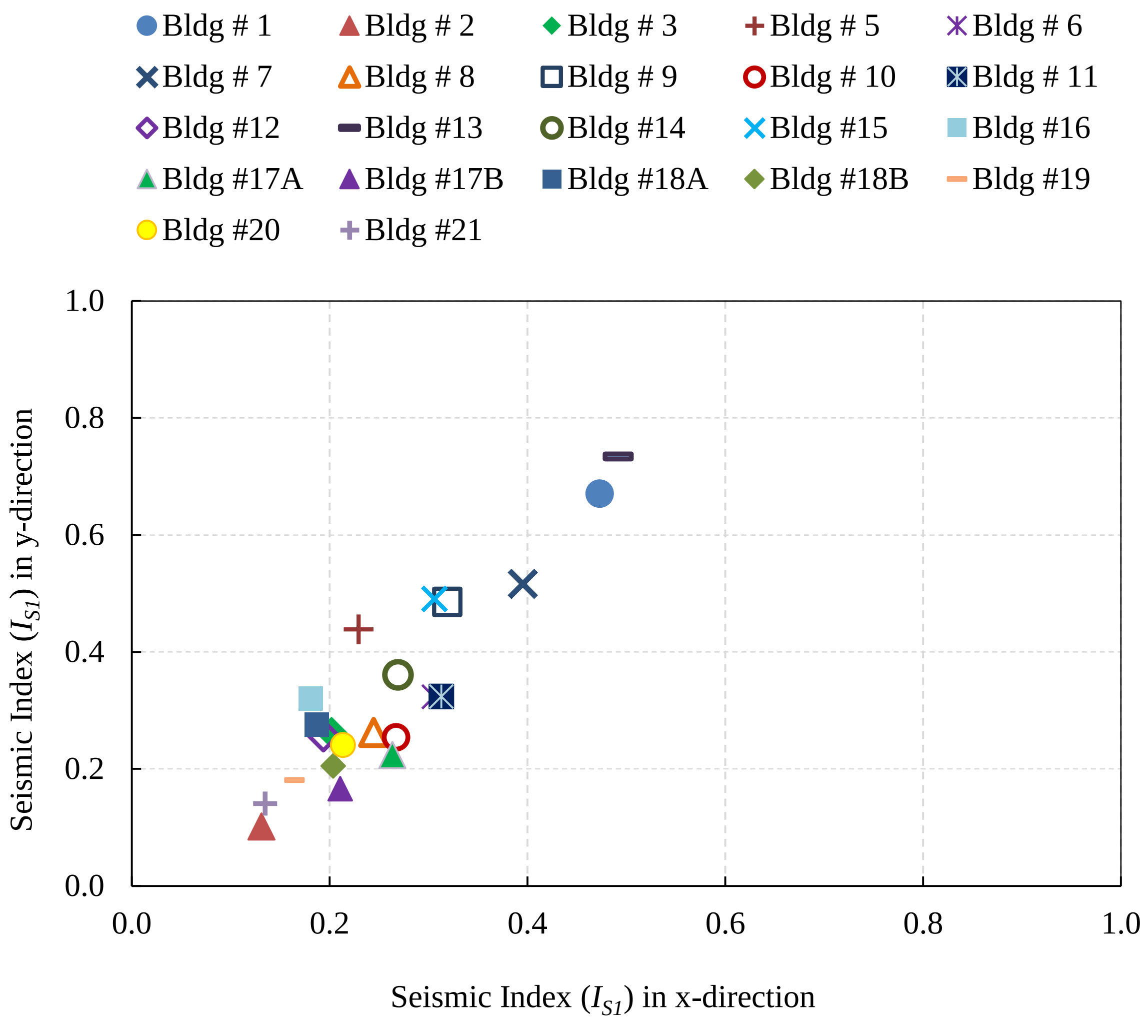


Figure 6.21 Seismic index (I_{S1}) of investigated buildings in x and y direction

6.6.2 An overview of second level evaluation

Second level evaluation has been performed as per seismic evaluation guideline proposed by CNCRP seismic evaluation manual (CNCRP, 2015), which has already adopted in Bangladesh. As previously mentioned, CNCRP seismic evaluation manual is based on JBDPA standard which does not consider the effect of masonry infill. Therefore, this study follows seismic evaluation guideline proposed by CNCRP manual for bare frame and the evaluation of the effect of masonry infill proposed by Al-Washali, 2018.

6.6.2.1 Methodology

For second level evaluation, the seismic index (I_{S2}) is also expressed using the Equation (6.1). Where, E_o is the basic seismic index is based on strength index (C) and ductility index (F).

Basic seismic index (E_0) has been calculated following the Equation (6.2) (in JBDPA standard the Equation 4) for ductility-dominant structure and Equation (6.3) (in JBDPA standard the Equation 5) for strength dominant structures. The details information about ductility-dominant and strength-dominant are referred in CNCRP manual (CNCRP, 2015). It should be noted that these Equations

The basic seismic index, E_0, for ductility-dominant structures is as follows:

$$E_0 = \frac{n+1}{n+i}\sqrt{(C_1.F_1)^2 + (C_2.F_2)^2 + (C_3.F_3)^2} \tag{6.2}$$

Where, C_1, C_2 and C_3 are the strength index of the first group, second group and third group respectively. F_1, F_2 and F_3 are the ductility index of the first group, second group and third group respectively.

The basic seismic index, E_0, for strength-dominant structures is as follows:

$$E_0 = \frac{n+1}{n+i}\left(C_1 + \sum \alpha_j.C_j\right).F_1 \tag{6.3}$$

Where, C_1 is the strength index of the first group and F_1 is the ductility index of the first group. α_j is the effective strength modification factor in the *j*-th group to reduce the strength of each member at failure state. α index has been calculated at the ultimate deformation R_1 corresponding to the first group (ductility index - F_1) as shown in seismic evaluation standard.

The basic concept for determining basic seismic index (E_0) has been described in the Figure 6.22. It has been observed that the members are divided into three groups according to ductility index (F), which are described as extremely brittle members, brittle members and ductile members.

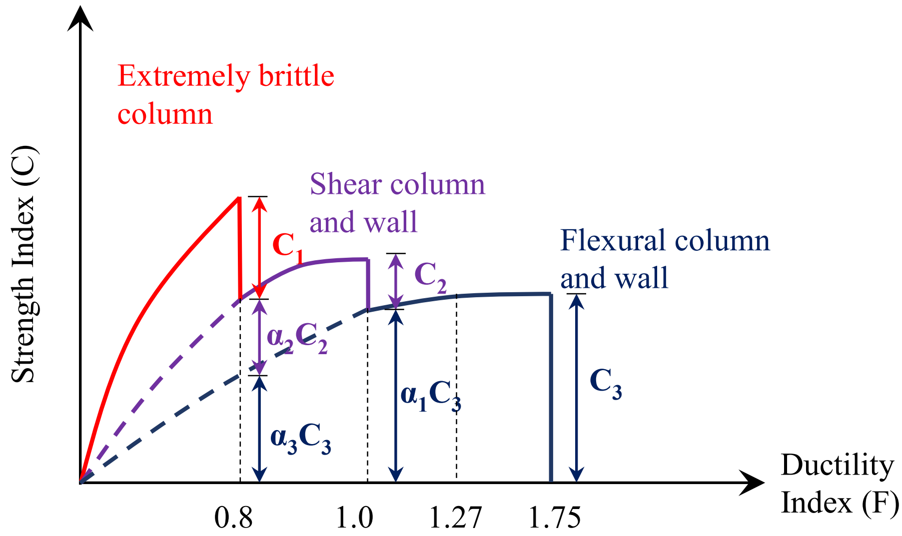


Figure 6.22 Illustration of the force-deformation relationship of three member's system

However, C index and F index are calculated based on detail information such as dimension, reinforcement detail and material properties of the investigated structure. The following sections describe the procedure for calculation of C and F index of the building to be evaluated.

6.6.2.2 Strength index (C)

Strength index (C) for RC column and RC wall is considered as per on the seismic evaluation manual in CNCRP standard. In this study, the strength index for RC column and RC wall is adopted from CNCRP standard. The calculation procedure for strength index describes as follows:

Strength index (C) in the second level procedure is calculated as per CNCRP standard (CNCRP, 2015) as expressed as Equation (6.4) as follows:

$$C = \frac{Q_u}{\sum W} \tag{6.4}$$

where: Q_u is the ultimate lateral load-carrying capacity of the vertical elements in the story to be evaluated.

ΣW = The total building weight which includes dead load and live load supported by the story concerned.

Strength index for masonry infill (C_{inf}):

The calculation procedure of strength index (C_{inf}) is followed the proposed evaluation procedure by Al-washali (2018). The proposed method considers the strength index is calculated separately for RC frame and masonry infill surrounded by RC frame as shown in Figure 6.23.

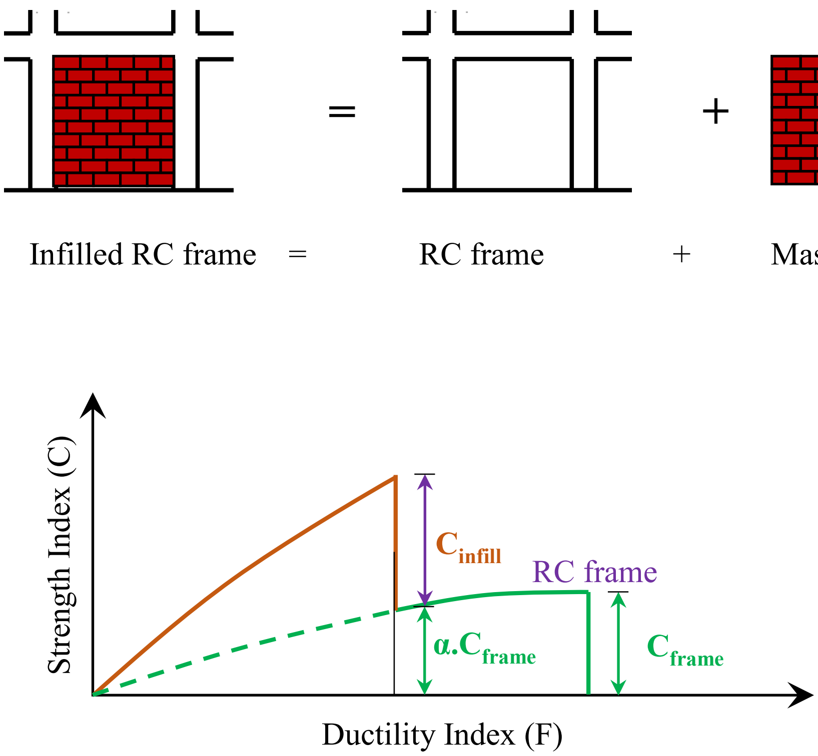


Figure 6.23 The basic idea for determining strength index of masonry infill

The strength index (C) is calculated using Equation (6.5) as follows:

$$C_{inf} = \frac{Q_u}{\sum W} = \frac{V_{inf}}{\sum W} \tag{6.5}$$

Where, $$V_{inf} = 0.04\, f_m . t_{inf} . l_{inf} . \gamma \tag{6.6}$$

f_m= masonry prism strength (9 *MPa* considered in this study)

t_{inf}= Thickness of masonry infill, mm

l_{inf}= Length of masonry infill, mm

γ= Confinement effect of masonry infill surrounded by RC frame which is based on proportion of lateral strength between RC frame and masonry infill.

Masonry infill with opening:

Opening in masonry infill is very common due to window and doors. In case of opening, the strength index is reduced by strength reduction factor. In this regard, the strength index is calculated by the following Equation (6.7).

Where, $$V_{inf} = 0.04\, f_m . t_{inf} . l_{inf} . \lambda_{op} \quad (6.7)$$

Where, λ_{op} is the strength reduction factor due to openings introduced Dawe and Seah (1988). It should be noted that the opening exceeding 40% of the panel area is not considered in the evaluation. λ_{op} is estimated is estimated using the following Equation (6.8) as follows:

$$\lambda_{op} = 1 - \frac{1.5 l_o}{l_{inf}}; \qquad \lambda_{op} \geq 0 \quad (6.8)$$

In case opening the following criteria is considered as shown in Figure 6.24.

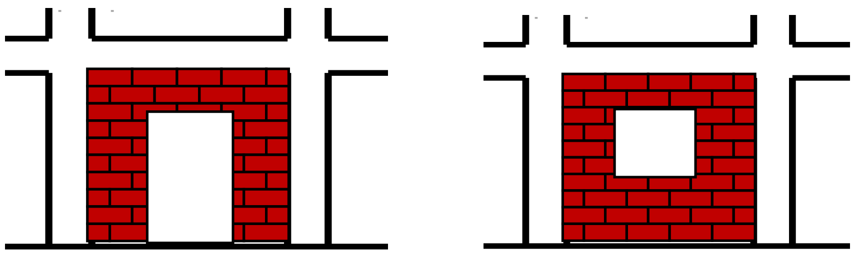


Figure 6.24 Opening in due to window and door in masonry infill.

6.6.2.3 Ductility index (F)

Ductility index (F) for RC column and wall is based on failure mode and deformation capacity at ultimate capacity. Ductility index is calculated by following the procedure as discussed in CNCRP seismic evaluation manual (CNCRP, 2015). First of all, ductility index (F) of each member is determined considering bare frame following the evaluation manual (CNCRP 2015). It should be noted that, the CNCRP standard (CNCRP, 2015) considers the maximum ductility index (F) at ultimate deformation is of 1/100 for ductile members.

As discussed in previous section, ductility index (F) is estimated following the evaluation procedure proposed by Al-washali (2018). In the proposed method, ductility index is based on the failure pattern of surrounding frame and strength proportion between masonry infill and surrounding frame. For non-ductile RC frame, ductility index of masonry infill is considered as Unity (F=1).

In case of masonry infill surrounded by ductile RC frame, ductility index of masonry infill (F) is depending on proportion of lateral strength of RC frame and masonry infill which is described as β index. The infill is classified into three cases as strong infill, weak infill and in between strong and weak infill. In case of opening in masonry infill, ductility Index (F) is considered as unity for conservative estimation. Table 6.7 shows summery of the proposed procedure for calculation of ductility index (F) of masonry infill.

Table 6.7 The proposed F-index calculation for masonry infill (Al-washali, 2018)

<table>
<tr><td></td><td>Strong infill</td><td>Transition area</td><td>Weak infill</td></tr>
<tr><td></td><td>$\beta<0.7$</td><td>$0.7<\beta<1.3$</td><td>$\beta>1.3$</td></tr>
<tr><td>Non-Ductile Column</td><td colspan="3">$F_{masonry}=1$</td></tr>
<tr><td rowspan="2">Ductile Column</td><td rowspan="2">$F_{masonry}=1$ and F_{column} should be revaluated (*1)</td><td>Case 1: $M_u>M_d$, minimum of:
$F_{masonry}$=1~1.75 based on β index,
F_{column} should be revaluated (*2)</td><td rowspan="2">$F_{masonry}$ minimum of:
(a) F=1.75,
(b) F_{column} should be revaluated *2)</td></tr>
<tr><td>Case 2: $M_u<M_d$:
$F_{masonry}=1$,
F_{column} should be revaluated (*1)</td></tr>
<tr><td colspan="4">M_d is the moment demand by exerted masonry infill forces,</td></tr>
<tr><td colspan="4">(*1) F_{column} should be calculated with $0.5h_0$,</td></tr>
<tr><td colspan="4">(*2) F_{column} should be calculated with $0.7h_0$</td></tr>
</table>

Since masonry infill is surrounded by RC frame, the ductility index of RC column should be reevaluated as mentioned in the Table 6.18. It should be noted that the reevaluated ductility index (F) of RC column should be considered for estimation of seismic index. In addition, the strength index (C) should be taken considering full height of RC column.

C-index and F-index have been estimated following the aforementioned procedure. Seismic index (I_s) has been calculated for all investigated buildings and are discussed in the following sections.

6.6.2.4 Application of second level evaluation

Detail evaluation has been performed as per the aforementioned procedure for second level evaluation. For material properties such as concrete strength, tensile strength of main and transverse reinforcement is found from design datasheet. However, reinforcement detail for main and transverse reinforcement have been found from the design datasheet. The masonry prism strength is considered as 9 MPa in absence of field data for conservative estimation (Al-washali, 2018).

An example of detail seismic evaluation has been described in following section. In this regard, buildings number 3 has been selected which is a 6 storied residential building as mentioned as staff quarter of medical college located at Dhaka. A general view is showing in Figure 6.25 describing outline of the building.

Figure 6.26 and Figure 6.27 showing the floor plan of first and second floor plan showing the location of column and masonry infill. The total floor area of the investigated buildings is about 174 m^2.

6.25 General view of the surveyed building no 3

Table 6.8 to Table 6.11 is showing the general information of the surveyed buildings. Figure 6.27 to 6.32 shows the elevation of the surveyed buildings. Location of doors and windows are shown in the Figures. However, the floor height is found as 3000mm. Figure 6.33 and 6.34 shows the dimension and reinforcement detail of column and beams of the investigated buildings.

Table 6.8 General information

Item	
Location	Dhaka
Structure type	RC with masonry infill
Year of construction	2008
Number of story	6
Soil type	SD type
Foundation type	Pile foundation
Floor area	174 m^2

Table 6.9 Material properties

Material	Material strength (MPa)
Concrete strength	25
Yield strength of reinforcement	400

Table 6.10 Column dimension

Legend for column	Dimension
Column (C1)	250X350
Column (C2)	250X400
Column (C3)	250X500

Table 6.11 Information of doors and windows

Legend for window and door	Dimension (mm)
Window (W1)	1530X1350
Window (W2)	1250X 1350
Window (W3)	1000X1350
High window (HW)	700X500
Door (D1)	770X500
Door (D2)	1000X2100

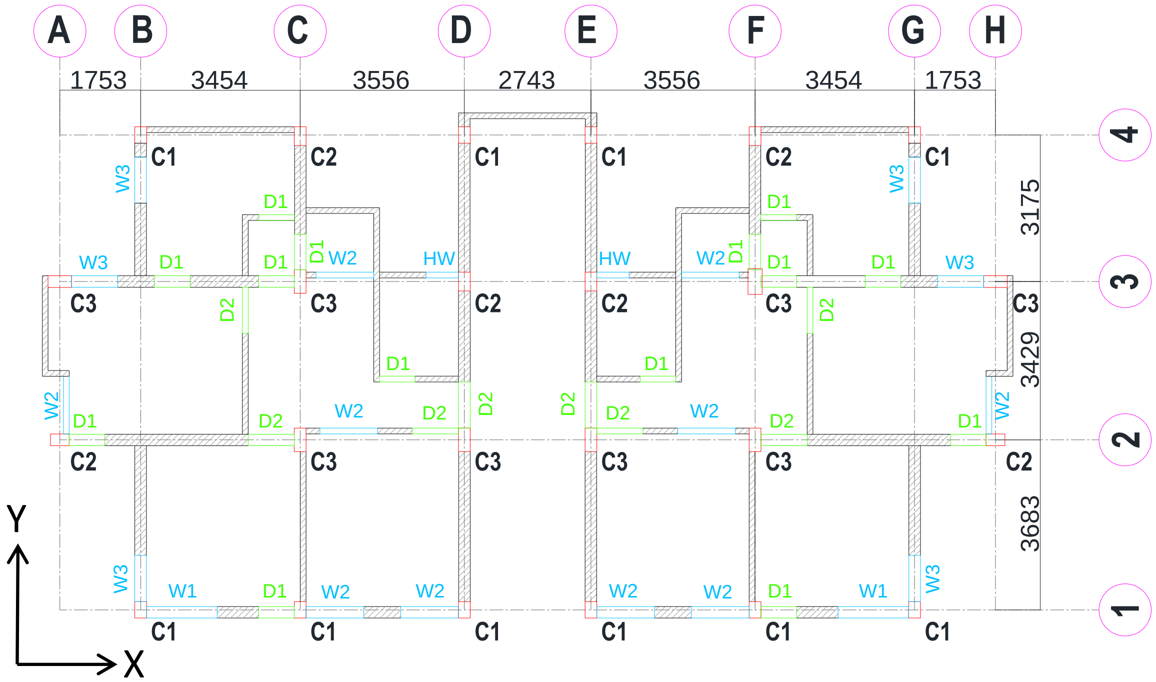


Figure: 6.25 Ground floor plan of building no. 3

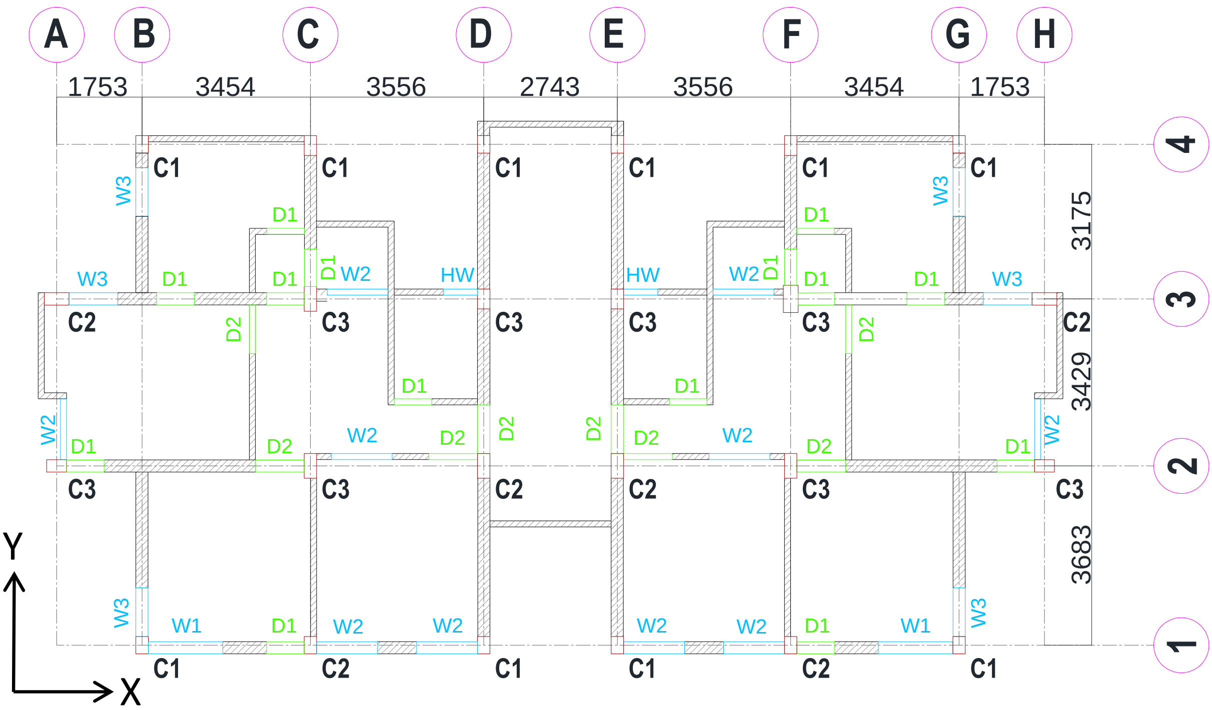


Figure: 6.26 Typical floor plan of building no. 3

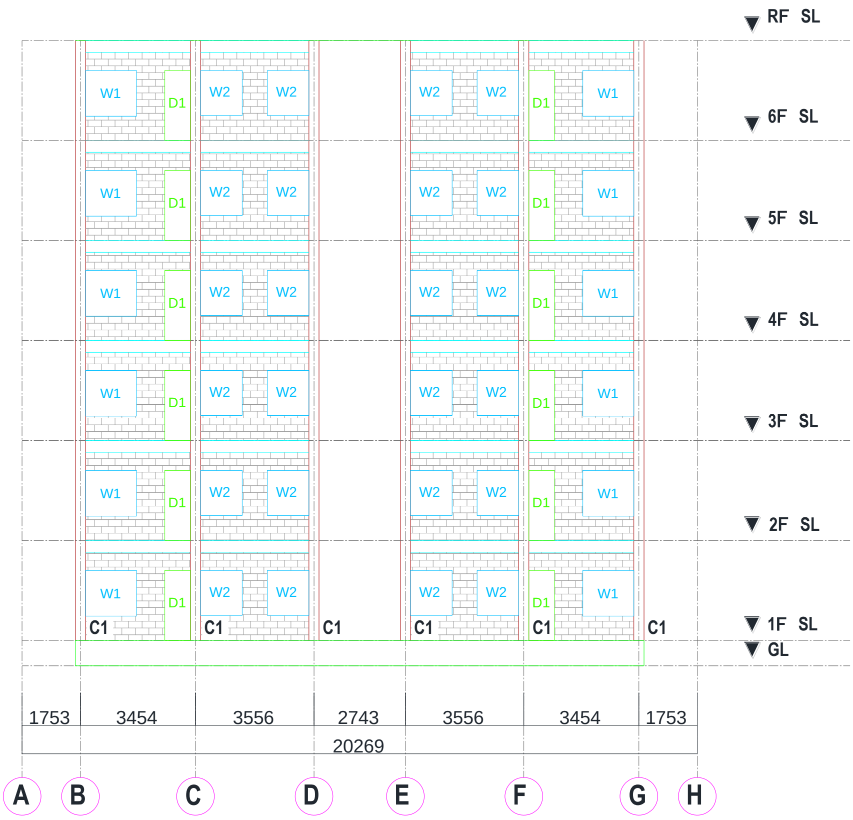


Figure: 6.27 Elevation at Frame 1 of building no. 3

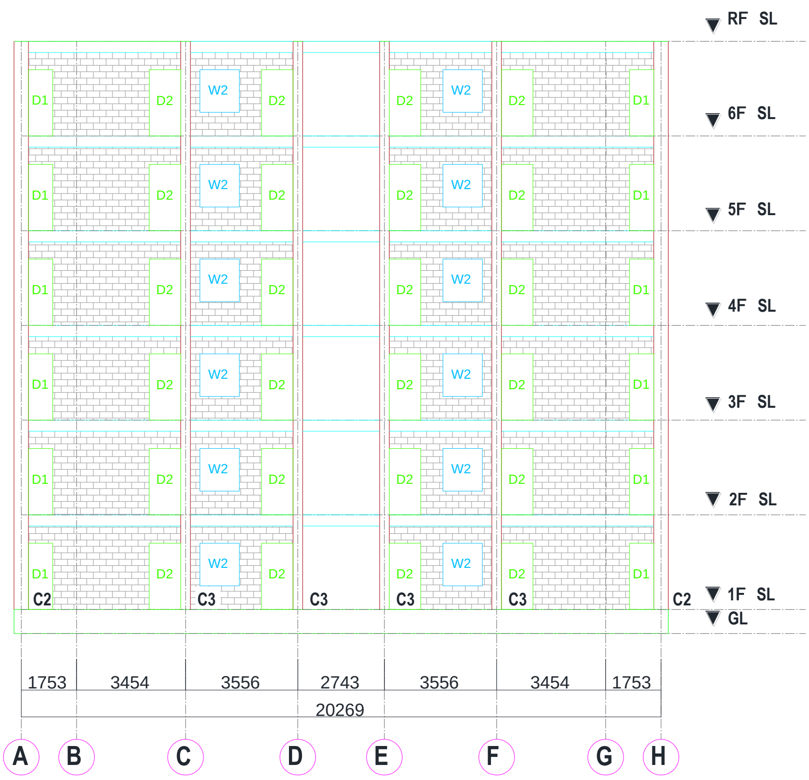


Figure: 6.28 Elevation at Frame 2 of building no. 3

Figure: 6.29 Elevation at Frame 3 of building no. 3

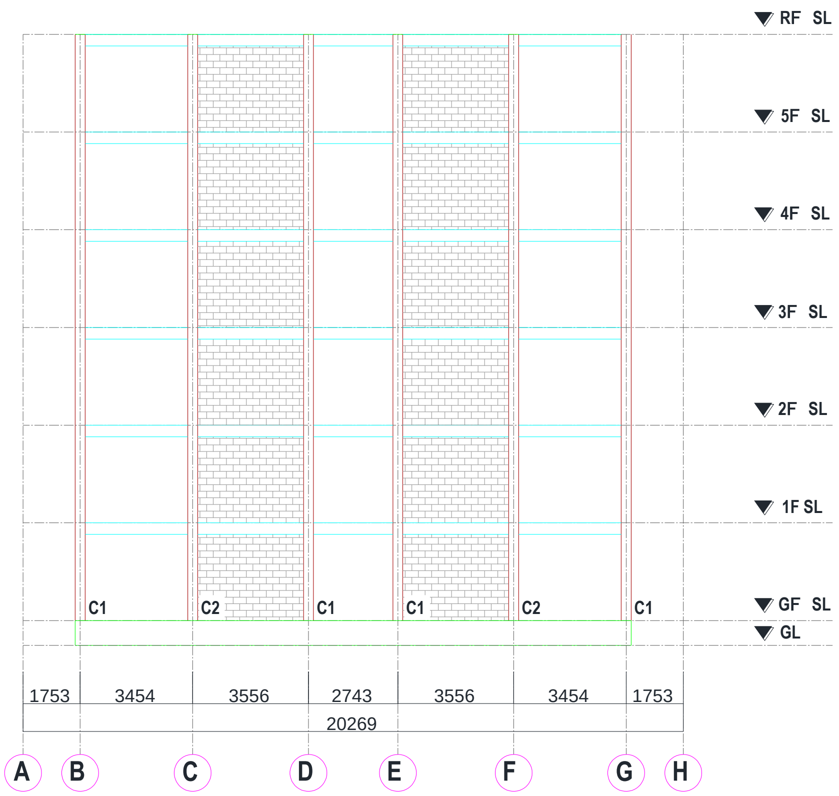


Figure: 6.30 Elevation at Frame 4 of building no. 3

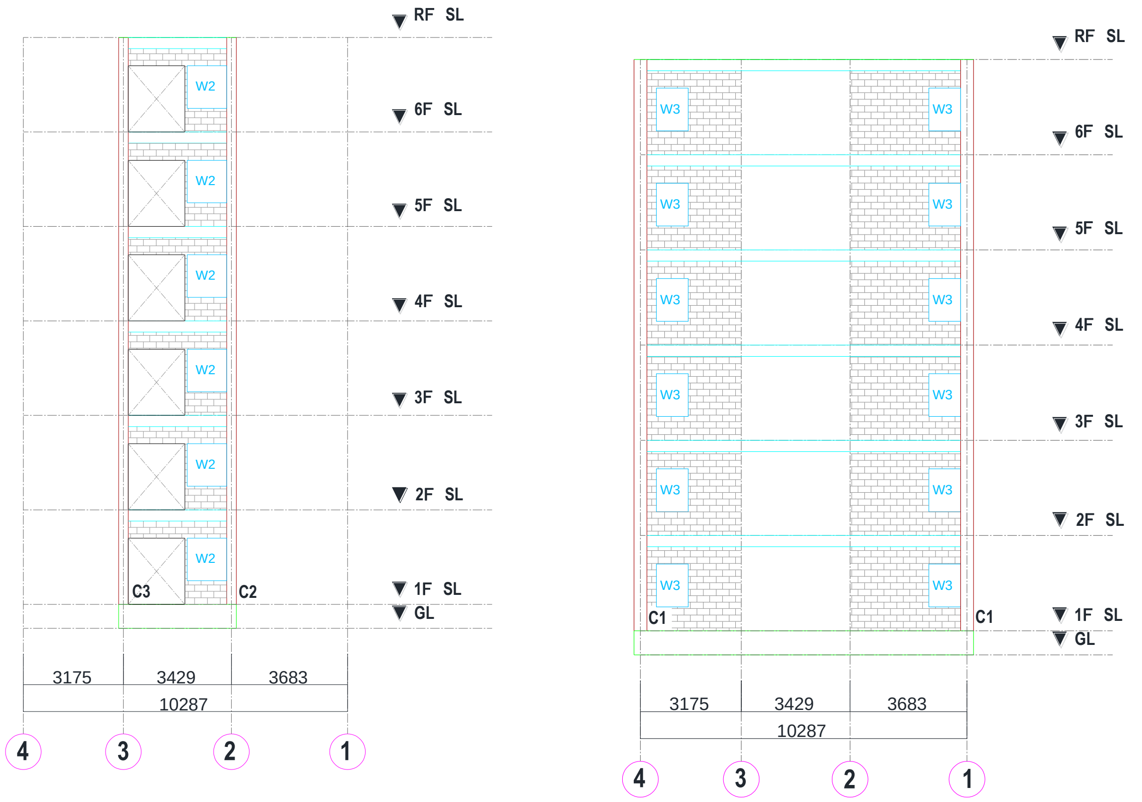


Figure: 6.31 Elevation at Frame A and H, B and G of building no. 3

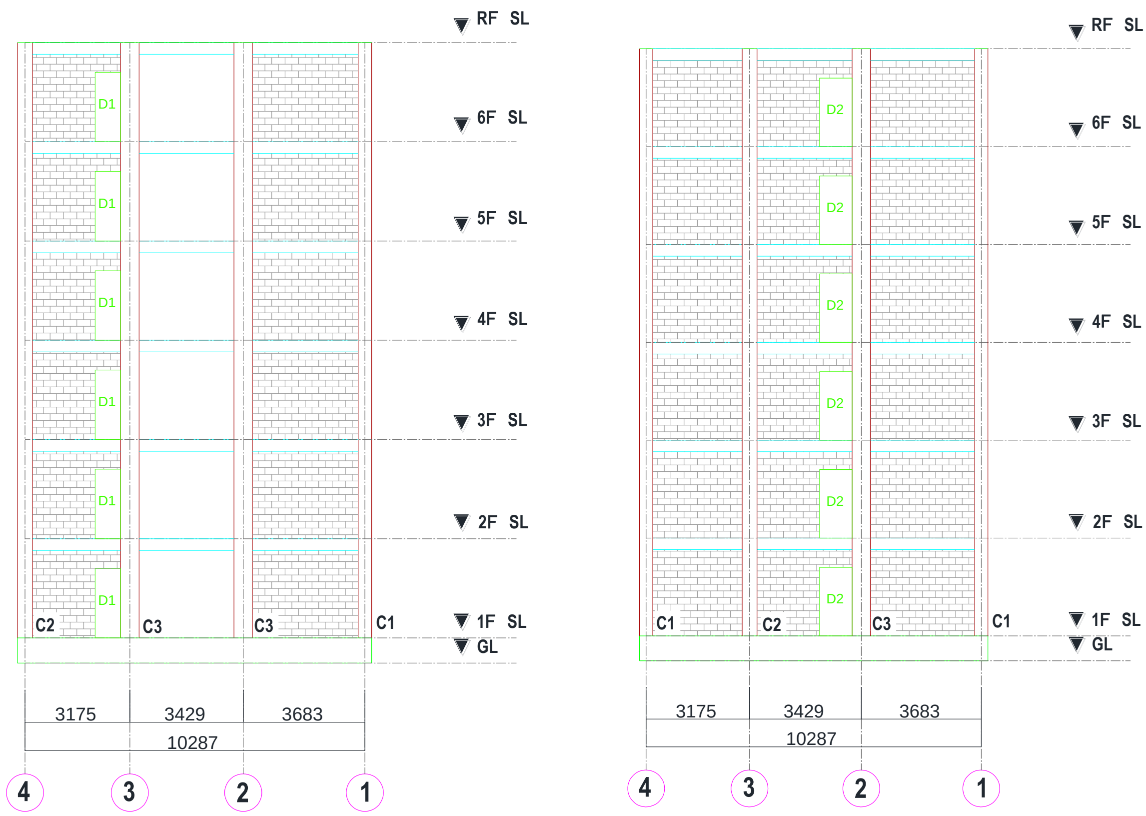
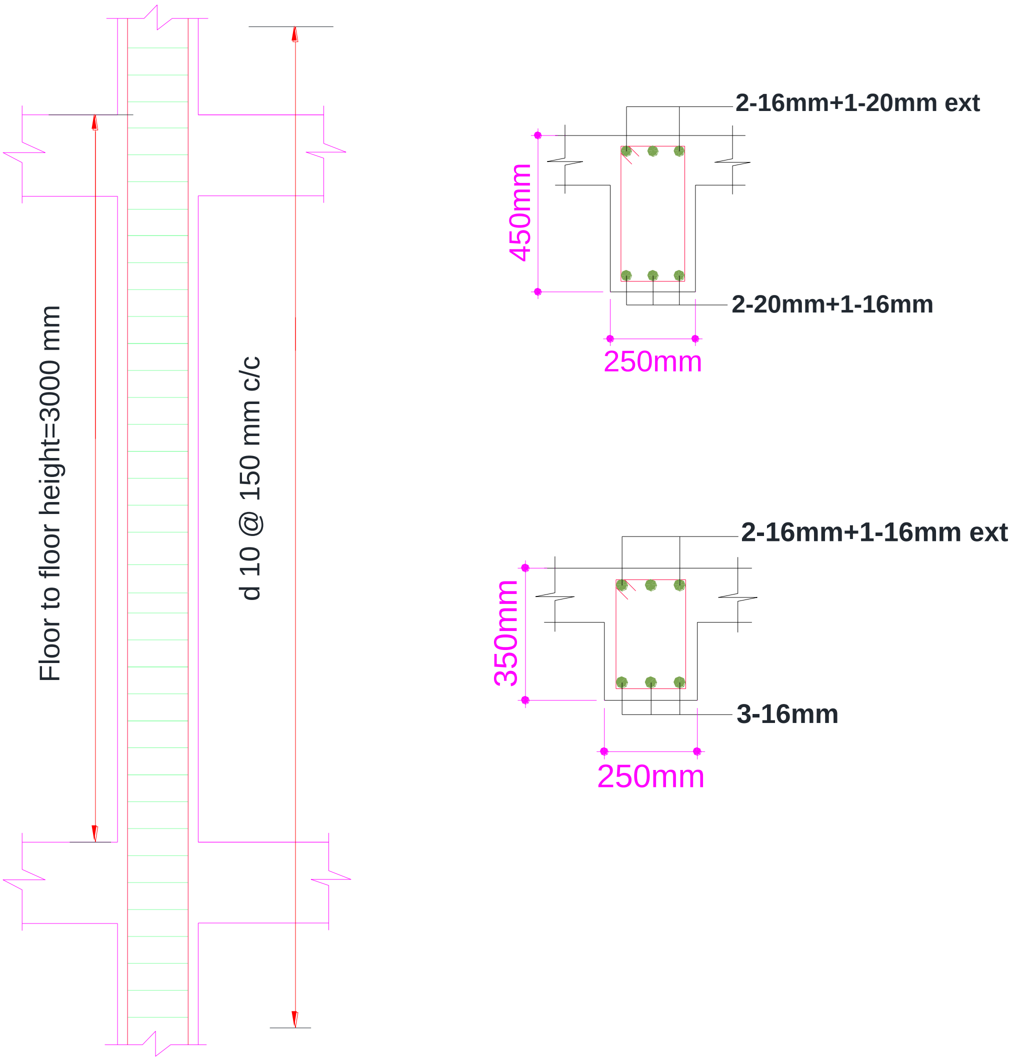


Figure: 6.32 Elevation at Frame C and F, D and E of building no. 3

COLUMN SCHEDULE :

	COLUMN REINFORCEMENT			
COLUMN MARK	BELOW GB	UPTO 2ND FLOOR	UPTO 4TH FLOOR	UPTO ROOF LEVEL
C1	400 mm 300mm 6-20mm Ø	350mm 250mm 6-20mm Ø	350mm 250mm 4-20mm Ø+ 2-16mm Ø	350mm 250mm 6-16mm Ø
C2	450 mm 300 mm 4-20mm Ø+ 6-16mm Ø	400 mm 250 mm 4-20mm Ø+ 6-16mm Ø	400 mm 250 mm 10-16mm Ø	400 mm 250 mm 10-16mm Ø
C3	550 mm 300 mm 10-20mm Ø	500mm 250mm 10-20mm Ø	500mm 250mm 4-20mm Ø+ 6-16mm Ø	500mm 250mm 10-16mm Ø

Figure 6.33 Column schedule of the building no 3



6.34 Typical section and rebar detail of beam and column

Detail evaluation i.e. second level evaluation has been done for the surveyed buildings using aforementioned information. The seismic evaluation is performed for both x and y direction (longitudinal direction and transverse direction). However, the detail evaluation procedure is described from Table 6.12 to Table 6.17 in x-direction and from Table 6.18 to Table 6.23 in y-direction. (For results and drawing other RC buildings, please see Appendix B, C)

Table 6.12 F-index of RC column in x-direction

Column Id	No of column	Tributed Area (m^2)	b (mm)	D (mm)	N (kN)	M_u (kN.m)	Qu (kN)	F-index
C1(1)	2	2.55	350	250	171.4	95	72	1.75
C1(1)	2	2.55	350	250	171.4	95	72	1.75
C1(2)	6	6.13	350	250	411.9	117	89	1.75
C2(1)	2	5.11	400	250	343.4	119	91	1.75
C2(2)	2	7.80	250	400	524.2	189	144	1.75
C2(3)	2	10.22	400	250	686.8	145	110	1.75
C3(1)	4	11.24	500	250	755.3	172	131	1.75
C3(2)	2	7.80	250	500	524.2	360	231	1.12
C3(3)	2	10.22	500	250	686.8	168	128	1.75

Table 6.13 C-index of RC column in x-direction

Column Id	Q (kN)	cQsu/c Qmu	Σw (kN)	Total buildign weight (kN)	C-index
C1(1)	72.49	1.805	342.7	11709	0.0124
C1(1)	72.49	1.805	342.7		0.0124
C1(2)	89.29	1.681	2471.6		0.0458
C2(1)	91.02	2.029	686.8		0.0155
C2(2)	144.01	1.291	1048.3		0.0246
C2(3)	110.25	1.925	1373.6		0.0188
C3(1)	131.14	1.857	3021.3		0.0448
C3(2)	231.06	0.841	1048.3		0.0395
C3(3)	127.63	1.866	1373.6		0.0218

Table 6.14 C-index and F-index of Masonry infill in x-direction

Wall Id	V_{frame} (kN)	Mu (kN-m)	No of infill wall	Length (mm)	Thickness (mm)	V_{inf} expected of wall (kN)	β-index	Vinf (recalculated) (kN)	C-index of masonry infill	M_{demand} (kN-m)	F-index
W1	72	95	2	3454	250	345.40	0.210	276	0.047	186.41	1

Table 6.15 C-index and F-index of Masonry infill in x-direction

Member Id	C-index	F-index
C1(1)	0.012	1.75
C1(1)	0.012	1.00
C1(2)	0.046	1.75
C2(1)	0.016	1.00
C2(2)	0.025	1.75
C2(3)	0.019	1.75
C3(1)	0.045	1.75
C3(2)	0.039	1.12
C3(3)	0.022	1.75
W1	0.047	1.00

Table 6.16 Basic seismic index (E_0) using equation 6.2 in x-direction

<table>
<tr><th>C-index</th><th>F-index</th><th>Eq.4</th></tr>
<tr><td>0.075</td><td>1.00</td><td rowspan="3">0.31</td></tr>
<tr><td>0.039</td><td>1.12</td></tr>
<tr><td>0.168</td><td>1.75</td></tr>
</table>

Table 6.17 Basic seismic index (E_0) using equation 6.3 in x-direction

<table>
<tr><th>C-index</th><th>F-index</th><th>Eq.4</th><th>E_0</th></tr>
<tr><td>0.23</td><td>1.00</td><td>0.23</td><td rowspan="3">0.27</td></tr>
<tr><td>0.17</td><td>1.12</td><td>0.19</td></tr>
<tr><td>0.16</td><td>1.75</td><td>0.27</td></tr>
</table>

Table 6.18 F-index of RC column in y-direction

Column Id	No of column	Tributed Area (m^2)	b (mm)	D (mm)	N (kN)	M_u (kN.m)	Qu (kN)	F-index (assuming bare frame)
C1(1)	4	2.55	250	350	171.4	98	75	1.75
C1(2)	2	6.13	250	350	411.9	129	98	1.75
C1(2)	2	6.13	250	350	411.9	129	98	1.75
C1(2)	2	6.13	250	350	411.9	129	98	1.75
C2(1)	2	5.11	250	400	343.4	165	107	1.13
C2(2)	2	7.80	400	250	524.2	134	102	1.75
C2(3)	2	10.22	250	400	686.8	206	124	1.07
C3(1)	2	11.24	250	500	755.3	395	124	1.00
C3(1)	2	11.24	250	500	755.3	395	124	1.00
C3(2)	2	7.80	500	250	524.2	155	118	1.75
C3(3)	2	10.22	250	500	686.8	385	121	1.00

Table 6.19 C-index of RC column in y-direction

Column Id	Q (kN)	cQsu/cQmu	Σw (kN)	Total buildign weight (kN)	C-index
C1(1)	75	1.321	685.4	11709	0.0255
C1(2)	98	1.145	823.9		0.0168
C1(2)	98	1.145	823.9		0.0168
C1(2)	98	1.145	823.9		0.0168
C2(1)	107	0.850	686.8		0.0183
C2(2)	102	3.116	1048.3		0.0175
C2(3)	124	0.793	1373.6		0.0212
C3(1)	124	0.412	1510.7		0.0211
C3(1)	124	0.412	1510.7		0.0211
C3(2)	118	3.845	1048.3		0.0202
C3(3)	121	0.412	1373.6		0.0207

Table 6.20 C-index and F-index of Masonry infill in y-direction

Wall Id	V_{frame} (kN)	Mu (kN-m)	No of infill wall	Length (mm)	Thickness (mm)	V_{inf} expected of wall (kN)	β-index	Vinf (recalculated) (kN)	C-index of masonry infill	M_{demand} (kN-m)	F-index
W1	98	129	2	3683	250	368.30	0.267	295	0.050	211.95	1
W2	98	129	2	3683	125	184.15	0.533	147	0.025	105.97	1
W2	98	129	2	3175	250	317.50	0.309	254	0.043	157.51	1

Table 6.21 C-index and F-index of Masonry infill in y-direction

Member Id	C-index	F-index
C1(1)	0.026	1.75
C1(2)	0.050	1.00
C1(2)	0.050	1.00
C1(2)	0.050	1.00
C2(1)	0.019	1.13
C2(2)	0.018	1.75
C2(3)	0.022	1.00
C3(1)	0.043	1.00
C3(1)	0.043	1.00
C3(2)	0.020	1.75
C3(3)	0.021	1.00
W1	0.050	1.00
W2	0.025	1.00
W3	0.043	1.00

Table 6.22 Basic seismic index (E_0) using Equation (6.2) in y-direction

C-index	F-index	Basic seismic index (E_0)
0.40	1.00	0.41
0.02	1.13	
0.06	1.75	

Table 6.23 Basic seismic index (E_0) using Equation (6.3) in y-direction

C- index	F-index	Eq.5	Basic seismic index (E_0)
0.46	1.00	0.46	0.46
0.08	1.13	0.09	
0.06	1.75	0.11	

Figure 6.35 and Figure 6.36 show the strength index (C) and ductility index (F) of the investigated building. It has been observed that the seismic capacity is higher in y-direction compared with x-direction. It indicates the major differences is due to volume of masonry infill. Therefore, these masonry infill increases the lateral strength resulted higher strength index. For

these reason, the seismic index (I_{S2}) increases in y-direction almost double comparing with x-direction. Table 6.24 shows seismic index for the investigated building.

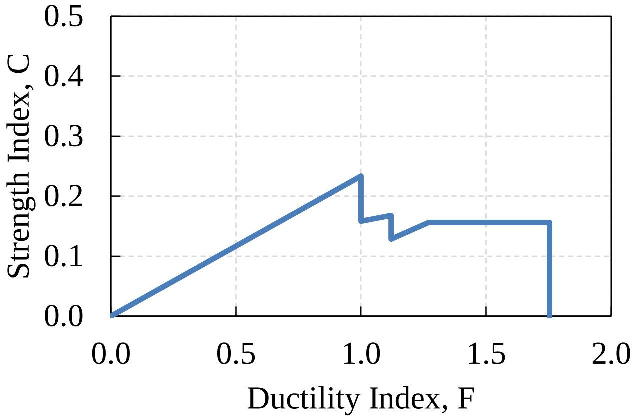


Figure 6.35 C-F relationship for x-direction

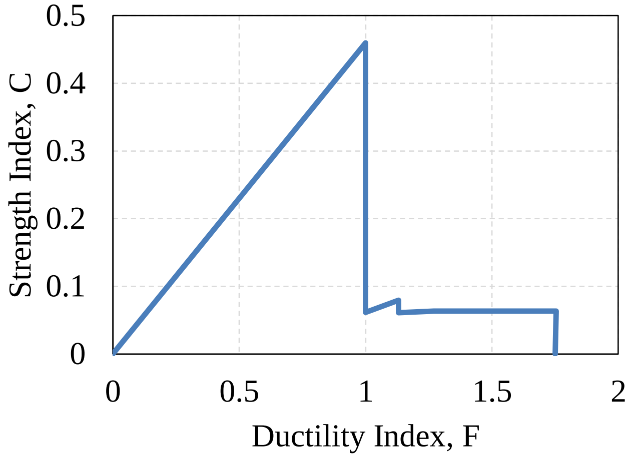


Figure 6.36 C-F relationship for y-direction

Table 6.24 Seismic Index (I_{S2}) for the investigated buildings

Basic seismic index (E_0)		Minimum, E_0	Irregularity index (S_d)	Time Index	Seismic Index (I_{S2})
x-direction	y-direction				
0.31	0.46	0.31	1	1	0.31

Seismic index (I_{S2}) has been calculated for all surveyed building following the similar procedure as mentioned above for both x and y direction. Figure 6.37 shows the estimated seismic index (I_{S2}) for both directions. It has been seen that most of the buildings showing higher values of seismic index. The building with higher values of seismic index (I_{S2}), for example, building no 1 and 7 consist of higher value because of low-rise buildings. From structural drawing, it has been found that the building number 1 has been designed for 6 storied but until 2 storied completed. In case of building number 7 has many masonry infill wall and hence strength index (C) has been increased. On the other hand, building number 2 and 19 shows low values of seismic index. Because, these are very old building. Although column size is larger, seismic index is lower due to low material strength of the buildings.

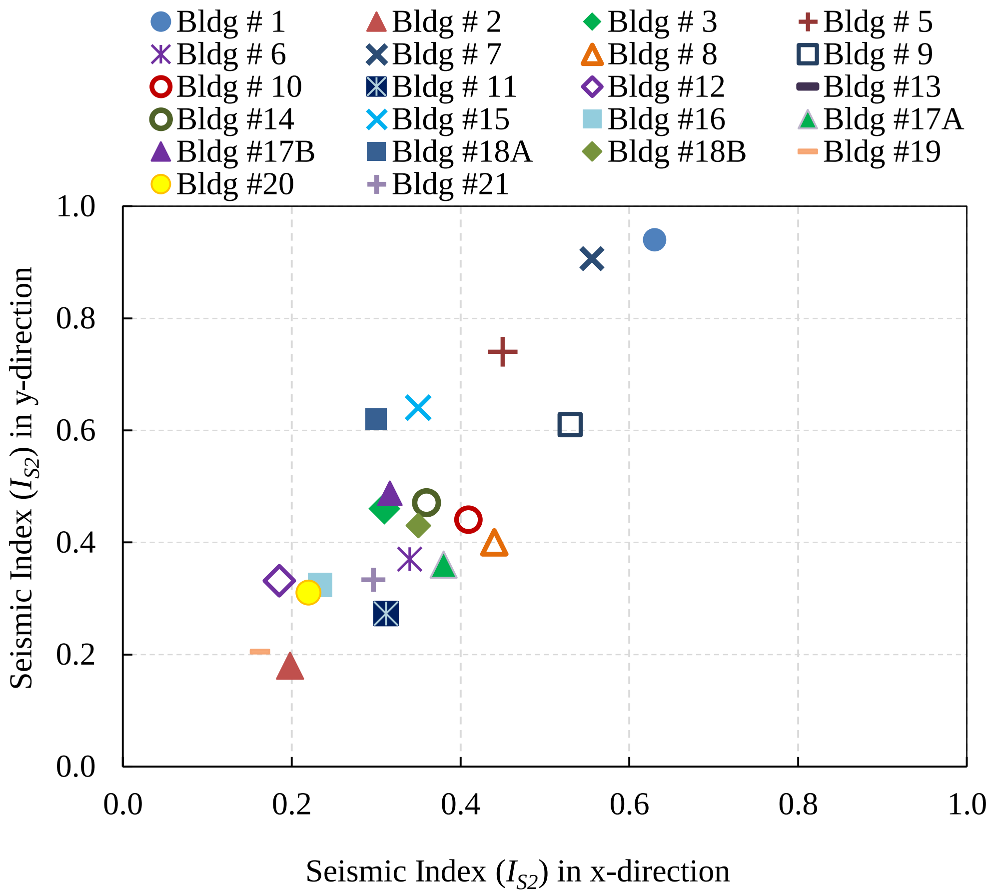


Figure 6.37 Seismic index (I_{S2}) for all investigated buildings

6.7 Comparison of Visual Rating method and detail seismic evaluation

This section presents a comparison between visual rating method with detail evaluation of the investigated buildings. First of all, column area ratio and masonry infill wall area ratio has been calculated and compared with simplified column area ratio and simplified masonry infill wall area ratio. Secondly, the estimated visual rating index has been compared with the results of detail seismic evaluation.

6.7.1 Comparison of actual column area and simplified column area ratio

Simplified column area ratio is compared with actual column area ratio of the investigated buildings. Figure 6.38 shows the comparison between these two parameters. It has been observed that the proposed Visual Rating method provides conservative estimation of column area ratio for all surveyed buildings. In every case, simplified column area ratio shows lower boundary of these buildings. It indicates that the assumed column size is lower than actual average column dimension. In addition, average span length multiplied by number of span length provides lager values of floor area of the buildings. As a result, this method provides lower column area ratio compared with actual column area ratio. However, the normalized actual column area ratio by the simplified column area ratio, the average 1.19 and coefficient of variation 23% shows a good correlation between these parameters.

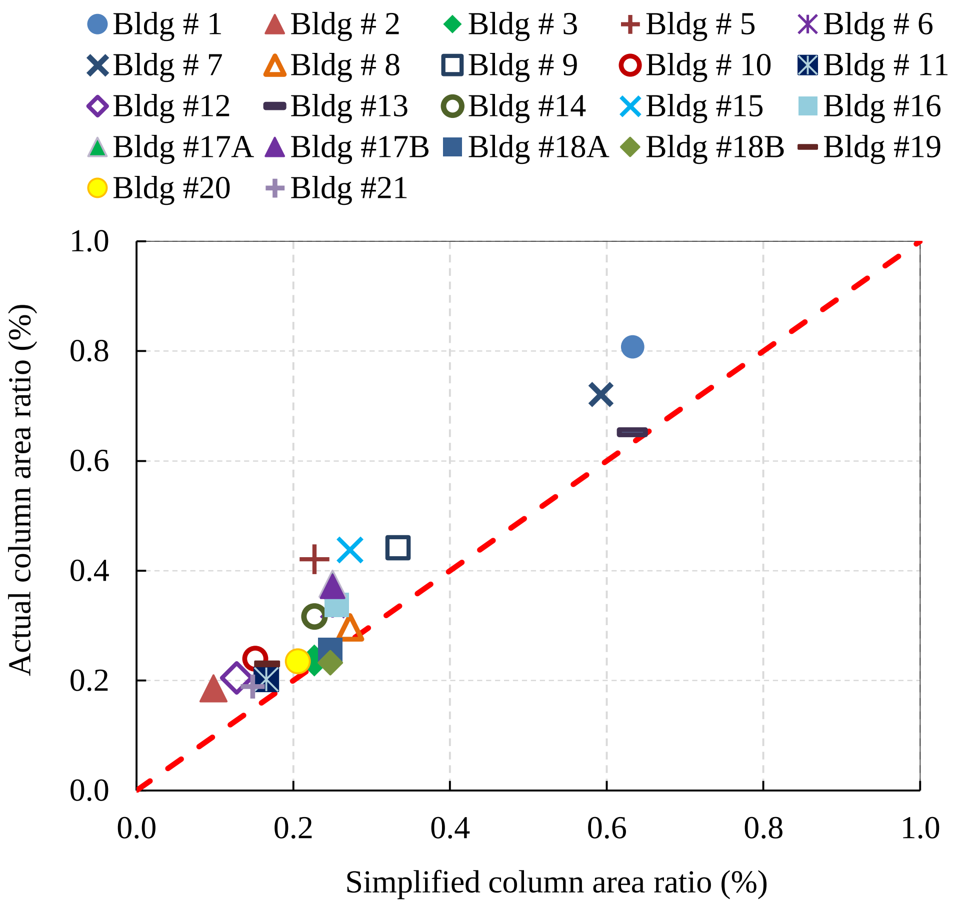


Figure 6.38 Comparison of actual column area ratio and simplified column area ratio

6.7.2 Comparison of actual masonry infill wall area and simplified masonry infill wall area ratio

The comparison between actual masonry infill area ratio and simplified masonry infill area ratio is shown in Figure 3.39. The simplified masonry infill area ratio shows conservative results compared with actual masonry infill area ratio except one building shows overestimated values due to higher masonry infill ratio. However, it has been observed that there is large variation in masonry wall area ratio. The main reason is that those buildings contains double layer of masonry infill (infill thickness 250mm), whereas the proposed method considers single layer of masonry infill (i.e. infill thickness 125 mm). Another reason, the visual rating method considers only solid masonry infill is counted during visual inspection. However, actual wall area ratio considers solid infill and also partial infill. As a result, a few of them consist of masonry infill ratio for infill with opening. However, the simplified masonry infill wall area ratio is zero due in absence of solid masonry infill.

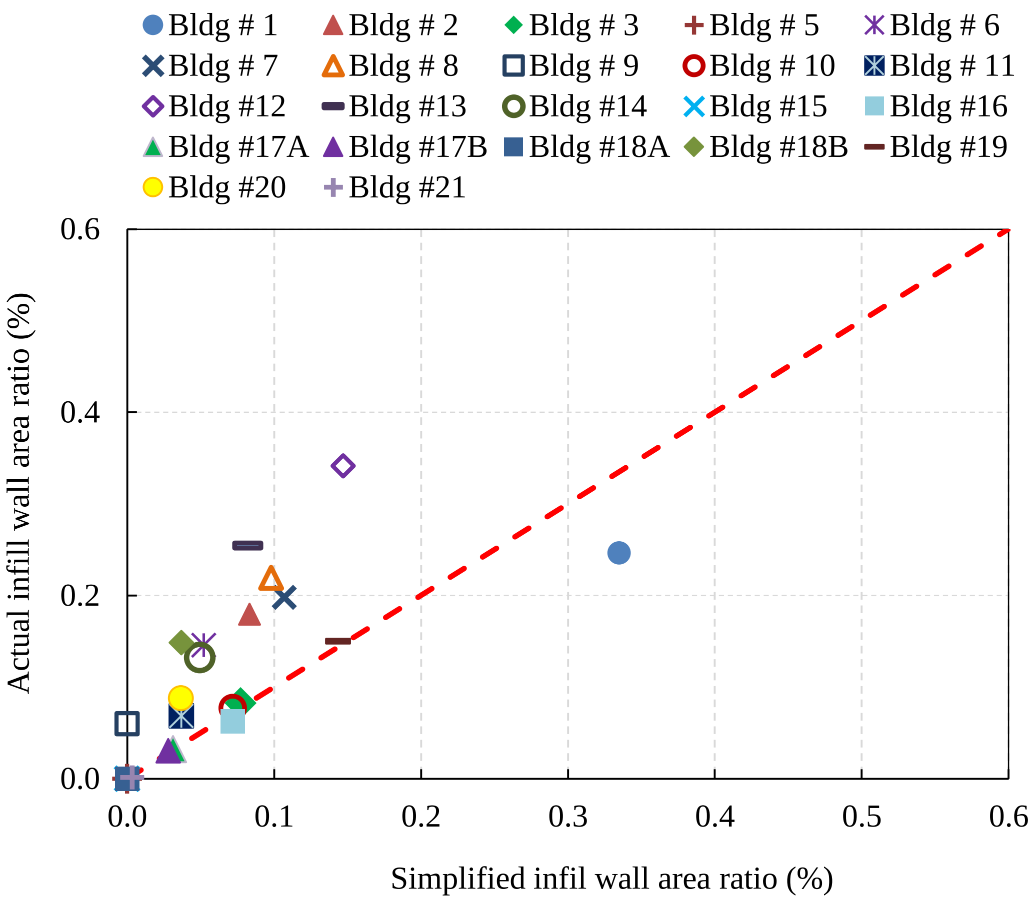


Figure 3.39 Comparison of actual infill wall area ratio and simplified infill wall area ratio.

6.7.3 Comparison with first level evaluation with Visual Rating method

The estimated Visual Rating Index (I_{VR}) as shown in Table 6.12 is compared with seismic index (I_{S1}). Figure 3.40 shows comparison between visual rating index and first level evaluation. It has been observed that the Visual Rating Index (I_{VR}) shows conservative estimation of first level seismic evaluation. In every case, the Visual Rating Index (I_{VR}) shows a lower boundary of first level evaluation except two buildings such as: building number 1 and building number 18A. This is due to detail material properties considered in detail evaluation. However, the normalized seismic index of first level evaluation and Visual Rating Index (I_{VR}), the average value is of 1.53 and coefficient of variation is of 35% shows a good estimation of seismic capacity. Therefore, it has been revealed that Visual Rating method provides seismic capacity in term of the Visual Rating Index (I_{VR}).

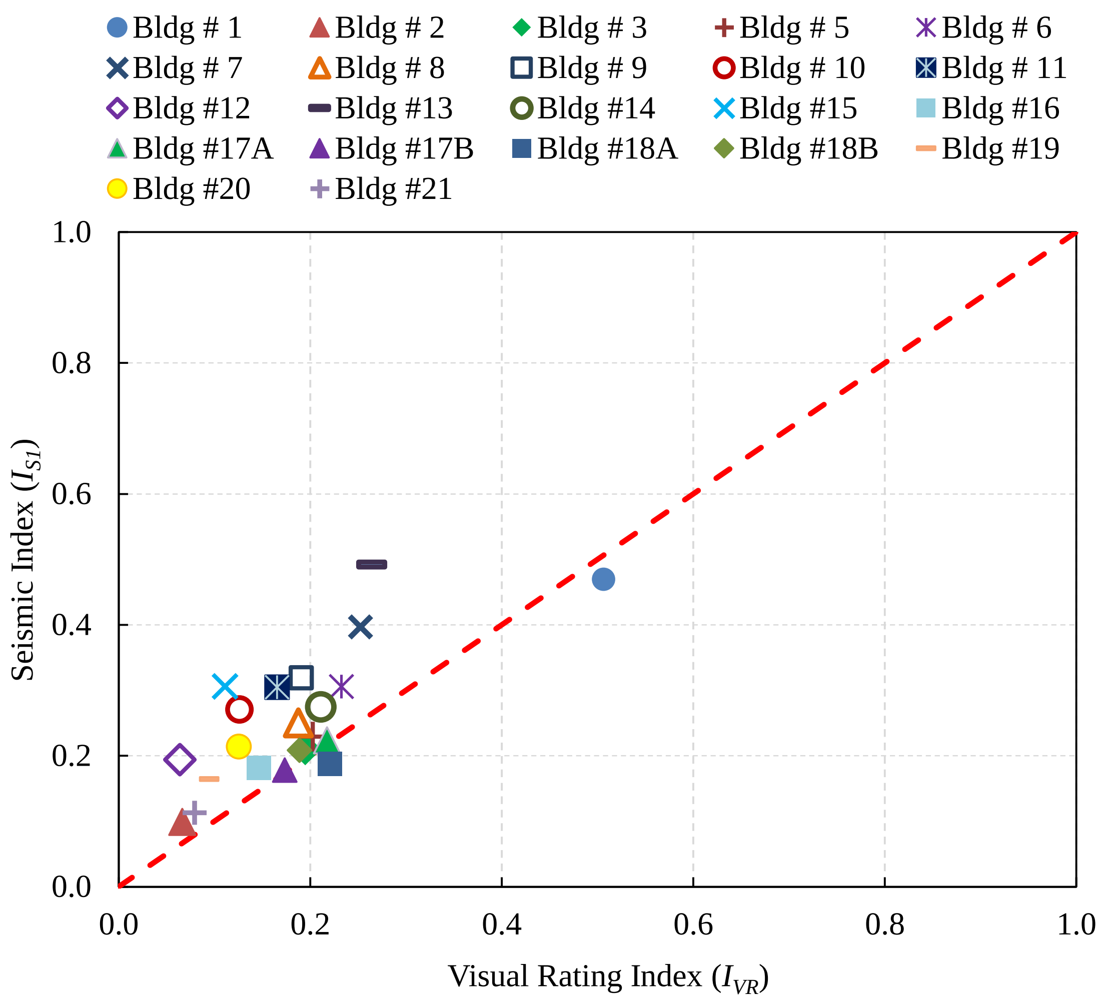


Figure 3.40 Comparison of Visual Rating Index (I_{VR}) and seismic index (I_{S1})

6.7.4 Comparison with second level evaluation with Visual Rating method

Furthermore, Visual Rating Index (I_{VR}) is compared with detail evaluation of second level evaluation of the investigated buildings. The comparison between Visual Rating Index (I_{VR}) and seismic index (I_{S2}) as shown in Figure 6.41. However, the normalized seismic index of second level evaluation and Visual Rating Index (I_{VR}), the average value is of 2.11 and coefficient of variation is of 33% shows the Visual Rating Index (I_{VR}) provides much conservative results as compared with second level evaluation. The main reason is that Visual Rating Index as well as first level evaluation consider ductility index is of unity whereas detail seismic evaluation considers ductility factors of structural members using reinforcement details. On the other hand, Visual Rating method estimates strength index based on only dimension of vertical members. However, detail evaluation requires detail material strength and reinforcement detail and based on detail structural drawing. Overall, it has been observed that Visual Rating Index (I_{VR}) also provides an estimation of second level evaluation.

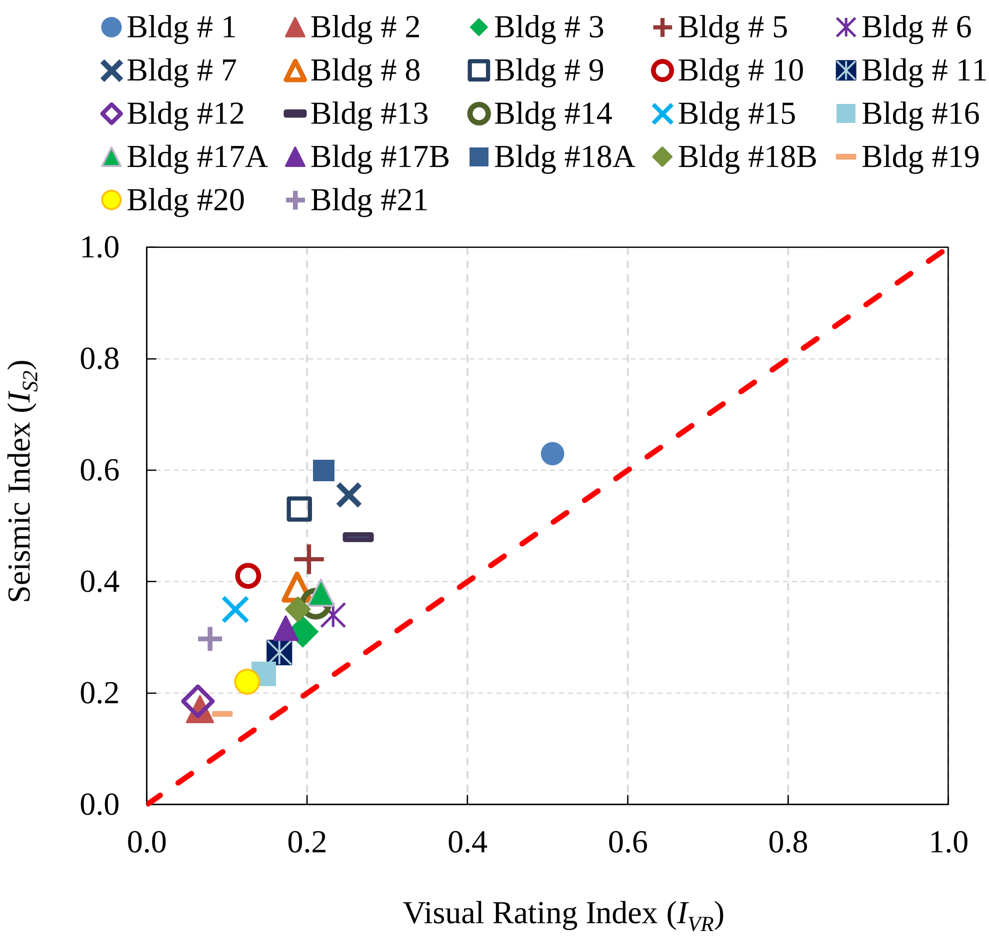


Figure 3.41 Comparison of Visual Rating Index (I_{VR}) and seismic index (I_{S2})

6.8 Summary of chapter 6

This chapter presents application of the proposed Visual Rating method. The main objective is to validate the effectiveness and applicability of the proposed method. In this regards, 22 existing RC buildings located at Dhaka, Bangladesh have been surveyed. The survey procedure has been subdivided into two major part. Part one is related to application of the proposed Visual Rating method. Part two is the preparation of as-built drawing because architectural drawings are not available of these surveyed buildings. As-built drawing is prepared in order to conduct detail seismic evaluation of these surveyed buildings.

A common survey datasheet is proposed and used for conducting of the Visual Rating method. The visual index has been calculated from information found from recorded survey datasheet. Detail evaluation has been done for first level and second level evaluation. The Visual Rating Index (I_{VR}) has been calibrated with the estimated first level and second level evaluation.

The following conclusions can be stated as follows:

1. The Visual Rating method considers the simplified column area ratio and the simplified wall area ratio, which estimates column area and infill wall area ratio efficiently. However, the normalized actual column area ratio by the simplified column area ratio, the average 1.19 and coefficient of variation 23% shows a good correlation between these parameters.
2. Visual Rating Index (I_{VR}) is efficient to estimate the seismic capacity of existing RC buildings. It has been observed that the normalized seismic index of first level evaluation and Visual Rating Index (I_{VR}), the average value is of 1.53 and coefficient of variation is of 35% shows a good estimation of seismic capacity of first level evaluation.
3. The average value of normalized seismic index (I_{S2}) by Visual Rating Index (I_{VR}) is 2.11 with coefficient of variation 33% indicates the Visual Rating Index (I_{VR}) score shows more conservative result with seismic index (I_{S2}) in second level evaluation. The reason is that I_{VR} assumes structural members as non-ductile members since ductility of column is difficult to be judged based only on visual inspection. Detailed information such as reinforcement details and actual material strength is needed to judge ductility which is considered in second level evaluation.

The proposed Visual Rating method is intended to estimate of seismic capacity of existing RC buildings in absence of detail seismic evaluation. From the above discussion, it has been observed that Visual Rating method provides lower boundary of seismic capacity of existing buildings. However, the estimated Visual Rating Index (I_{VR}) score is useful to provide judgement and prioritization of detail seismic evaluation which is the main of objective of the proposed Visual Rating Method.

Chapter 7

Judgement criteria for priority setting of detail evaluation

7.1 Introduction

Chapter 5 and chapter 6 describe about the development and application procedure of the proposed Visual Rating (VR) method. As previously explained, the main purpose of the Visual Rating (VR) method is to categorize the most vulnerable buildings for detail seismic evaluation on the basis of Visual Rating Index (I_{VR}). Therefore, it is necessary to set judgement criteria for categorization of existing RC buildings. The main objective of this chapter is to propose a judgement criterion for prioritization of existing RC buildings for detail or higher level seismic evaluation. A several model RC buildings representing the existing RC buildings in Bangladesh have been considered in this study. Response spectrum method has been conducted on these model buildings for evaluation of seismic capacity and demand ratio. A correlation has been developed between capacity demand ratio and seismic index (I_{S2}). Using the obtained correlation, judgment criteria has been proposed according to seismic index (I_{S2}). Besides, a correlation between seismic index (I_{S2}) and Visual Rating Index (I_{VR}) is developed and described in Chapter 6. Using the correlation of I_{S2} vs I_{VR}, judgement criteria has been proposed on the basis of Visual Rating Index (I_{VR}). The overall flow of the procedure of chapter 7 has been shown in Figure 7.1.

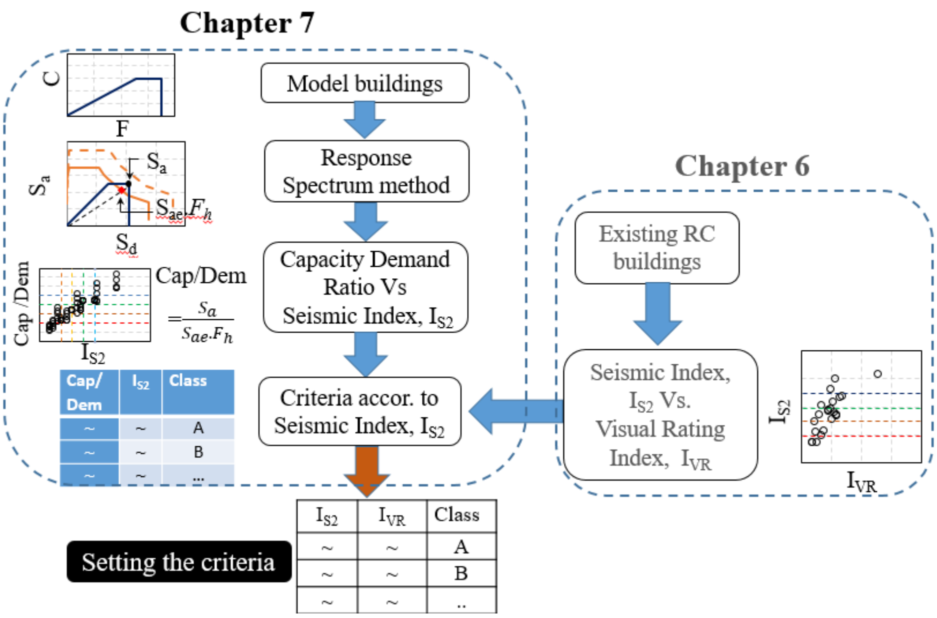


Figure 7.1 Main flowchart of the chapter

7.2 Background

In general, judgement criteria are used to understand the performance level of an existing building during earthquake. The seismic safety can be judged by comparing seismic demand and capacity through detail evaluation of existing building. Therefore, judgement criteria can be set based on seismic capacity and performance of existing building during earthquake.

In high seismic region such as Japan, the judgement criteria have been proposed based on detail seismic evaluation and performance level of existing buildings experienced past earthquake. In this regard, Japanese seismic evaluation standard (JBDPA 2001) proposed seismic demand index (i.e. $I_{SO}=0.6$) as judgment criteria for seismic safety evaluation. It indicates that the seismic capacity of existing building is higher than seismic demand index is considered as safe building during earthquake.

Developing countries such as Bangladesh has been adopting Japanese seismic evaluation standard (JBDPA 2001) in CNCRP seismic evaluation manual (CNCRP 2015) for seismic evaluation of existing RC buildings. In the CNCRP evaluation manual (CNCRP 2015), the judgment criteria are proposed for seismic demand index ranging from 0.28 to 0.36 based on seismic demand correlation of Bangladesh National Building Code (BNBC 2015) and Japanese standard (JBDPA 2001). However, due to lack of past earthquake database in Bangladesh, the proposed judgement criteria by evaluation standard (CNCRP 2015) needs further verification. Therefore, criteria setting for identification of vulnerable building is a key issue regarding seismic evaluation and/or retrofitting of existing RC buildings in Bangladesh.

7.3 The main concept

Bangladesh National Building Code (BNBC 2015) proposes response acceleration spectra based on earthquake ground motion and different soil condition. Generally, structural safety requirements consider seismic capacity should be larger than seismic demand. Seismic capacity can be estimated using seismic evaluation standard (CNCRP 2015). As there is no past earthquake damage database, seismic demand can be set according to ground motion considered in Bangladesh National Building Code (BNBC). Hence, structural safety can be judged by ratio of seismic capacity and seismic demand.

This study proposes judgement criteria based on performance evaluation of existing buildings considering ground motion in Bangladesh National Building Code (BNBC 2015). This study estimates capacity demand ratio based on a simple procedure of existing buildings whereas the seismic demand can be estimated using the proposed response acceleration. However, judgment criteria are set based on capacity demand ratio which indicates level of seismic performance of existing buildings. A schematic diagram is shown in Figure 7.2. It has been seen that if seismic capacity is higher that seismic demand i.e. capacity demand ratio is higher than unity can be referred as safe building. Conversely, if capacity demand ratio is lower than unity, the building will have high probability of collapse. Buildings are to be categorized into different classes (See Figure 7.2) on the basis of capacity-demand ratio.

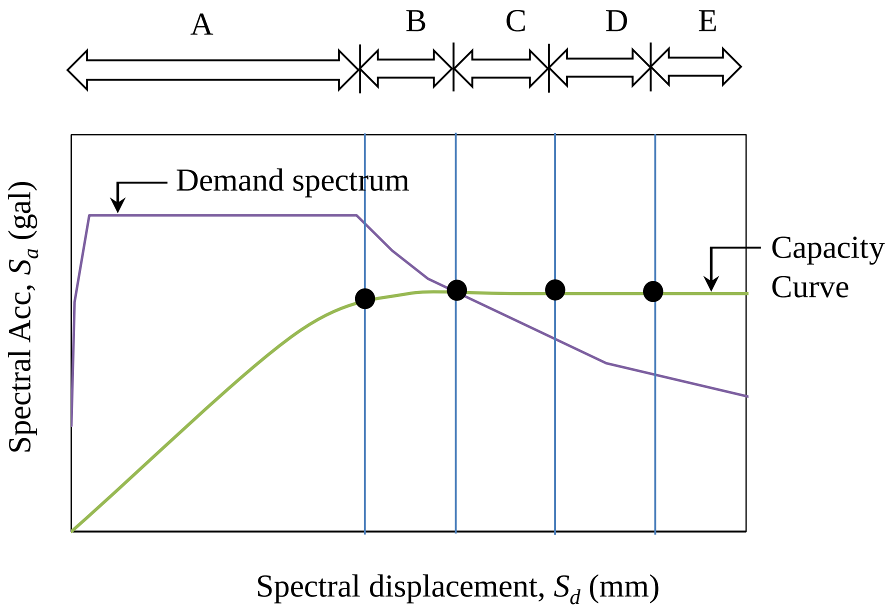


Figure 7.2 Basic idea of proposal categorization for judgement criteria

Several model buildings representing the existing buildings in Bangladesh have been chosen for seismic performance evaluation to estimate demand capacity ratio according local ground motion. The basic criteria of those model buildings are explained and described in the following sections.

7.4 Overview of model buildings

A total of 105 model RC buildings, representing the existing RC buildings in Bangladesh, have been considered in this study. The selection criteria of those model buildings are based on several basic parameters: number of stories (n), strength index (C) and ductility index (F). The number of stories have been considered ranging from two to six storied which is representing the existing RC buildings in Bangladesh. Figure 7.3 showing distribution according to number of storied of existing RC buildings investigated in Bangladesh. The strength index (C) of model buildings is ranging from 0.10 to 0.40 which is similar as found in investigation of existing RC buildings in Bangladesh as shown in Figure 7.4. In addition, the model buildings are divided into 3 (three) categories according to ductility index (F) ranging from 1.0 to 1.75. Figure 7.1 showing the model buildings varying with number of stories, strength index and ductility index. The floor height of the model buildings is considered as 3000mm which is also common practice in Bangladesh.

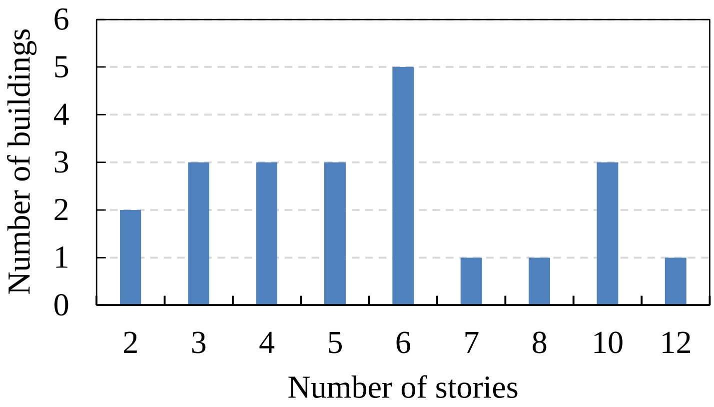


Figure 7.3 Distribution according to number of stories of investigated RC buildings

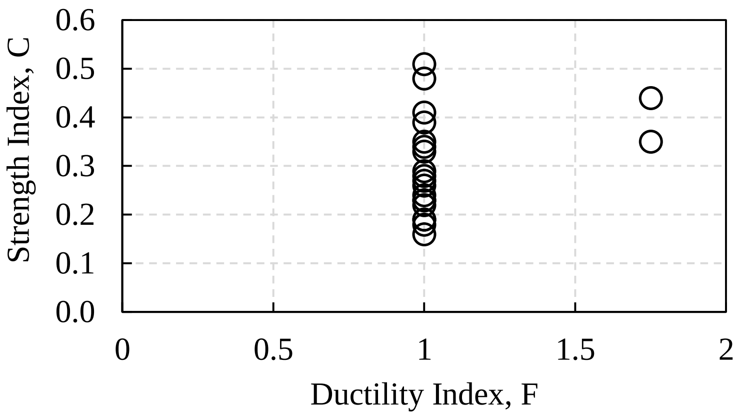


Figure 7.4 Strength and ductility relationship of investigated RC buildings

Basic characteristics of model RC buildings:

Case one:

Numbers of buildings:35

Number of stories: 2 to 6

Strength index (C)	Ductility index (F)
0.10	1.00
0.15	1.00
0.20	1.00
0.25	1.00
0.30	1.00
0.35	1.00
0.40	1.00

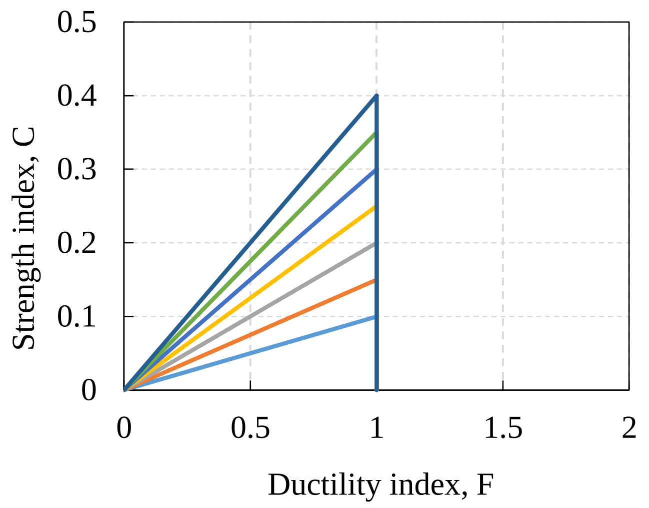


Figure 7.5 Force-deformation relationship for case one.

Case two:

Numbers of buildings:35

Number of stories: 2 to 6

Strength index (C)	Ductility index (F)
0.10	1.27
0.15	1.27
0.20	1.27
0.25	1.27
0.30	1.27
0.35	1.27
0.40	1.27

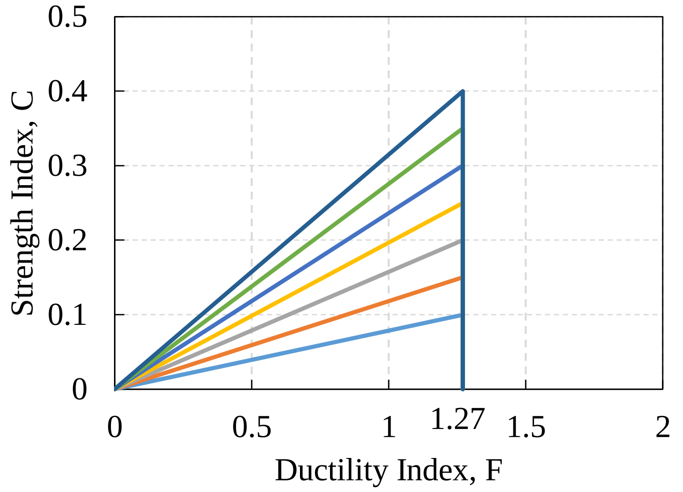


Figure 7.6 Force-deformation relationship for case two.

Case three:

Numbers of buildings:35

Number of stories: 2 to 6

Strength index (C)	Ductility index (F)
0.10	1.27
0.15	1.27
0.20	1.27
0.25	1.27
0.30	1.27
0.35	1.27
0.40	1.27

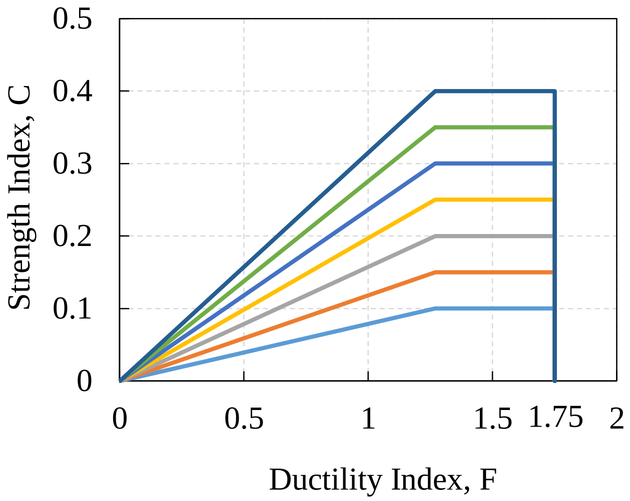


Figure 7.7 Force-deformation relationship for Case three.

7.5 Calculation procedure of Capacity Demand Ratio

Capacity demand ratio has been calculated for these model RC buildings using response spectrum method. Response spectrum method is an approximate way to compare seismic capacity of an existing building with seismic demand corresponding to ground motion as per seismic design code. The following sections describes about the calculation procedure.

7.5.1 Flow of the method

Response spectrum method is adopted in this study to evaluate seismic response to ground motion. This study aim is to understand the capacity and demand of the model RC buildings. The application procedure of response spectrum is shown in Figure 7.8.

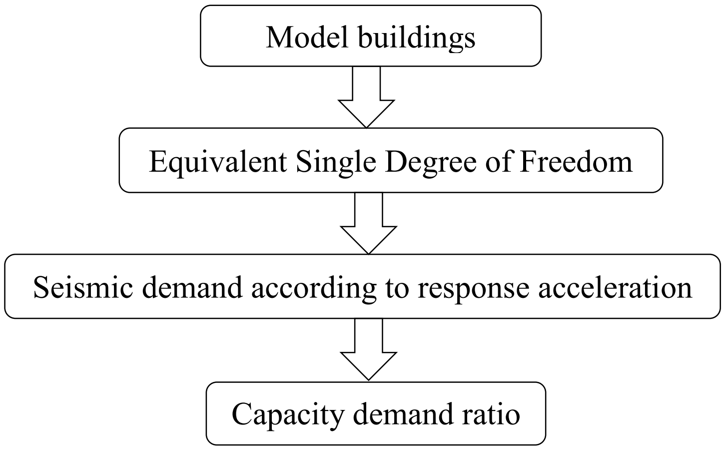


Figure 7.8 Capacity demand ratio calculation procedure.

7.5.2 Conversation of Equivalent Single Degree of Freedom

Several research efforts have focused on simple procedures to evaluate seismic capacity and demand of multistory buildings under ground motion actions (Reference). Generally, these procedures consider equivalent single-degree-of-freedom (ESDOF) system as a basis for calculating the response of a multi-degree-of-freedom (MDOF) system. The properties such as equivalent mass and equivalent height of ESDOF system are determined based on a force-deformation relationship (i.e. C-F relationship) of MDOF system. In general, a plot of base shear versus roof displacement is used as the basis for establishing the properties of the ESDOF system. In this study, force deformation relationship of model buildings is used for calculating the properties of the ESDOF system.

The conversion procedure of ESDOF system consists of the following steps:

Step 1: Force-deformation relationship has been plotted considering strength index (C) and ductility index (F) for each model building in each case as shown in Figure 7.9.

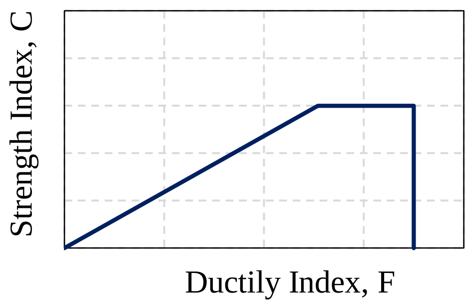


Figure 7.9 Force-deformation relationship of model buildings

Step 2: The properties of equivalent-single-degree-of-freedom (ESDOF) system is calculated by considering equivalent mass and equivalent height as shown in Figure 7.10.

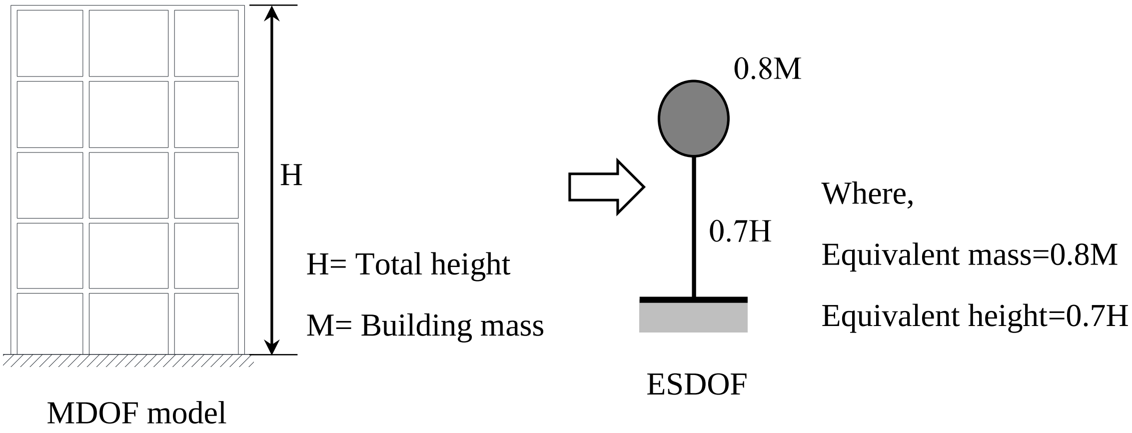


Figure 7.10 Conversion of equivalent single degree of freedom (ESDOF)

Step 3: A capacity spectrum using spectral acceleration and displacement (S_a-S_d relationship) is produced for equivalent single degree-of-freedom as shown in Figure 7.11.

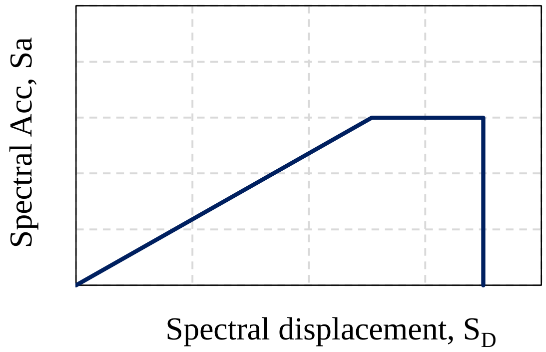


Figure 7.11 ADRS format of force-deformation of model RC buildings

7.5.3 Seismic demand in Bangladesh

Bangladesh National building code (BNBC 2015) proposes seismic zoning map based on peak ground acceleration (PGA). The country has been divided into four seismic zones with zone coefficient Z equal to 0.12 (Zone 1), 0.2 (Zone 2), 0.28 (Zone 3) and 0.36 (Zone 4) as shown in Figure 7.12. The zone coefficient represents the PGA value on rock or very stiff soil site.

Generally, seismic design of building is carried on using design response spectrum which represents earthquake ground motion. The response spectrum is defined as spectral acceleration depending on natural period and ground motion intensity. BNBC proposes design response spectrum varying with different types of soil categories. The model buildings are located at Dhaka, therefore the seismic zone coefficient is of 0.20g (where, g is 981 cm/s^2). Figure 7.13 showing response acceleration for different types of soil considering 5% damping considering seismicity at Dhaka, Bangladesh.

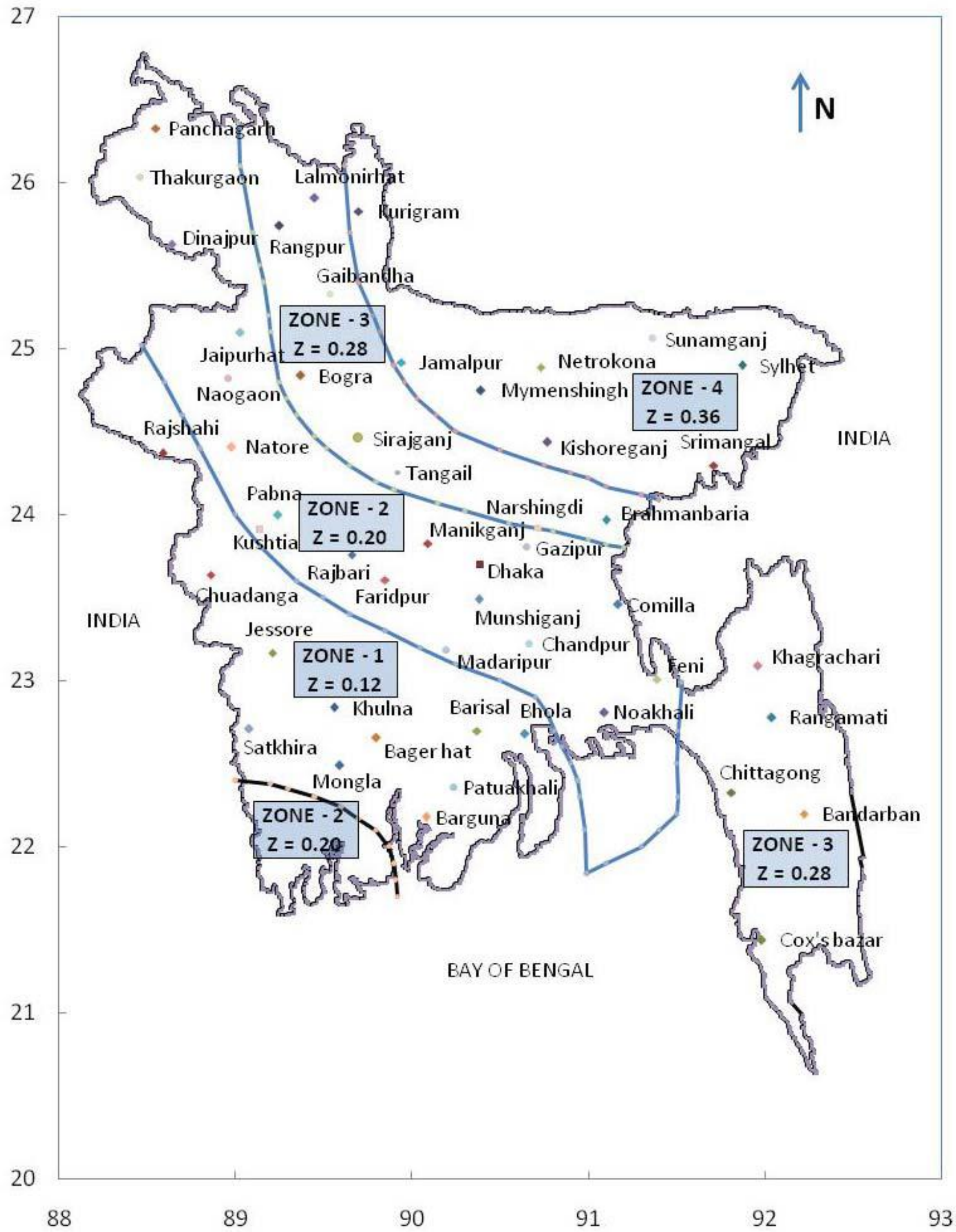


Figure 7.12 Seismic zoning map of Bangladesh (BNBC 2015)

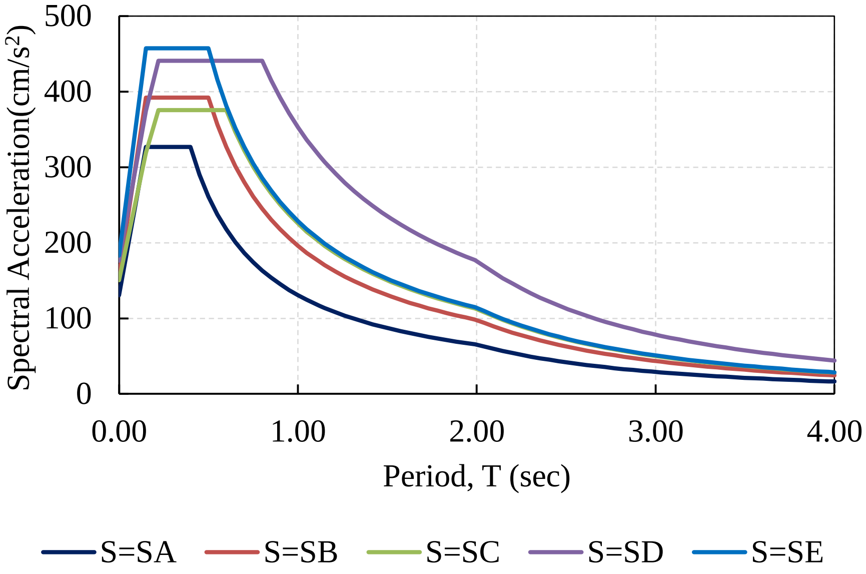


Figure 7.13 Design response spectra at seismic zone 2 (BNBC 2015)

Seismic demand has been estimated based on response acceleration based on BNBC (BNBC 2015). This study considers response acceleration corresponding to soil type SD for judgement criteria for categorization of existing buildings. It should be noted that soil type SD is assumed as conservative approach. Elastic response acceleration has been converted using Equation (7.1) into acceleration and displacement response spectrum (ADRS) for Single Degree of Freedom (SDOF) system as shown in Figure 7.14.

$$S_d = \frac{T^2}{4.\pi^2} S_a \tag{7.1}$$

where, S_d= Spectral displacement

S_a= Spectral acceleration

T= Period (sec)

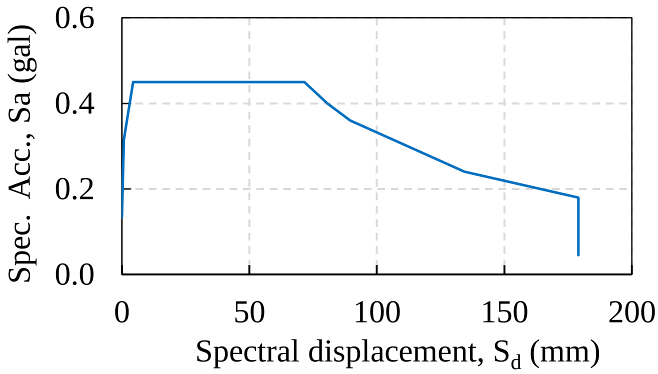


Figure 7.14 Acceleration-displacement spectrum for SD type soil (BNBC 2015)

7.5.4 Response acceleration reduction factor (F_h)

Generally, in order to estimate maximum response of non-linear system, response spectrum method has been applied using equivalent linearization techniques. As previously mentioned, response spectrum is prepared for a damping ratio of 5% considering elastic range stage. Therefore, the elastic response spectrum is reduced by multiplying spectral acceleration (S_{ae}) with response reduction factor (F_h). Response reduction factor has been calculated by using Equation (7.2).

$$F_h = \frac{1.5}{(1+10*h_{eq})} \quad (7.2)$$

where, h_{eq}= equivalent damping ratio

The equivalent damping ratio (h_{eq}) of equivalent single degree of freedom system is used to correlate the maximum response of an equivalent linear system and a nonlinear system under a random earthquake ground motion. Here, h_{eq} is calculated using following Equation (7.3).

$$h_{eq} = 0.05 + 0.25 * 1 - \frac{1}{\sqrt{\mu}} \quad (7.3)$$

where, μ is the ductility factor which is defined as the ratio of ultimate deformation (Δ_u) and yield deformation (Δ_y) of equivalent single degree of freedom (ESDOF). Therefore, the ductility is can be calculated using Equation (7.4) as follows:

$$\mu = \frac{\Delta_u}{\Delta_y} \quad (7.4)$$

In this study, the ultimate deformation (Δ_u) is calculated at ultimate drift (R_u) and yield deformation (Δ_y) is calculated at yield drift (R_y) of equivalent single degree of freedom (ESDOF) system as illustrated in Figure 7.15. It should be noted that yield drift is considered as 1/250 deformation angle.

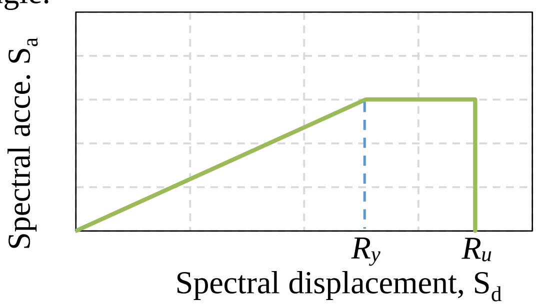


Figure 7.15: Capacity curve showing ultimate deformation and yield deformation

As shown in Figure 7.16, elastic response acceleration is plotted for damping ratio (5%) considering ductility factor as unity (i.e. μ=1). However, elastic response spectrum is reduced using response reduction factor (F_h) considering equivalent damping ratio at ultimate deformation. In this case, ductility factor (μ) is larger than considering non-linear range of buildings. Figure 7.16 illustrates an example of response spectrum at non-linear range.

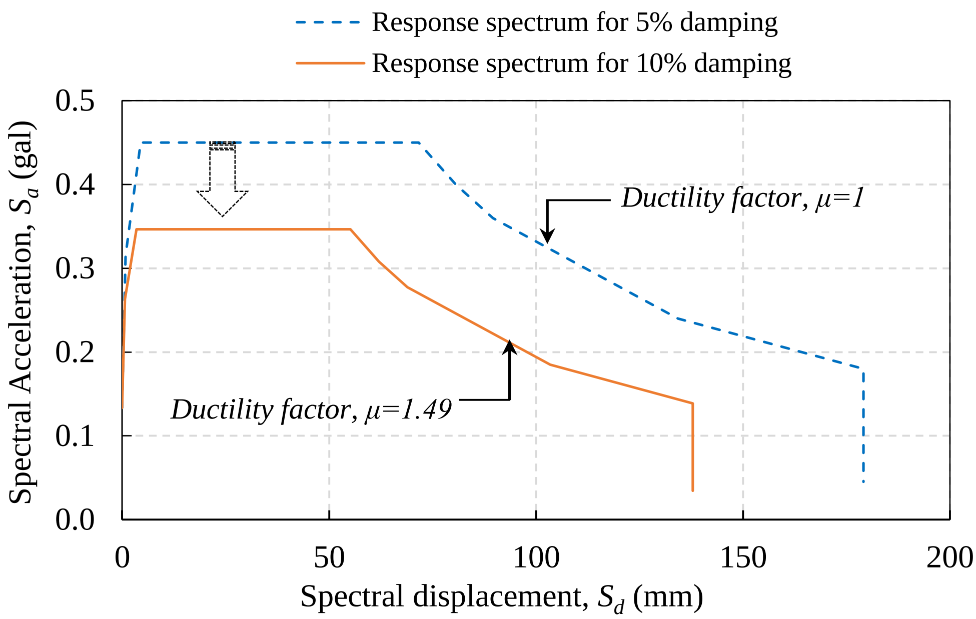


Figure 7.16 Reduction of elastic response spectrum considering equivalent damping ratio

7.5.5 Capacity-demand ratio

The capacity curve of each model building, considering equivalent single degree of freedom system, has been plotted using the procedure explained in the previous section. At the same time, response spectrum is drawn corresponding equivalent damping ratio at ultimate deformation of each model building. The obtained capacity curve has been plotted with damped response spectrum in order to compare the seismic capacity and seismic demand ratio of the model buildings.

Figure 7.17 showing a typical calculation procedure of capacity-demand ratio of model building. From the Figure 7.17, it has been seen that capacity (S_a) indicates the ultimate lateral strength of building at demand spectrum line which represents safety limit of the building. On the other hand, seismic demand is obtained by reducing the elastic response spectrum by response reduction factor. Capacity demand ratio can be calculated by using Equation (7.5) as follows:

$$Capacitydemand\ ratio\ (CDR) = \frac{S_a}{S_{ae}.F_h} \tag{7.5}$$

where, S_{ae} =Spectral acceleration at elastic response acceleration

S_a= Capacity in terms of spectral acceleration at safety limit

F_h= Ductility reduction factor

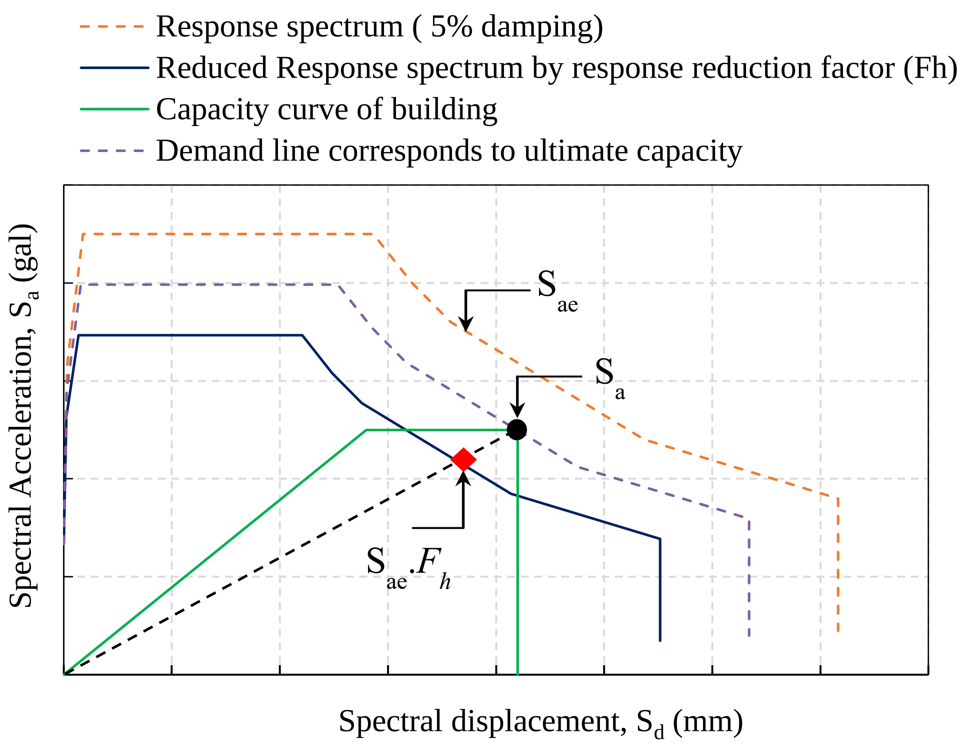


Figure 7.17 A typical diagram showing capacity demand ratio of model buildings

7.6 Correlation between capacity-demand Ratio (CDR) and seismic index (I_{S2})

Capacity demand ratio of each model building has been calculated considering ground motion acceleration in BNBC (2015) for soil SD type. On the other hand, the seismic index of each model building is calculated using strength index and ductility index as mentioned in previous section. The calculated capacity demand ratio is plotted with seismic index of model building as shown in Figure 7.18. It has been observed that the seismic index greater than 0.40 shows the buildings contains capacity demand ratio greater than unity (1). It indicates that these building has sufficient seismic capacity to resist seismic demand during earthquake. In contrast, the buildings with capacity demand ratio lower than 1 indicating those building might have been severely damaged during earthquake.

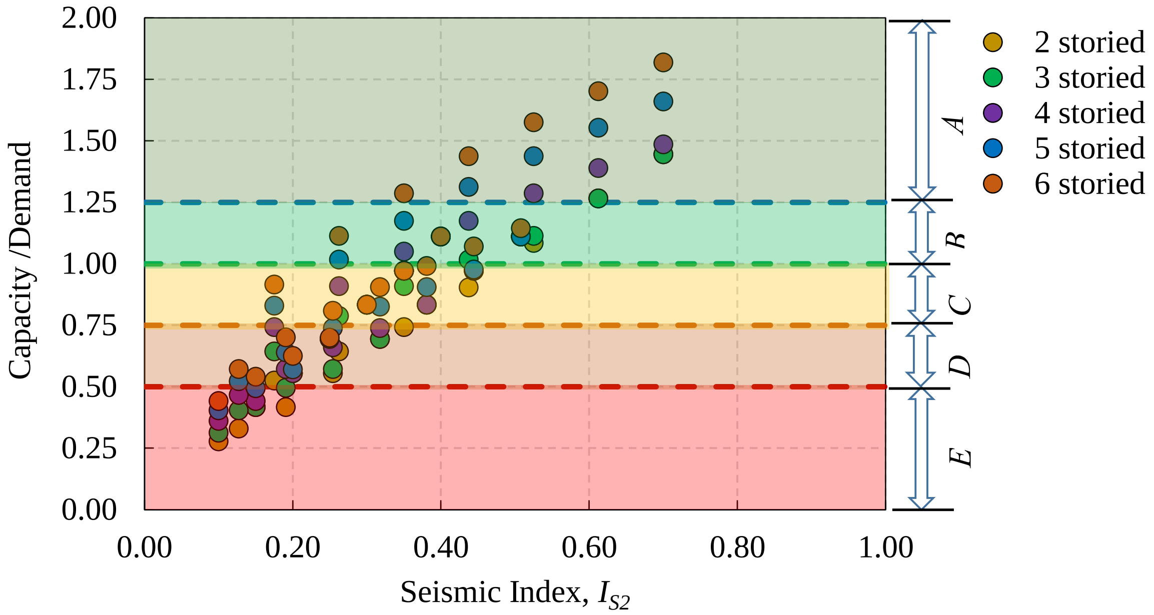


Figure 7.18 Proposal of boundary for capacity demand ratio of model buildings

Generally, in evaluation scheme, the main target is to screen out these buildings which seismic capacities are lower than seismic demand. However, in case of large number of vulnerable buildings with lower seismic capacity, it is necessary to categorize the vulnerable buildings into less to high vulnerable depending on their seismic capacity. Therefore, in this study, categorization has been made on the basis of capacity demand ratio.

As previously mentioned, buildings with capacity-demand ratio is less than 1 are considered as vulnerable buildings. Based on the current study, buildings are categorized into 5 groups namely A, B, C, D and E. It should be noted that the building categorized in group B are considered as less vulnerable with light to moderate damage but usable after earthquake. At the same time, a category buildings are termed as no damage as because of capacity demand ratio is as much larger than 1.5. Table 7.1 shows the categorization of buildings according to capacity demand ratio and description of probable behavior during earthquake.

Table 7.1 Proposal of categories of building according to capacity-demand ratio

Capacity/ Demand Ratio	Categories	Description
1.5<	A	No damage
1.00~1.5	B	Light damage
0.75~1.00	C	Less Possibility of collapse
0.5~0.75	D	Moderate possibility of collapse
~0.50	E	High possibility of collapse

7.7 Proposal of Judgement Criteria of Seismic Index (I_{S2})

As discussed in previous section, the buildings have been categorized into 5 groups and judgement criteria of each groups have been described corresponding to capacity-demand ratio. Since the objective of seismic evaluation scheme is to evaluate seismic index and compare the seismic judgement index for screening. Therefore, it is essential to set a boundary for seismic judgement index and buildings are beyond this boundary is considered as sufficient capacity to resist an earthquake. Hence, the obtained capacity demand ratio is compared with seismic index of each model buildings. From the Figure 7.18, it has been observed that the boundary for safe seismic capacity is approximately set as of 0.40 comparing with capacity demand ratio of model buildings. However, CNCRP also proposes the seismic demand index is of 0.36 as per SD type soil based on study and performance evaluation. Therefore, the boundary considered in this study is conservative compared with CNCRP standards.

Furthermore, the buildings are also categorized into 5 groups according to seismic index such as A to E. Table 7.2 describes the categorization according seismic index (I_{S2}). It means that the buildings located at zone E are the most vulnerable buildings. On the other hand, the buildings located at zone C mean less vulnerable.

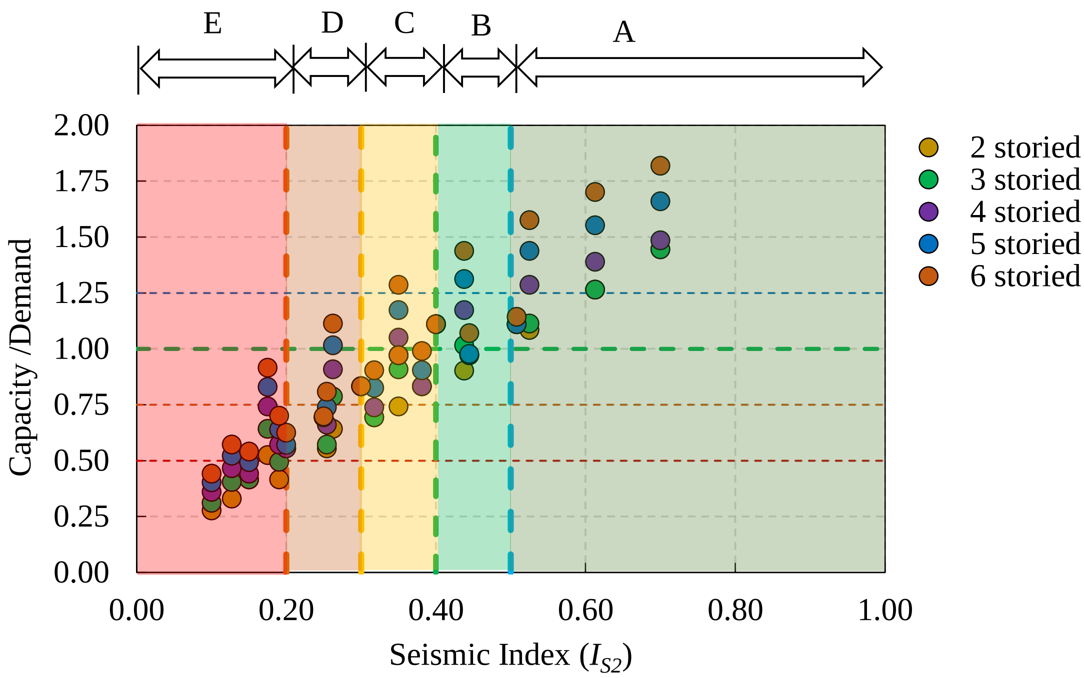


Figure 7.18 Proposal of boundary for Seismic Index (I_{S2}) of model buildings

Table 7.2 Proposed criteria according to seismic index (I_{S2})

Capacity/ demand ratio	I_{S2}	Categories	Description
1.5<	0.50~	A	No damage
1.00~1.5	0.40~0.50	B	Light damage
0.75~1.00	0.30~0.40	C	Less Possibility of collapse
0.5~0.75	0.20~0.30	D	Moderate possibility of collapse
~0.50	<0.20	E	High possibility of collapse

From above discussion, the boundary of seismic capacity as well as judgment criteria have been set for detail evaluation results. Since the main objective is to set boundary for judgement criteria for priority setting of detail evaluation, it is necessary to set boundary line on basis of Visual Rating index. However, by using correlation between seismic index (I_{S2}) and Visual Rating Index (I_{VR}) the judgement criteria can be set. The following section will discuss about the proposed judgment criteria according to Visual Rating Index (I_{VR}).

7.8 Judgement criteria based on Visual Rating Index

As previously mentioned in Chapter 6, there are 22 existing RC buildings have been investigated in order to validate the effectiveness and applicability of the proposed Visual Rating method. In addition, seismic capacity evaluation has been done for all of these investigated RC buildings and discussed in Chapter 6. The correlation has been developed between the results obtained from detail evaluation and the calculated Visual Rating index (I_{VR}). In addition, seismic capacity of surveyed buildings has been compared with the investigated model RC buildings. Furthermore, the judgement criteria according to Visual Rating index (I_{VR}) have been set according to the correlation between these seismic indices.

7.8.1 Seismic capacity of model buildings and surveyed buildings in Bangladesh

The seismic capacity of model buildings has been compared with the seismic evaluation result of the surveyed existing RC buildings in Bangladesh. Table 7.3 shows the mean and standard deviation of seismic capacity of both model RC building and surveyed building in Bangladesh. It has been observed that the model buildings represent the seismic capacity of surveyed buildings. buildings.

Table 7.3 Comparison between model buildings and investigated buildings

Buildings type	Mean	Standard deviation
Model buildings	0.33	0.16
Surveyed buildings in Bangladesh	0.31	0.12

Figure 7.19 shows the distribution of model buildings and surveyed buildings. It has been observed that the average values of model building are of 0.34 which is closer with existing investigated RC buildings.

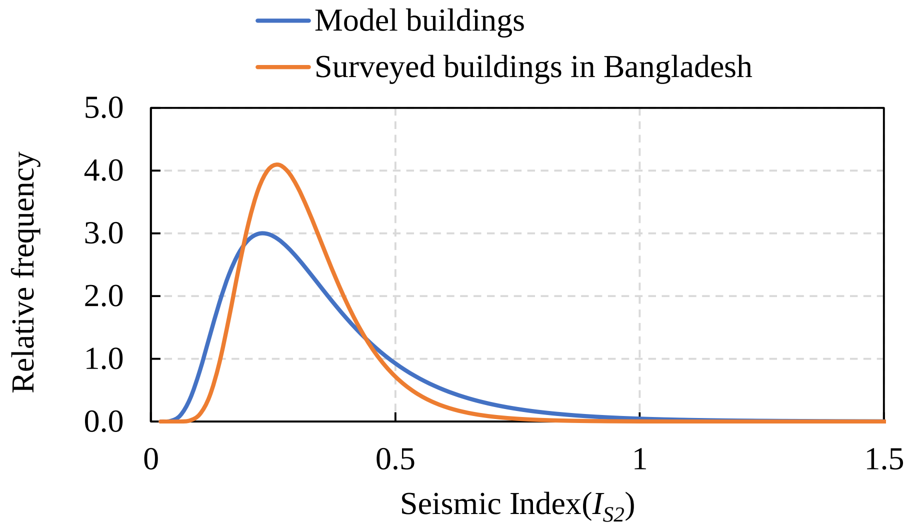


Figure 7.19 Distribution of seismic index (I_{S2}) level evaluation of both databases

7.8.2 Categorization of Visual Rating index (I_{VR}) corresponding to seismic index (I_{S2})

A correlation between seismic index (I_{S2}) and Visual Rating index (I_{VR}) as obtained in previous chapter as shown in Figure 7.20. Judgment criteria with respect to seismic index (I_{S2}) already developed in previous section has been applied on surveyed RC building in Bangladesh in the Figure 7.20. In the plot, these investigated buildings are categorized into 5 categories according to judgement criteria and boundary proposed for seismic index (I_{S2}).

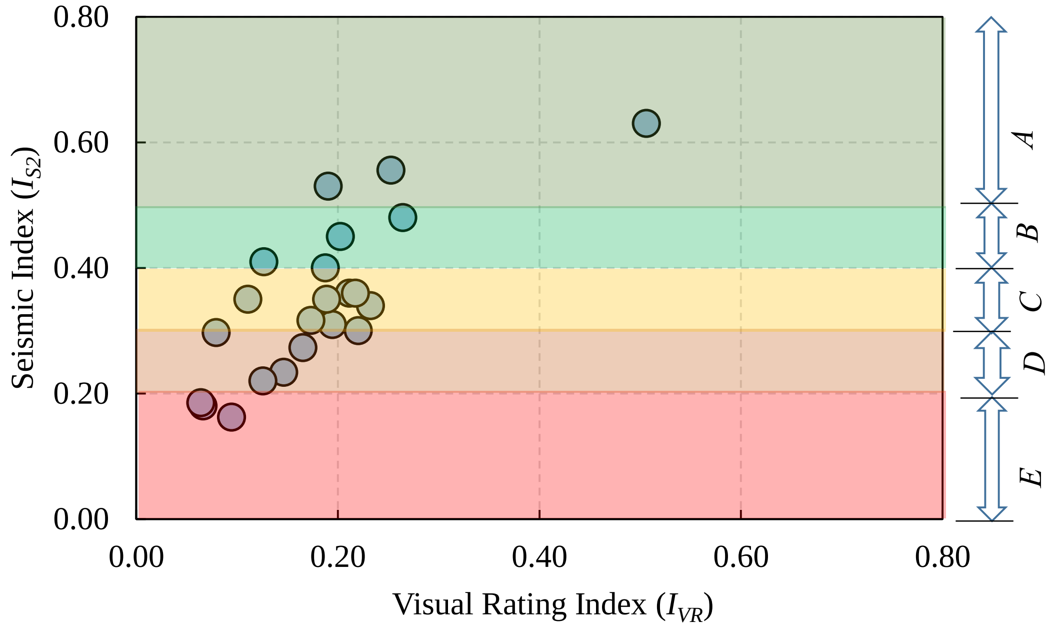


Figure 7.20 Correlationship between seismic index (I_{S2}) and Visual Rating index (I_{VR})

From above Figure 7.20, it has been observed that there is large variation of Visual Rating Index (I_{VR}) of each range of seismic index (I_{S2}). The variation of Visual Rating Index (I_{VR}) of each range of seismic index has been shown in Figure 7.21. It has been observed that the variations are increasing while increasing the range of seismic index (I_{S2}). From this Figure, it is quite difficult to set boundaries for each categories due to large variation for each range of visual rating index.

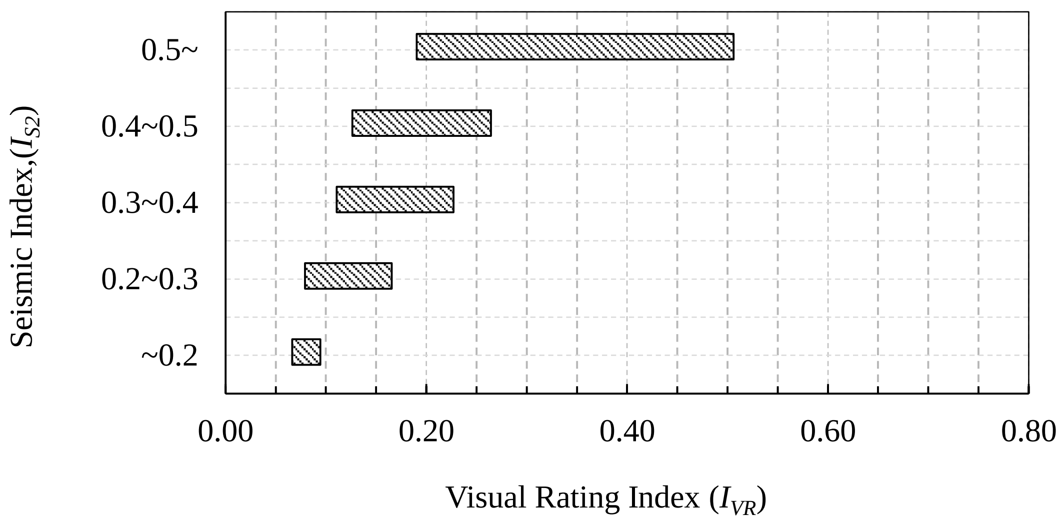


Figure 7.21 Variation of Visual Rating Index (I_{VR}) in each range of seismic index (I_{S2})

In order to propose boundary of Visual Rating Index (I_{VR}), this study considers two approaches. The following sections describe as follows:

7.8.3 Proposal of boundaries according to Visual rating index

7.8.3.1 Proposal of Visual rating index based on one standard deviation

As previously explained, there are large variation in Visual Rating Index (I_{VR}) for each range of seismic index (I_{S2}). Table 7.5 showing the variation of Visual Rating Index (I_{VR}) for mean and standard deviation. It has been seen that the variation is larger while large values of seismic index.

Table 7.5 Variation of Visual Rating Index (I_{VR}) for each seismic index (I_{S2})

Seismic Index, I_{S2}	Visual Rating Index, (I_{VR})			
	Average	Standard Deviation	+1SD	+2SD
~0.2	0.075	0.014	0.09	0.10
0.2~0.3	0.129	0.032	0.16	0.19
0.3~0.4	0.193	0.034	0.23	0.26
0.4~0.5	0.198	0.056	0.25	0.31
0.5~	0.316	0.137	0.45	0.59

Distribution of values of Visual Rating Index (I_{VR}) are plotted using mean and standard deviation of each range of seismic index. Figure 7.22 shows the normal distribution of Visual Rating Index (I_{VR}) for each range of seismic index (I_{S2}). Since there is large variation of Visual Rating Index (I_{VR}) in each range, the boundaries are assumed based on first standard deviation. In this section, the boundaries are considered as from Table 7.5 as 0.09, 0.16, 0.23, 0.25, 0.45 for defining into 5 categories E, D, C, B, and A, respectively. The plots are divided into 5 categories as shown in Figure 7.22.

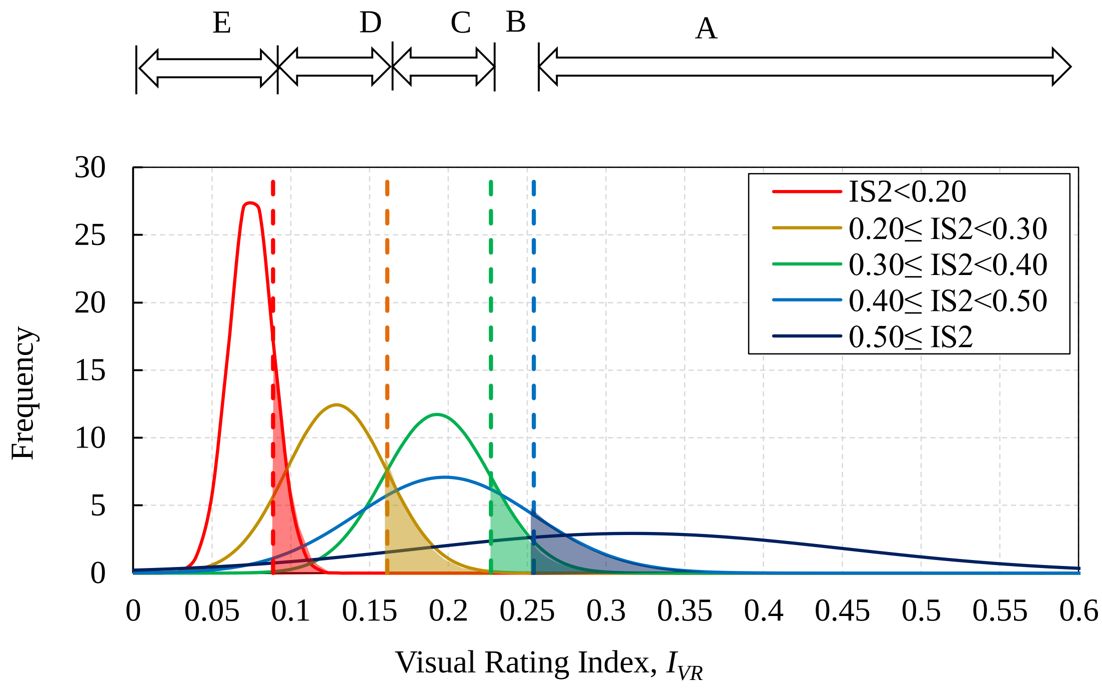


Figure 7.22 Normal distribution of Visual Rating Index (I_{VR}) cor. to seismic index (I_{S2})

Table 7.6 shows the proposed boundary and number of buildings (in percentages) are to be screened out for each categories of seismic index (I_{S2}). It is seen that the boundary is of 0.09 can screen 86% of total buildings in this range. However, the boundary larger than 0.23 and lower than 0.27 can screen out 86% of total buildings. It implies that there is variation in screening of building in each ranges Visual Rating Index (I_{VR}). Table 7.7 showing the proposed boundaries as per first standard deviation. Furthermore, cumulative number of buildings (in percentage) for each boundary is carried out for each boundary. The next section will describe about the proposal of boundaries according to cumulative percentage.

Table 7.6 Percentages of buildings to be screened out for each boundaries

Visual Rating Index, I_{VR}	The percentage (%) of building to be screened within the range
$0.23\leq I_{VR}<0.25$	86%
$0.16\leq I_{VR}<0.23$	87%
$0.09\leq I_{VR}<0.16$	83%
$I_{VR}<0.09$	86%

Table 7.7 Proposed judgement criteria according to Visual Rating index (I_{VR})

Categories	Description	Visual Rating Index (I_{VR})
A	No damage	$0.25 \le I_{VR}$
B	Light damage	$0.23 \le I_{VR} < 0.25$
C	Less Possibility of collapse	$0.16 \le I_{VR} < 0.23$
D	Moderate possibility of collapse	$0.09 \le I_{VR} < 0.16$
E	High possibility of collapse	$I_{VR} < 0.09$

7.8.3.2 Proposal of boundary based on cumulative percentage of building corresponding to Visual Rating Index (I_{VR})

Table 7.9 shows the mean and standard deviation of cumulative summation of visual rating index for each range of seismic index (I_{S2}). It has been observed that there is also large variation in visual rating index for every boundary corresponding to Seismic Index (I_{S2}).

Table 7.8 Variation between Visual Rating Index (I_{VR}) corresponding

Seismic index, I_{S2}	Visual Rating Index, (I_{VR})		
	Average	Standard Deviation	+1SD
$I_{S2} < 0.50$	0.16	0.06	0.22
$I_{S2} < 0.40$	0.15	0.06	0.21
$I_{S2} < 0.30$	0.11	0.04	0.15
$I_{S2} < 0.20$	0.08	0.01	0.09

Cumulative distribution function has been calculated for each range of seismic indices using mean and standard deviation of values of visual rating index which are log-normally distributed. Figure 7.23 shows distribution of building percentage for each range has been plotted according to visual rating index (I_{VR}). It has been observed that there is very small variation in cumulative distribution function in between seismic index (I_{S2}) is of 0.4 and 0.5. The main reason is that the average of these two ranges are almost similar. However, these variations will be increased by increasing the number of investigated buildings.

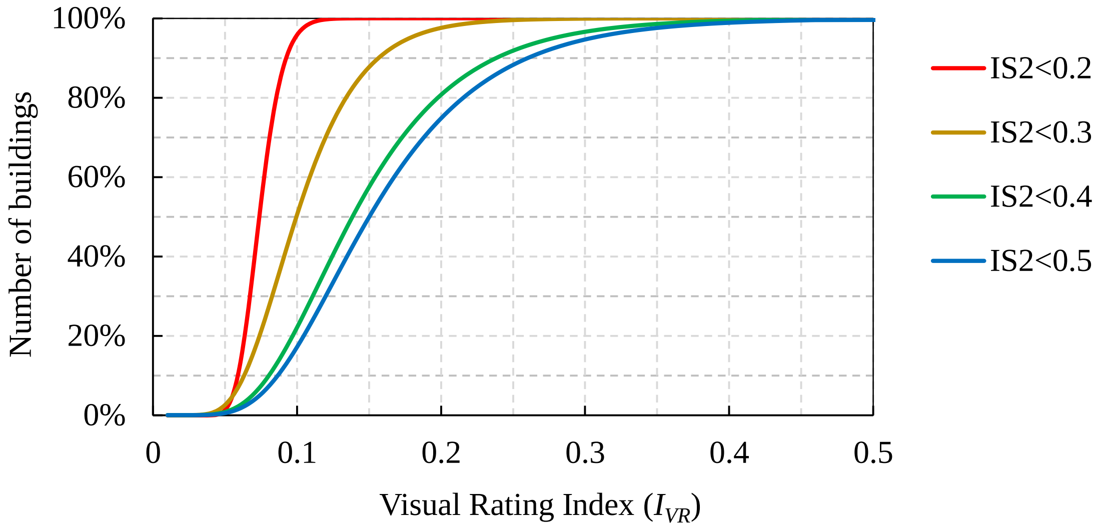


Figure 7.23 Cumulative percentage of building according to Visual rating index

In general, target of seismic evaluation procedure is all of vulnerable buildings should be captured using the borders or boundary line. Therefore, boundaries should set is such way that all vulnerable buildings are to be captured. In addition, it is acceptable even if some not vulnerable buildings are also included inside the boundary. Since there is large variation in each group of visual rating index, boundaries are set according to number of building can be screening out for each range of Visual rating index. Table 7.6 shows number of buildings can be screened corresponding to each case of proposed boundaries. It is observed that increasing target of captured buildings increase variation in higher range. This is due large deviation in higher visual rating index.

Table 7.9 Number of building to be identified for each boundaries

Number of buildings (percentages) identified in each categories	90%	95%
Visual Rating Index range	I_{VR} <0.26 I_{VR} <0.24 I_{VR} <0.16 I_{VR} <0.095	I_{VR} <0.31 I_{VR} <0.27 I_{VR} <0.18 I_{VR} <0.10

From the above discussion, it is evident that the border lines of each boundary varies on number of building screened in percentages. It has been concluded that the range of each boundary has been set according to reduce the range with 90% accuracy. Table 7.10 showing the proposed boundaries line according to Visual Rating Index (I_{VR}) for setting the priority for detailed evaluation.

Table 7.10 Proposed boundaries for Visual Rating method

Range of each Categories	Categories	Description
$0.26 \leq I_{VR}$	A	No damage
$0.24 \leq I_{VR} < 0.26$	B	Light damage
$0.16 \leq I_{VR} < 0.24$	C	Less Possibility of collapse
$0.10 \leq I_{VR} < 0.16$	D	Moderate possibility of collapse
$I_{VR} < 0.10$	E	High possibility of collapse

7.9 Summary of chapter 7

This chapter describes about proposal of judgment criteria for classification of existing RC buildings that are required for detail seismic evaluation. First of all, several model RC buildings have been chosen according to strength index (C), ductility index (F), and number of story. A response spectrum method has been applied on these model buildings to estimate the capacity demand ratio. The capacity demand ratio has been compared with seismic index (I_{S2}) of detail evaluation for establishing judgement criteria. Furthermore, judgement criteria have been proposed according to seismic index (I_{S2}) based on capacity-demand ratio. Finally, judgement criteria according to visual rating index (I_{VR}) has been proposed considering the obtained correlationship between seismic index (I_{S2}) and Visual rating index (I_{VR}) in chapter 6.

The conclusion of this chapter as follows:

1) This study proposes judgement criteria for seismic index (I_{S2}) is of 0.40 considering local seismicity and soil type, which is close to the value proposed in CNCRP manual (CNCRP 2015) of Bangladesh.
2) The judgement criteria have been proposed according the Visual Rating Index (I_{VR}) and the buildings are to be categorized into 5 classes such as A, B, C, D and E describing from less vulnerable to most vulnerable buildings.

3) From the criteria, the existing RC buildings with Visual Rating Index (I_{VR}) lower than 0.24 are regarded as vulnerable buildings, and the buildings with I_{VR}<0.10 are categorized as the most vulnerable buildings and detail evaluation is required for these buildings.

The proposed judgement criteria based on seismic evaluation of 22 existing RC buildings in Bangladesh. In order to increase the accuracy and effectiveness of the proposed judgement criteria, additional RC building survey and investigation is required.

Chapter 8

Conclusions and Recommendation

Past devastating earthquakes in developing countries have highlighted the existence of a large stock of vulnerable reinforced concrete buildings. Developing countries which are located in earthquake prone area, such as Bangladesh, do not have experience of recent major earthquakes; however, collapse of existing RC buildings such as Rana Plaza collapse (Dhaka city, Bangladesh) without earthquake also indicates the presence of a large stock of vulnerable buildings. The reason behind is an absence of updated seismic design codes and lack of legal enforcement of national building code. Furthermore, public awareness of safety is also lacking. Therefore, there is an urgent need to conduct seismic capacity evaluation of the existing RC building stock to identify cases where seismic capacity is deficient and take pragmatic action (such as strengthening and/or retrofitting) as countermeasure for future earthquakes. There are several seismic evaluation methods for evaluation of the seismic capacity of existing RC buildings. However, detailed seismic evaluations are very challenging for a large stock of existing RC buildings. There are several reasons for this, including requirements for detailed architectural and structural drawings along with other information that is not available in most of existing RC buildings in developing countries. In addition, there is a lack of expertise, budget, and time to conduct rigorous analysis and calculations, which is generally required for conducting the detailed seismic evaluation. In this regard, identification of the most vulnerable building is one of the effective ways to reduce the aforementioned limitations. Therefore, rapid seismic evaluation is very urgent and promising for managing these huge number of RC buildings stock with limited budget and time.

This research work focuses on the development of a rapid seismic evaluation method for identifying the most vulnerable buildings and proposes a strategy for further detailed evaluation of existing RC buildings. The development of the rapid seismic evaluation procedure involves understanding and simplification of the fundamental parameters which are required for seismic capacity estimation of existing RC buildings.

The objectives of the research are as follows:

Objective 1: Understand the basic characteristics of existing RC buildings and determine correlations with seismic damage.

Objective 2: Identify the most fundamental parameters that influence the seismic capacity.

Objective (Main Goal) 3: Develop a rapid seismic evaluation method and propose a strategy of detailed evaluation of existing RC buildings.

Significance of the research work:

As mentioned earlier, developing countries have huge stock of vulnerable buildings and are exhibiting interest in preparedness for the future earthquake disasters. Therefore, it is necessary to prepare a strategy or roadmap for the seismic evaluation of huge existing RC buildings stock within limited resources and budget. In this aspects, preliminary screening of existing RC buildings before detail evaluation is an effective strategy for seismic evaluation scheme. Here, preliminary screening stands for the identification of the most vulnerable buildings and prioritizing for detail evaluation. This research proposes a rapid seismic evaluation method for preliminary evaluation to identify the most vulnerable building and provides recommendation for detail evaluation. Furthermore, this research output will be helpful for policy makers to make strategic plan for seismic evaluation scheme of large building stock.

The major findings of this research are as follows:

Chapter 1: Introduction

This chapter described background, problem identification, major objectives and significant of the research and research framework. In background, the requirement of an effective rapid seismic evaluation method has been presented. In this aspect, several existing rapid seismic evaluation methods in different countries have been briefly reviewed. The limitations and shortcomings of existing rapid seismic evaluation method has been explained. Addressing the existing limitations, the research objectives are presented as to development of a rapid seismic evaluation which is effective for preliminary evaluation of existing buildings. Afterward, research significant and organization of the thesis are presented. Furthermore, several past researches and guidelines related to visual screening, simplified seismic evaluation and detail seismic evaluation of existing building, are discussed.

Chapter 2: Study on past earthquake damage databases

This chapter described the seismic capacity evaluation of past earthquake damaged RC building's database in different developing countries such as Ecuador, Nepal and Taiwan. The main objective of this chapter is to identify the most vulnerable parameters which influence the seismic capacity of RC buildings. This chapter has been divided into two major parts: understanding the basic characteristics of existing building and a correlation has been developed between seismic capacity and damage state of the investigated buildings.

The following conclusions are made as follows:

1) A correlation between basic parameters and seismic damage indicated that column area ratio and masonry infill wall area ratio has good correlation with damage ratio.
2) These simple parameters are regarded as the most influencing parameters for identifying the seismic capacity of existing buildings in other seismic region.
3) A correlation between seismic capacity and damage ratio is useful information to identify the seismic vulnerability of existing RC buildings of those countries where past earthquake recorded building database are not available.

Chapter 3 Study on existing RC buildings in Bangladesh

This chapter presented seismic evaluation of existing RC buildings in developing country where past earthquake damage database is not available. As a case study, existing RC building in Bangladesh have been collected for seismic capacity evaluation. These buildings database are originated from comprehensive disaster management program (CDMP) project of Government of Bangladesh. Seismic capacity has been evaluated based on basic information found from the database. The identified basic parameters of those existing RC buildings are compared with the earthquake damaged buildings as described in chapter 2 in other developing countries to identify a correlation between those parameters. Afterward, seismic capacity has also been compared with the damaged buildings databases for identifying the extent of damage level of existing buildings.

The summary of this chapter are as follows:

1) <u>Column area ratio and masonry infill wall area ratio are found lower (1.2 to 1.6 times</u> less) than other buildings database from different developing countries such as Ecuador, Nepal and Taiwan earthquake damage database.

2) The lower masonry infill ratio (≈1.7 times less) comparing with other databases indicates most of the investigated buildings in Bangladesh ground floor are open.
3) Seismic capacity of Bangladesh buildings is found much lower (≈1.5 times less) than comparing with other past earthquake damage databases of Ecuador, Nepal and Taiwan.
4) Probability of damage ratio for Bangladesh buildings has been estimated comparing with seismic capacity and ground motion intensity of each ground motion. Study shows that probability of severely damaged building is approximated about 36%, 43%, and 33% comparing with Ecuador, Nepal, and Taiwan earthquake damage database, respectively.

Chapter 4 Study on existing rapid visual screening methods

This chapter presents several existing rapid visual screening (RVS) methods such as FEMA P154, Turkish method, and other RVS methods. Main objective is to understand the background and application procedure of the existing RVS methods and to identify the effectiveness of such existing rapid visual screening methods in the world. However, these RVS methods have been applied in past earthquake damaged databases. In this study, Taiwan earthquake damage database has been chosen for application of the existing RVS method. The major findings from this chapter as follows:

1) Study shows that the score computed from these methods do not have correlation with corresponding seismic capacity of buildings.
2) The main limitation of these existing RVS methods is that those methods do not consider the basic parameter such as column area, wall area which are regarded as most influential parameters for seismic capacity estimation.
3) Thus, existing rapid visual screening methods are not effective for identifying the vulnerable buildings.

Chapter 5 Development of Visual Rating method

This chapter describes a proposal of rapid seismic evaluation method herein referred as Visual Rating (VR) method for screening of existing RC buildings. The proposed Visual Rating (VR) method considers fundamental parameters, buildings dimensions such as column and infill wall area ratio and their shear strength. The Visual Rating (VR) method approximately estimates the seismic capacity of existing RC buildings in terms of Visual Rating Index (I_{VR}). The development and application procedure have been described in this chapter.

The following conclusions are discussed as follows:

1) The Visual Rating (VR) method considers the simplified column area ratio and the simplified infill wall area ratio, which estimates the seismic capacity of existing RC buildings.
2) The inclusion of those column and infill wall area ratio in Visual Rating (VR) method is the new concept that have not been considered in the existing visual screening methods.
3) The Visual Rating Index (I_{VR}) proposed which approximates the seismic capacity of existing RC buildings.

However, the assumptions considered for column, masonry infill and concrete wall need further investigation for each countries according to local materials. Even though, this method is intended to buildings in Bangladesh, but could be easily adjusted to other countries by modifications for suitable characteristics of buildings and materials strength properties in the intended region.

Chapter 6 Survey of existing RC buildings in Bangladesh

This chapter presents the applicability and effectiveness of the proposed visual rating method. The main objective is to validate the effectiveness and applicability of the proposed method. In this regards, 22 existing buildings located at Dhaka, Bangladesh have been surveyed. The survey procedure has been subdivided into two major part. Part one is related into application of visual rating method. Part two is the preparation of as-built drawing because architectural drawings are not available of these surveyed buildings. As-built drawing is prepared due to conduct detail evaluation on these surveyed buildings.

A common survey datasheet is proposed for conducting of the visual rating method. The visual index has been calculated from information found from recorded survey datasheet. Detail evaluation has been done for first level and second level evaluation. The Visual Rating Index (I_{VR}) has been calibrated with the estimated first level and second level evaluation. Finally, a correlation has been established between visual rating index and seismic capacity of the surveyed buildings.

The following conclusions can be stated as follows:

1) The Visual Rating method considers the simplified column area ratio and the simplified wall area ratio, which estimates column area and infill wall area ratio efficiently. However, the normalized actual column area ratio by the simplified column area ratio, the average 1.19 and coefficient of variation 23% shows a good correlation between these parameters.
2) Visual Rating Index (I_{VR}) is efficient to estimate the seismic capacity of existing RC buildings. It has been observed that the normalized seismic index of first level evaluation and Visual Rating Index (I_{VR}), the average value is of 1.53 and coefficient of variation is of 35% shows a good estimation of seismic capacity of first level evaluation.
3) The average value of normalized seismic index (I_{S2}) by Visual Rating Index (I_{VR}) is 2.11 with coefficient of variation 33% indicates the Visual Rating Index (I_{VR}) score shows more conservative result with seismic index (I_{S2}) in second level evaluation. The reason is that I_{VR} assumes structural members as non-ductile members since ductility of column is difficult to be judged based only on visual inspection.

The proposed Visual Rating method is intended to estimate of seismic capacity of existing RC buildings in absence of detail seismic evaluation. From the above discussion, it has been observed that Visual Rating method provides lower boundary of seismic capacity of existing buildings. However, the estimated Visual Rating Index (I_{VR}) score is useful to provide judgement and prioritization of detail seismic evaluation which is the main of objective of the proposed Visual Rating Method.

Chapter 7 Judgement criteria for priority setting for detail evaluation

This chapter described about proposal of judgment criteria for classification of existing building that are required for detail seismic evaluation. First of all, some model RC buildings have been chosen as per strength index (C) and ductility index (F). A simplified response spectrum method is applied on these model buildings to estimate the capacity demand ratio. The capacity demand ratio is compared with seismic index of detail evaluation. These model buildings are investigated for establishing a correlation between capacity-demand ratio and seismic index of detail seismic evaluation. Furthermore, judgement criteria have been proposed according to seismic index (I_{S2}) based on capacity-demand ratio. Finally, judgement criteria according to visual rating index (I_{VR}) has been proposed considering the obtained correlation between seismic index (I_{S2}) and Visual rating index (I_{VR}) in chapter 6.

The conclusion of this chapter as follows:

1) This study proposes judgement criteria for seismic index (I_{S2}) is of 0.40 considering local seismicity and soil type, which is close to the judgement criteria proposed in CNCRP manual (CNCRP 2015) of Bangladesh.
2) The judgement criteria have been proposed according the Visual Rating Index (I_{VR}) and the buildings are to be categorized into 5 classes such as A, B, C, D and E describing from less vulnerable to most vulnerable buildings.
3) From the criteria, the existing RC buildings with Visual Rating Index (I_{VR}) lower than 0.24 are regarded as vulnerable buildings, and the buildings with I_{VR}<0.10 are categorized as the most vulnerable buildings and detail evaluation is required for these buildings.

The proposed judgement criteria based on seismic evaluation of 22 existing RC buildings in Bangladesh. In order to increase the accuracy and effectiveness of the proposed judgement criteria, additional RC building survey and investigation is required.

Chapter 8 Conclusions and recommendation

This chapter summarizes the major conclusions of all the chapters. This chapter discuss the limitations of the proposed method that needs further study such as material properties, modification factors for Visual Rating method and judgement criteria for priority settings.

Recommendation for future research:

- More buildings survey is required for increasing the accuracy of the proposed Visual Rating method and judgement criteria for priority settings.
- The material properties considered in this study requires further investigation to increase the accuracy for local materials.

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Table A: List of CDMP buildings database

Bldg. ID	No of Floors	Total floor Area (m^2)	Area of column (m^2)	Masonry wall area in x direction (m^2)	Masonry wall area in Y direction (m^2)
W01_001	6	1680	2.84	2.46	4.84
W01_003	6	1404	2.65	4.66	5.79
W01_008	6	1434	2.31	2.56	0.56
W01_010	6	1770	3.81	1.66	1.24
W01_015	6	996	2.17	1.66	1.21
W01_061	6	1602	2.19	0.46	1.24
W01_067	6	1272	2.22	1.08	0.93
W01_069	6	1572	3.19	1.63	0.00
W01_070	5	1240	3.21	1.66	0.62
W01_071	6	1266	2.36	0.66	0.45
W01_100	6	1584	2.88	0.70	1.55
W01_151	5	775	1.43	0.45	1.90
W01_159	6	918	1.83	1.20	2.90
W01_162	6	846	1.91	4.43	4.10
W01_166	6	1158	2.10	2.71	2.19
W01_174	5	800	1.35	0.70	1.86
W01_178	6	1068	3.41	2.50	1.14
W01_192	6	2238	2.94	1.20	1.20
W01_195	6	1314	2.33	2.73	0.52
W01_206	6	2502	3.49	5.09	1.24
W01_221	6	1848	2.95	1.27	1.45
W01_222	6	2046	2.70	1.16	2.52
W01_223	6	1758	1.95	0.23	1.97
W01_227	6	1548	2.95	2.28	4.22
W01_233	6	1986	4.35	3.06	2.46
W01_234	6	2430	3.06	1.28	1.82
W01_235	6	2406	3.42	1.56	1.70
W01_242	6	1398	2.37	1.84	0.59
W01_249	6	1530	3.52	0.54	0.54
W01_250	6	2082	4.29	0.40	0.79
W01_251	6	2430	2.78	2.21	1.31
W01_257	6	1326	2.31	0.62	0.54
W01_259	6	1560	2.40	1.94	2.96
W01_263	6	1506	1.92	1.86	1.22
W01_267	6	1272	2.72	3.46	4.51
W01_272	6	1854	2.18	0.74	0.54
W01_274	6	1572	2.42	1.30	2.13

Bldg. ID	No of Floors	Total floor Area (m^2)	Area of column (m^2)	Masonry wall area in x direction (m^2)	Masonry wall area in Y direction (m^2)
W01_280	6	2400	2.26	1.90	1.66
W01_281	6	2472	3.61	4.53	3.89
W01_285	6	2040	3.62	2.05	1.73
W01_331	6	1470	2.21	1.94	1.90
W01_332	6	1734	2.15	3.97	1.80
W01_333	6	1938	3.08	0.70	2.83
W01_334	6	1218	3.86	1.14	1.87
W01_335	6	1536	2.81	1.64	1.28
W01_336	6	1428	3.66	2.05	1.63
W01_337	6	1494	3.15	1.94	0.89
W01_338	6	1332	3.83	1.60	2.19
W01_339	6	1662	2.92	1.32	0.54
W01_341	6	858	2.25	1.54	2.71
W01_342	6	912	2.06	1.28	1.12
W01_343	5	680	1.33	1.88	0.97
W01_344	6	1008	1.38	1.20	0.87
W01_345	6	714	1.63	0.50	0.39
W02_026	6	660	1.39	0.39	2.28
W02_033	3	306	1.55	0.43	0.00
W02_060	6	786	1.11	2.25	0.39
W02_061	6	654	1.16	0.50	2.55
W02_063	7	637	1.39	0.00	0.00
W02_087	6	570	1.16	0.00	0.00
W03_002	6	598	0.77	0.89	1.05
W03_012	3	261	1.16	0.85	0.97
W03_016	6	1026	2.04	0.85	0.85
W03_030	6	984	1.39	2.07	3.19
W03_062	6	732	1.16	0.97	3.91
W03_071	6	828	1.16	1.34	2.94
W03_101	3	906	2.39	0.85	0.85
W03_119	5	720	1.65	0.93	0.70
W04_008	5	570	1.32	0.97	1.16
W04_042	5	535	0.83	1.45	1.63
W04_060	1	112	0.77	0.85	0.85
W04_066	3	348	1.08	1.32	1.43
W04_086	5	680	1.20	0.93	0.66
W04_093	2	270	1.01	0.85	1.47

Bldg. ID	No of Floors	Total floor Area (m^2)	Area of column (m^2)	Masonry wall area in x direction (m^2)	Masonry wall area in Y direction (m^2)
W04_110	5	375	1.29	0.46	1.08
W04_113	4	456	1.16	2.90	3.87
W05_011	7	2226	2.65	2.19	1.34
W05_012	6	1500	2.65	2.17	1.92
W05_047	6	570	1.67	0.48	0.62
W06_003	5	570	1.11	0.46	1.01
W06_004	5	565	1.26	0.27	1.01
W06_012	5	600	1.72	0.27	1.01
W06_033	6	444	1.43	0.41	1.74
W06_037	6	474	1.43	1.63	1.74
W06_079	3	279	0.97	0.93	0.70
W07_005	6	1278	2.16	0.64	3.39
W07_017	6	768	1.43	3.23	0.43
W07_044	5	515	0.88	0.00	0.00
W07_049	6	816	1.74	0.52	0.00
W07_079	3	417	0.90	0.00	0.00
W08_009	5	400	1.55	0.79	0.00
W08_012	4	776	0.89	0.00	0.00
W08_023	2	212	0.90	1.08	1.94
W08_026	3	255	0.83	0.77	0.85
W08_032	2	142	0.45	0.93	0.58
W09_042	6	918	1.24	0.00	0.00
W10_004	7	1932	2.18	0.93	0.00
W10_007	3	414	1.16	0.93	0.70
W10_021	5	485	2.55	0.54	0.00
W10_028	3	564	2.32	2.09	2.13
W10_079	4	1144	2.23	2.17	0.00
W11_010	1	112	1.24	0.00	0.00
W11_011	6	1122	1.70	1.86	2.01
W11_013	6	2136	1.74	0.00	3.10
W11_056	6	2508	3.94	1.51	0.00
W11_118	6	2694	3.09	1.66	1.86
W12_006	2	210	0.77	0.46	1.16
W12_010	4	420	1.61	7.01	3.10
W12_028	4	572	1.16	0.00	0.46
W12_029	5	580	1.30	0.31	0.46
W12_038	5	675	1.67	0.46	0.31

Bldg. ID	No of Floors	Total floor Area (m^2)	Area of column (m^2)	Masonry wall area in x direction (m^2)	Masonry wall area in Y direction (m^2)
W12_043	4	508	1.16	1.86	3.02
W12_085	3	606	1.49	0.77	0.77
W12_090	5	1175	2.04	1.24	1.24
W13_011	2	404	1.29	0.93	1.55
W13_017	6	660	1.39	0.00	0.43
W13_021	3	369	1.03	1.16	0.00
W13_022	3	546	1.49	1.63	1.08
W13_033	3	363	0.77	0.00	0.00
W13_043	2	210	1.03	0.93	0.93
W13_047	4	492	1.58	0.31	0.00
W13_048	5	395	1.11	0.70	0.31
W13_050	3	549	1.48	4.03	2.32
W13_057	3	378	0.90	0.85	1.32
W13_073	3	567	1.49	0.50	0.39
W13_081	6	636	1.74	0.00	1.59
W13_090	3	246	1.56	0.46	0.31
W13_135	4	484	1.67	0.46	0.93
W13_153	3	408	1.03	0.39	0.54
W13_172	5	635	1.48	0.85	0.00
W13_175	2	276	1.30	0.39	0.31
W13_176	3	336	1.03	0.00	0.62
W13_178	2	366	1.78	0.00	0.00
W13_183	3	534	1.16	0.31	0.97
W13_185	3	381	2.55	0.70	0.31
W13_193	5	620	1.16	0.46	0.85
W13_194	3	477	1.10	0.31	0.46
W14_026	6	1518	3.25	0.62	0.62
W14_056	3	525	1.10	1.08	0.50
W14_057	5	515	1.26	2.01	0.62
W14_058	4	436	0.90	0.77	0.93
W14_067	6	660	0.93	3.14	0.97
W14_068	3	408	1.21	0.66	1.12
W14_069	6	852	1.44	0.00	1.05
W14_077	4	544	1.10	0.81	0.70
W14_078	4	660	1.10	1.55	2.79
W14_094	6	1020	1.67	1.01	1.12
W14_112	2	620	0.77	0.93	0.93

Bldg. ID	No of Floors	Total floor Area (m^2)	Area of column (m^2)	Masonry wall area in x direction (m^2)	Masonry wall area in Y direction (m^2)
W14_118	3	384	1.67	4.03	2.36
W14_142	3	312	0.71	1.05	1.51
W14_146	5	620	1.21	2.25	3.33
W14_147	6	900	1.21	1.63	1.59
W15_013	1	56	0.84	1.28	0.00
W16_022	2	236	1.45	1.03	1.30
W16_025	4	532	1.10	1.55	0.85
W16_044	6	588	1.16	0.62	1.55
W16_049	3	951	3.48	5.73	2.63
W16_060	6	1260	2.44	8.52	3.45
W16_138	2	158	1.48	0.00	2.79
W16_147	4	556	1.82	1.55	1.86
W16_165	6	936	1.70	0.62	1.86
W16_169	5	585	1.08	4.95	2.13
W16_173	5	1030	1.42	2.94	3.10
W16_174	4	408	1.65	1.86	0.31
W16_190	4	352	1.16	0.77	0.77
W17_008	3	351	1.08	3.02	1.78
W17_040	5	515	0.94	2.75	2.90
W17_044	4	584	0.93	0.62	0.27
W17_059	4	564	1.08	0.00	1.12
W17_060	4	404	1.05	0.27	1.12
W18_020	6	2784	5.92	0.00	0.00
W18_021	6	2658	2.83	0.00	0.00
W18_036	5	650	2.90	0.00	0.00
W18_065	6	1668	2.39	0.00	0.00
W18_078	7	2394	3.97	0.00	0.00
W19_032	6	2628	4.31	4.26	3.25
W19_062	6	2742	3.37	1.65	0.00
W19_070	6	1926	3.25	0.70	2.90
W19_080	6	3624	5.53	1.61	1.28
W19_088	6	3534	5.46	0.00	0.00
W19_100	6	2334	4.41	0.27	0.85
W20_011	6	4038	2.69	0.00	0.00
W20_021	9	2151	1.63	0.00	0.00
W20_038	2	398	3.59	4.78	3.56
W20_063	4	652	1.95	1.47	0.81

Bldg. ID	No of Floors	Total floor Area (m^2)	Area of column (m^2)	Masonry wall area in x direction (m^2)	Masonry wall area in Y direction (m^2)
W20_079	6	732	1.55	3.91	3.54
W21_014	2	420	0.71	2.86	2.01
W21_032	4	384	0.76	3.29	1.16
W21_043	2	366	1.35	1.63	0.58
W22_081	3	477	1.16	1.56	0.00
W22_085	5	460	0.77	0.00	0.00
W22_091	2	222	1.29	0.31	0.00
W22_096	1	156	1.35	1.06	0.67
W22_098	3	423	1.42	0.00	0.00
W22_101	6	1272	1.86	1.16	0.00
W22_119	3	327	1.03	0.31	0.00
W22_125	2	556	2.90	0.00	0.00
W22_126	2	226	2.79	1.59	1.69
W22_129	4	524	1.16	0.54	0.35
W22_130	5	655	1.32	0.93	0.85
W22_132	3	609	2.55	1.24	0.00
W23_007	6	396	1.35	3.25	1.16
W23_013	6	756	2.55	4.92	0.70
W23_035	5	1155	1.39	4.41	0.77
W23_038	3	993	3.47	2.28	2.01
W23_047	7	5229	2.09	4.92	1.16
W24_012	6	798	1.23	1.55	1.86
W24_076	6	936	1.32	0.00	0.00
W24_079	6	408	1.35	0.00	0.00
W24_098	5	610	1.65	0.00	0.00
W24_120	2	846	2.23	0.00	0.00
W24_125	6	1326	3.66	3.10	3.99
W24_126	6	1188	3.25	0.00	0.00
W25_001	3	792	1.55	2.28	4.92
W25_003	3	303	0.77	2.94	2.32
W25_010	1	113	1.01	0.00	0.00
W25_015	4	356	0.97	1.70	2.48
W25_017	2	458	2.28	3.10	5.19
W25_019	2	174	0.88	0.00	0.00
W25_020	4	528	1.08	1.08	0.00
W25_028	3	264	0.90	0.00	0.00
W25_034	3	597	1.14	0.00	0.00

Bldg. ID	No of Floors	Total floor Area (m^2)	Area of column (m^2)	Masonry wall area in x direction (m^2)	Masonry wall area in Y direction (m^2)
W25_038	1	166	1.06	2.17	2.01
W26_005	6	1350	3.99	1.32	1.12
W26_010	7	1421	1.86	5.26	0.00
W26_013	3	639	1.51	0.00	1.39
W26_017	3	534	1.46	0.35	0.93
W26_021	4	648	1.46	0.35	0.93
W26_022	4	648	1.46	0.35	0.93
W26_031	2	228	1.01	3.79	1.94
W27_007	6	1980	3.35	0.00	0.00
W27_022	5	615	4.46	0.00	0.00
W27_038	6	708	1.24	0.00	0.00
W27_045	6	1092	1.86	0.00	1.08
W27_085	6	738	1.16	1.32	0.62
W27_117	1	89	0.58	0.62	1.24
W28_001	6	1368	2.78	1.63	0.00
W28_006	5	695	1.86	0.62	1.25
W28_009	2	104	0.97	0.77	0.00
W29_016	4	364	1.45	0.00	0.35
W29_018	2	266	0.97	0.85	0.77
W29_021	4	556	2.00	0.00	0.00
W29_031	2	246	2.25	0.00	0.00
W29_051	3	510	1.39	0.50	0.00
W29_056	2	360	1.42	1.70	0.00
W29_062	3	165	1.74	0.00	0.00
W29_067	4	444	0.77	0.00	0.00
W32_009	3	1758	7.43	0.00	0.00
W32_014	4	2552	3.14	0.00	0.00
W32_034	4	408	1.61	0.00	0.00
W32_035	6	756	1.16	2.13	0.00
W32_051	4	744	3.19	0.00	0.00
W32_052	6	1998	4.06	2.40	0.00
W32_053	8	2648	4.94	0.00	0.00
W35_014	6	2742	4.65	1.08	0.81
W35_015	4	2120	3.83	0.00	0.00
W35_019	6	1572	2.13	0.00	0.93
W35_021	4	656	2.19	0.00	0.00
W35_045	3	558	2.17	0.00	0.00

Bldg. ID	No of Floors	Total floor Area (m^2)	Area of column (m^2)	Masonry wall area in x direction (m^2)	Masonry wall area in Y direction (m^2)
W35_053	4	1136	2.32	0.00	3.41
W35_060	4	400	1.16	0.50	0.50
W35_061	4	1420	4.88	0.00	4.65
W35_071	5	1535	2.81	0.00	0.00
W35_101	6	876	2.09	0.97	0.00
W35_141	4	472	1.16	0.77	0.66
W35_143	2	372	2.32	0.00	2.67
W36_012	13	6045	8.05	2.71	2.79
W36_019	6	1770	1.90	1.47	0.81
W36_030	6	456	1.30	0.77	0.00
W36_034	6	2112	3.47	1.55	0.00
W36_037	6	642	2.55	0.00	0.00
W36_058	5	920	2.43	2.09	1.86
W36_059	7	889	1.92	0.00	0.77
W36_080	5	865	1.84	0.46	0.00
W36_081	6	1080	1.70	0.00	0.00
W36_090	6	1254	1.26	0.62	0.00
W36_114	4	436	1.11	0.00	0.54
W37_005	2	340	1.94	0.00	0.00
W37_015	10	4670	6.77	2.09	0.77
W37_106	5	1790	1.86	0.31	1.01
W37_117	7	1526	1.39	0.70	0.46
W37_125	3	498	1.63	0.00	0.00
W37_140	6	930	1.65	1.94	1.86
W37_142	6	1110	2.13	3.10	2.61
W38_025	6	576	1.16	2.44	5.11
W38_028	5	670	1.42	4.65	2.79
W38_040	5	660	3.16	1.22	0.85
W38_054	5	1190	1.39	1.20	1.86
W38_089	4	396	1.23	3.52	3.10
W38_116	6	1212	2.41	1.78	3.79
W38_138	6	648	1.65	3.17	3.79
W38_144	7	448	2.06	2.25	2.01
W38_150	5	485	1.16	3.25	1.34
W39_008	6	978	2.79	0.00	0.00
W39_011	6	1044	2.23	0.00	0.00
W39_013	6	3072	2.79	0.00	0.00

Bldg. ID	No of Floors	Total floor Area (m^2)	Area of column (m^2)	Masonry wall area in x direction (m^2)	Masonry wall area in Y direction (m^2)
W39_072	5	620	1.08	0.00	0.00
W39_073	5	765	2.09	0.00	0.00
W39_074	6	1488	3.59	0.00	0.00
W39_077	7	1554	1.75	0.00	0.00
W39_087	4	492	1.23	0.00	0.00
W39_108	5	605	1.30	0.00	0.00
W39_136	7	1029	3.82	0.00	0.00
W39_137	6	1590	3.72	0.00	0.00
W39_139	6	2730	3.56	0.00	0.00
W40_004	6	1524	5.02	0.00	0.31
W40_005	6	1482	1.72	1.90	0.39
W40_023	3	357	1.49	1.35	2.01
W40_047	5	970	1.74	2.79	2.01
W40_052	6	1524	2.25	1.86	2.90
W40_066	3	420	1.63	1.24	1.24
W40_070	5	410	2.19	0.00	0.93
W40_083	3	270	1.28	0.00	0.46
W40_087	2	288	1.89	0.00	0.39
W40_103	3	441	1.37	0.00	0.39
W40_123	4	592	1.97	0.00	0.46
W40_130	4	716	2.23	0.00	0.85
W40_146	5	925	1.74	0.00	0.00
W40_153	6	1122	1.60	0.00	0.00
W40_160	3	330	1.74	0.31	0.46
W40_169	2	388	1.67	0.00	0.00
W40_175	3	600	1.24	0.31	0.00
W40_182	4	204	1.11	0.00	0.58
W40_197	8	1304	1.63	0.46	0.23
W40_198	3	297	1.63	0.35	0.00
W40_213	4	220	1.65	4.34	2.17
W40_218	4	532	1.39	3.60	2.32
W41_004	6	1368	2.79	1.39	0.00
W41_018	4	672	2.23	2.94	2.40
W41_030	4	500	1.86	2.40	2.40
W41_038	4	784	2.09	3.02	1.63
W41_045	5	985	2.44	2.01	0.46
W41_061	3	666	2.23	5.65	3.17

Bldg. ID	No of Floors	Total floor Area (m^2)	Area of column (m^2)	Masonry wall area in x direction (m^2)	Masonry wall area in Y direction (m^2)
W41_073	3	642	2.90	2.71	5.26
W42_002	9	5643	9.41	3.10	2.86
W42_013	5	580	1.67	2.61	1.75
W42_014	6	996	2.09	0.00	0.56
W42_035	3	843	1.16	6.23	1.16
W42_039	6	960	1.58	3.72	0.31
W42_068	6	1062	1.39	4.34	0.00
W42_069	6	516	1.16	2.94	2.36
W42_073	2	336	2.09	0.00	4.03
W42_091	6	942	1.66	0.43	0.46
W42_092	9	2187	4.06	1.39	2.17
W42_096	6	1854	3.02	0.50	2.48
W42_097	5	905	1.94	3.02	1.16
W42_113	5	1160	1.97	0.93	2.55
W42_123	6	972	2.17	0.43	2.09
W43_008	6	1722	3.21	0.00	0.93
W43_014	5	605	1.19	3.62	1.35
W43_020	4	536	1.23	1.28	0.89
W43_028	5	1085	1.99	2.36	3.46
W43_031	5	770	1.37	1.12	0.81
W43_034	6	1500	2.32	0.35	1.32
W43_050	6	990	1.65	0.31	0.54
W43_057	6	852	1.32	3.87	2.21
W43_063	5	1355	0.58	3.79	3.02
W43_072	6	1512	1.69	2.01	3.02
W43_077	6	1956	1.19	1.20	0.50
W43_084	6	1896	1.77	0.93	0.46
W43_097	4	460	1.05	0.46	1.78
W43_102	7	2128	2.65	0.00	0.93
W44_015	3	1182	5.11	0.00	4.84
W44_016	4	636	3.25	0.00	5.19
W44_027	6	750	1.16	3.02	1.86
W44_033	6	762	1.67	2.28	2.17
W44_034	6	582	1.16	3.17	1.95
W44_036	9	3915	6.03	0.00	4.26
W44_066	3	969	3.83	2.01	0.00
W44_068	6	2268	2.52	1.16	0.35

Bldg. ID	No of Floors	Total floor Area (m^2)	Area of column (m^2)	Masonry wall area in x direction (m^2)	Masonry wall area in Y direction (m^2)
W45_007	5	1565	1.94	5.77	2.71
W45_021	6	846	2.06	0.00	0.81
W45_039	6	1116	2.26	0.00	0.39
W45_052	6	942	1.30	4.06	0.96
W45_071	6	1566	3.29	1.30	1.43
W45_077	6	1680	2.26	0.35	0.31
W45_110	6	792	1.39	4.26	2.34
W45_115	6	834	1.48	1.09	2.05
W46_005	6	1380	2.60	0.00	0.00
W46_015	3	498	3.62	1.34	0.39
W46_055	6	1224	2.17	0.81	0.89
W46_060	4	872	3.83	0.74	2.21
W46_063	7	1708	3.41	1.12	0.50
W46_109	6	1254	1.86	0.39	1.20
W46_110	8	2128	1.03	4.49	3.12
W46_128	4	864	2.76	1.01	0.41
W46_141	6	3480	8.24	1.43	2.36
W46_169	6	1164	2.48	0.23	0.81
W46_170	6	1980	2.32	1.08	0.00
W46_179	6	834	1.73	0.41	0.46
W46_182	6	516	2.37	0.75	1.01
W46_184	6	1578	2.90	1.24	0.00
W47_011	3	480	3.60	0.00	0.00
W47_038	5	470	4.35	0.00	0.00
W47_062	3	1392	2.55	0.00	0.00
W47_064	3	153	2.13	0.00	0.00
W47_082	3	186	0.90	1.55	0.00
W47_088	6	900	1.65	0.00	0.00
W47_089	6	3546	3.87	0.00	0.00
W47_096	6	2142	4.21	0.00	0.00
W47_109	5	650	2.19	0.00	0.00
W47_111	6	2688	4.39	0.00	0.00
W47_144	5	340	1.32	0.00	0.00
W48_002	5	880	2.09	3.19	1.70
W48_007	6	1182	2.17	0.77	0.31
W48_069	12	7164	8.18	0.73	3.04
W48_070	7	2219	3.62	0.00	0.00

Bldg. ID	No of Floors	Total floor Area (m^2)	Area of column (m^2)	Masonry wall area in x direction (m^2)	Masonry wall area in Y direction (m^2)
W49_011	6	1092	3.16	0.00	0.00
W49_013	6	732	2.04	0.00	0.00
W49_023	6	1950	3.61	0.00	0.00
W49_031	6	3654	4.39	0.00	0.00
W49_048	11	2673	3.15	0.00	0.00
W49_052	6	1200	2.67	0.00	0.00
W49_055	10	2480	3.90	0.00	0.00
W49_056	9	1629	2.52	0.00	0.00
W49_103	6	5232	3.34	0.00	0.00
W49_105	6	2232	2.79	0.00	0.00
W49_107	6	2622	2.97	0.00	0.00
W49_109	6	1662	3.95	0.00	0.00
W49_114	6	2436	6.19	0.00	0.00
W49_117	5	1565	3.05	0.00	0.00
W49_120	5	965	2.97	1.35	0.00
W49_125	6	2376	5.76	0.00	0.00
W49_128	6	3594	6.27	0.00	0.00
W49_130	6	1788	2.32	0.00	0.00
W49_131	6	1428	2.93	0.00	0.00
W49_199	6	2592	3.72	0.00	0.00
W50_002	6	1284	3.34	2.55	0.00
W50_016	5	810	1.39	0.00	0.39
W50_028	4	312	2.60	2.48	0.39
W50_036	6	1008	3.14	0.93	0.00
W50_050	6	972	3.80	0.54	0.00
W50_054	3	264	1.11	0.46	0.00
W50_070	3	213	1.39	0.00	0.00
W50_076	3	510	1.65	0.04	0.70
W51_012	5	600	0.93	0.00	0.93
W51_023	3	672	2.23	0.00	0.00
W51_048	6	1704	1.65	0.00	0.00
W51_051	7	4172	10.84	0.00	0.00
W51_070	6	900	3.48	0.77	0.00
W51_074	6	2520	3.87	0.00	0.00
W53_008	6	1674	4.84	1.55	0.00
W53_012	6	1290	2.79	0.00	0.00
W53_016	10	5170	5.29	0.39	1.51

Bldg. ID	No of Floors	Total floor Area (m^2)	Area of column (m^2)	Masonry wall area in x direction (m^2)	Masonry wall area in Y direction (m^2)
W53_037	8	1656	2.10	0.00	0.00
W53_045	6	1140	2.71	0.58	0.00
W53_050	10	5890	7.53	0.00	0.00
W53_063	9	4716	6.97	1.08	0.00
W53_074	7	1498	2.76	1.39	0.27
W53_078	5	820	1.95	0.46	0.62
W53_086	6	792	1.21	0.70	1.12
W53_104	5	1880	4.06	0.00	5.11
W53_111	6	1518	2.58	0.93	0.00
W53_112	12	2904	3.10	0.00	0.00
W53_136	7	1855	3.10	2.01	1.78
W54_002	5	620	0.84	0.50	1.06
W54_008	6	1092	1.66	1.12	0.00
W54_048	5	985	2.81	0.00	0.00
W54_076	6	768	9.96	0.00	0.00
W56_010	10	5300	8.28	1.24	0.00
W56_011	8	4184	12.90	1.12	0.00
W56_019	6	3048	8.52	3.17	1.47
W56_024	9	2547	5.16	1.51	1.20
W56_028	9	4608	6.19	0.00	0.00
W56_039	11	2233	3.95	0.00	0.00
W56_043	5	1595	4.46	1.86	1.24
W56_044	5	1310	6.97	1.55	2.05
W56_048	6	3006	6.97	1.55	0.93
W56_058	9	2376	2.71	0.00	0.31
W56_070	9	3420	6.77	0.00	0.54
W56_073	7	3878	7.93	0.00	0.70
W57_007	8	1048	1.49	0.00	0.00
W57_008	11	2134	2.65	0.00	0.77
W57_057	6	1800	2.91	0.00	0.00
W57_082	4	1312	3.48	3.56	7.74
W58_010	3	810	3.72	0.00	4.35
W58_036	5	560	1.39	1.20	0.52
W58_040	4	1024	4.06	0.00	1.06
W58_043	2	312	1.74	2.21	4.49
W58_071	5	225	1.58	0.99	1.39
W58_085	4	616	2.90	1.70	1.05

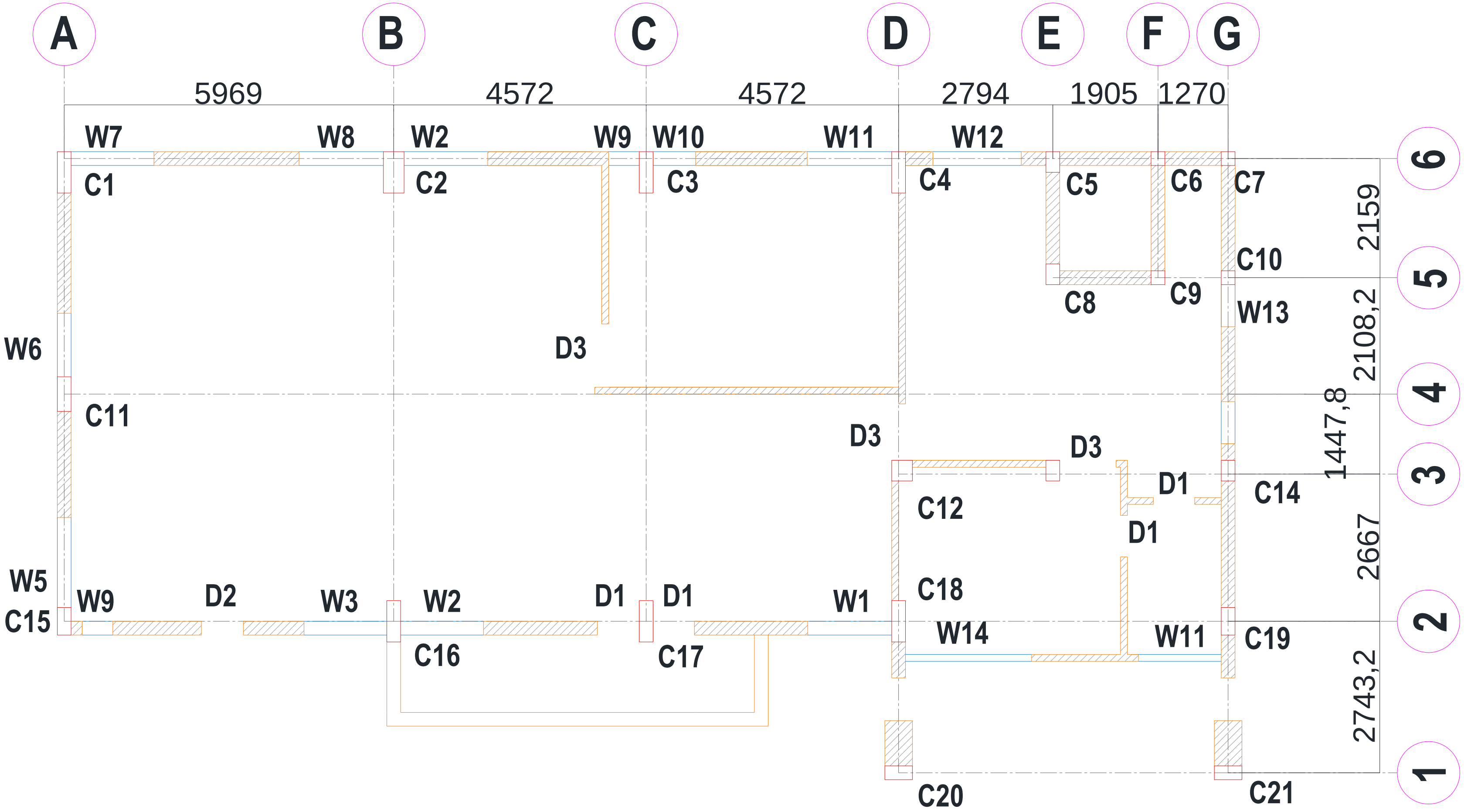
Bldg. ID	No of Floors	Total floor Area (m^2)	Area of column (m^2)	Masonry wall area in x direction (m^2)	Masonry wall area in Y direction (m^2)
W58_087	5	3420	2.26	3.34	1.22
W58_100	4	716	4.09	0.70	0.70
W58_107	6	282	0.77	0.52	0.00
W58_127	4	208	0.45	0.00	0.00
W58_128	6	354	1.11	1.90	1.78
W58_143	2	388	3.48	0.00	3.37
W59_004	3	342	0.87	1.70	2.32
W59_013	6	708	0.88	1.16	1.78
W59_024	5	1320	2.79	0.00	0.00
W59_025	6	2202	3.87	0.00	0.39
W59_045	6	306	1.21	0.00	0.00
W59_069	4	252	0.77	1.55	0.93
W59_077	4	404	1.11	0.00	2.17
W59_080	3	822	1.28	0.43	0.00
W59_090	7	1232	2.21	2.59	1.63
W59_097	5	475	1.49	1.47	1.28
W59_103	4	1560	0.84	1.43	2.17
W59_110	3	198	0.70	1.43	2.17
W60_009	4	588	1.39	1.24	1.94
W60_015	3	393	1.10	1.16	3.72
W60_033	2	144	0.77	2.17	2.17
W60_082	2	250	1.39	2.01	0.77
W61_036	4	388	1.55	0.00	0.00
W61_099	3	597	1.03	0.00	0.00
W61_101	5	1050	3.25	0.00	0.00
W62_002	3	162	0.74	1.16	1.01
W62_014	5	470	1.16	0.00	1.51
W62_032	4	852	2.00	1.95	1.83
W62_033	4	620	1.45	1.47	0.35
W63_047	7	2016	1.63	2.32	3.10
W64_010	6	930	1.74	1.16	0.00
W64_027	7	441	1.39	1.01	1.16
W64_028	6	834	1.58	1.63	0.45
W64_057	6	252	0.84	0.66	0.00
W65_015	5	340	0.93	0.00	1.08
W65_017	6	468	1.49	0.00	1.70
W65_027	6	1812	4.65	0.00	6.04

Bldg. ID	No of Floors	Total floor Area (m^2)	Area of column (m^2)	Masonry wall area in x direction (m^2)	Masonry wall area in Y direction (m^2)
W65_032	6	738	2.09	0.27	0.58
W65_033	6	558	1.74	0.54	0.35
W65_063	6	1854	4.65	0.00	6.04
W65_070	4	684	2.79	5.26	1.18
W67_017	5	370	2.01	0.00	0.00
W70_032	7	490	1.17	0.00	0.00
W70_039	6	1062	1.53	0.00	0.00
W71_014	6	924	2.45	0.60	0.00
W71_028	5	405	0.78	0.00	0.00
W72_009	2	68	1.11	0.46	0.58
W72_010	2	228	1.74	0.00	0.66
W72_025	3	396	1.55	0.00	0.00
W72_057	3	603	1.89	0.54	0.00
W72_060	5	225	1.74	0.00	0.00
W73_017	4	984	3.34	0.00	10.37
W73_025	5	670	2.51	1.39	0.68
W74_008	3	420	2.44	3.29	2.94
W74_021	3	822	2.79	2.71	3.87
W74_030	5	460	0.93	0.93	3.17
W74_052	4	392	1.24	2.32	2.17
W74_055	6	924	2.90	2.48	3.72
W75_004	6	1254	1.86	0.43	0.79
W75_005	5	260	0.84	0.65	0.39
W75_006	6	774	1.00	0.34	1.05
W75_012	8	3848	6.27	1.59	0.54
W75_016	8	2312	1.86	1.28	0.00
W75_028	6	858	2.01	2.40	1.70
W76_011	2	148	0.77	0.89	3.72
W76_026	3	288	0.90	2.45	1.88
W76_028	3	147	1.29	1.70	4.52
W76_032	6	738	1.37	0.49	0.18
W77_020	4	260	0.93	0.85	1.28
W78_005	6	948	1.74	0.31	0.46
W78_012	3	591	1.87	0.87	3.48
W78_022	7	2191	2.12	0.82	0.95
W79_042	6	1266	1.82	1.47	0.00
W79_058	5	295	1.02	0.93	0.00

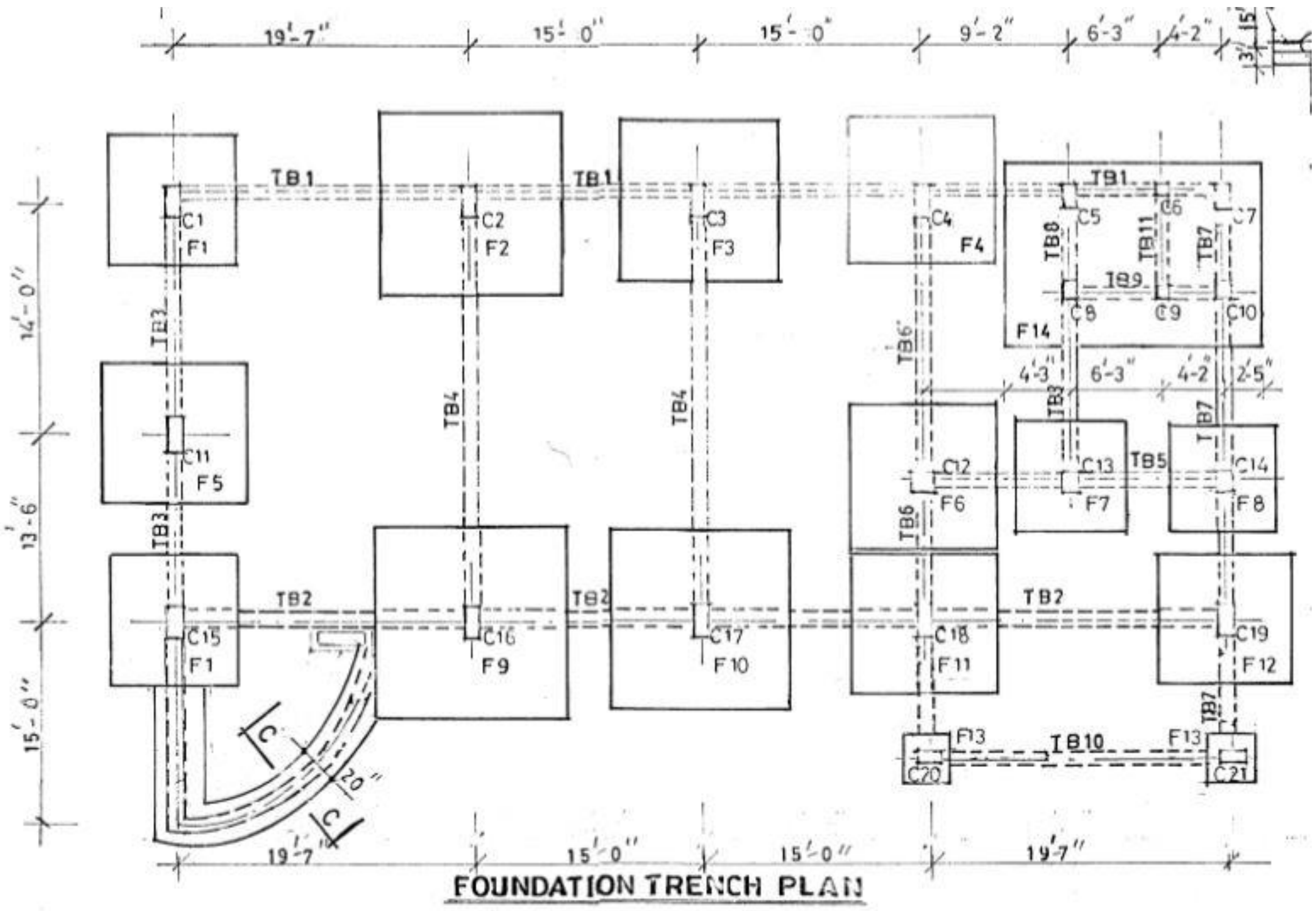
Bldg. ID	No of Floors	Total floor Area (m^2)	Area of column (m^2)	Masonry wall area in x direction (m^2)	Masonry wall area in Y direction (m^2)
W79_064	3	477	1.74	1.94	0.00
W79_072	6	336	1.54	0.97	0.00
W79_081	4	416	1.19	0.54	0.58
W81_012	5	675	1.03	0.39	0.00
W82_028	5	170	1.03	0.00	0.00
W84_020	4	608	1.29	0.97	0.00
W84_021	3	363	0.72	1.39	0.00
W84_037	6	822	2.51	1.20	0.93
W84_039	6	1134	3.66	0.93	0.00
W84_050	3	588	5.37	0.00	0.00
W85_008	2	58	1.02	1.53	0.27
W85_011	3	261	1.82	1.16	1.82
W86_004	5	570	3.25	1.17	0.00
W86_023	2	280	2.61	1.86	0.87
W86_046	3	189	2.11	0.89	0.00
W86_049	3	111	1.39	0.29	0.77
W87_030	4	496	1.49	0.00	0.00
W87_114	3	237	0.77	0.00	0.00
W88_001	3	201	0.71	0.60	3.15
W88_002	3	144	0.90	0.00	0.91
W88_003	3	222	1.63	2.01	1.48
W89_042	3	138	1.74	0.00	0.00
W89_045	4	388	1.77	0.00	0.00
W90_014	4	1696	1.29	0.00	0.00
W90_033	5	595	1.86	0.50	0.00
W90_037	5	875	2.23	0.32	0.00
W90_084	2	228	0.97	0.00	0.81

Building #1

Architectural Plan



Columns Layout:



Schedule of Column

COLUMN SCHEDULE

SL. NO.	COLUMN MARK	BELOW G.L./P.L.	GROUND FLOOR	1ST FLOOR	2ND FLOOR	3RD FLOOR	4TH FLOOR	5TH FLOOR	TIE
1.	C1	13" × 33"; 12–16 mm. ϕ	10" × 30"; 12–16 mm. ϕ	10" × 30"; 10–16 mm. ϕ	10" × 30"; 10–16 mm. ϕ	10" × 30"; 10–16 mm. ϕ	10" × 30"; 10–16 mm. ϕ	10" × 30"; 10–16 mm. ϕ	10mm. ϕ TIE 10 C/C
2.	C2	18" × 33"; 16–25 mm. ϕ	15" × 30"; 16–25 mm. ϕ	15" × 30"; 16–25 mm. ϕ	15" × 30"; 12–25 mm. ϕ	15" × 30"; 8–25 mm. ϕ	15" × 30"; 8–25 mm. ϕ	15" × 30"; 8–25 mm. ϕ	DO
3.	C3 SAME AS C2	12" × 33"; 16–20 mm. ϕ	10" × 30"; 16–20 mm. ϕ	CANCELLED 10" × 30"; 12–20 mm. ϕ	10" × 30"; 10–20 mm. ϕ	10" × 30"; 10–20 mm. ϕ	10" × 30"; 10–20 mm. ϕ	10" × 30"; 10–20 mm. ϕ	DO
4.	C4	13" × 33"; 14–20 mm. ϕ	10" × 30"; 14–20 mm. ϕ	10" × 30"; 10–20 mm. ϕ	10" × 30"; 4–20 mm. ϕ + 4–16 mm. ϕ	10" × 30"; 4–20 mm. ϕ + 4–16 mm. ϕ	10" × 30"; 4–20 mm. ϕ + 4–16 mm. ϕ	10" × 30"; 4–20 mm. ϕ + 4–16 mm. ϕ	DO
5.	C5	13" × 18"; 8–20 mm. ϕ	10" × 15"; 8–20 mm. ϕ	10" × 15"; 4–20 mm. ϕ + 4–16 mm. ϕ	10" × 15"; 8–16 mm. ϕ	10" × 15"; 6–16 mm. ϕ	10" × 15"; 6–16 mm. ϕ	10" × 15"; 6–16 mm. ϕ	DO
6.	C6	13" × 13"; 4–20 mm. ϕ	10" × 10"; 4–20 mm. ϕ	10" × 10"; 4–20 mm. ϕ	10" × 10"; 4–16 mm. ϕ	10" × 10"; 4–16 mm. ϕ	10" × 10"; 4–16 mm. ϕ	10" × 10"; 4–16 mm. ϕ	DO
7.	C7	13" × 13"; 4–16 mm. ϕ	10" × 10"; 4–16 mm. ϕ	10" × 10"; 4–16 mm. ϕ	10" × 10"; 4–16 mm. ϕ	10" × 10"; 4–16 mm. ϕ	10" × 10"; 4–16 mm. ϕ	10" × 10"; 4–16 mm. ϕ	DO
8.	C8	13" × 18"; 8–20 mm. ϕ	10" × 15"; 8–20 mm. ϕ	10" × 15"; 4–20 mm. ϕ + 4–16 mm. ϕ	10" × 15"; 8–16 mm. ϕ	10" × 15"; 6–16 mm. ϕ	10" × 15"; 6–16 mm. ϕ	10" × 15"; 6–16 mm. ϕ	DO
9.	C9	13" × 13"; 4–22 mm. ϕ + 4–20	10" × 10"; 4–22 mm. ϕ + 4–20 mm. ϕ	10" × 10"; 8–20 mm. ϕ	10" × 10"; 4–20 mm. ϕ + 4–16 mm. ϕ	10" × 10"; 6–20 mm. ϕ	10" × 10"; 4–16 mm. ϕ	10" × 10"; 4–16 mm. ϕ	DO
10.	C10	13" × 13"; 8–16 mm. ϕ	10" × 10"; 8–16 mm. ϕ	10" × 10"; 6–16 mm. ϕ	10" × 10"; 4–16 mm. ϕ	10" × 10"; 4–16 mm. ϕ	10" × 10"; 4–16 mm. ϕ	10 × 10"; 4–16 mm. ϕ	DO

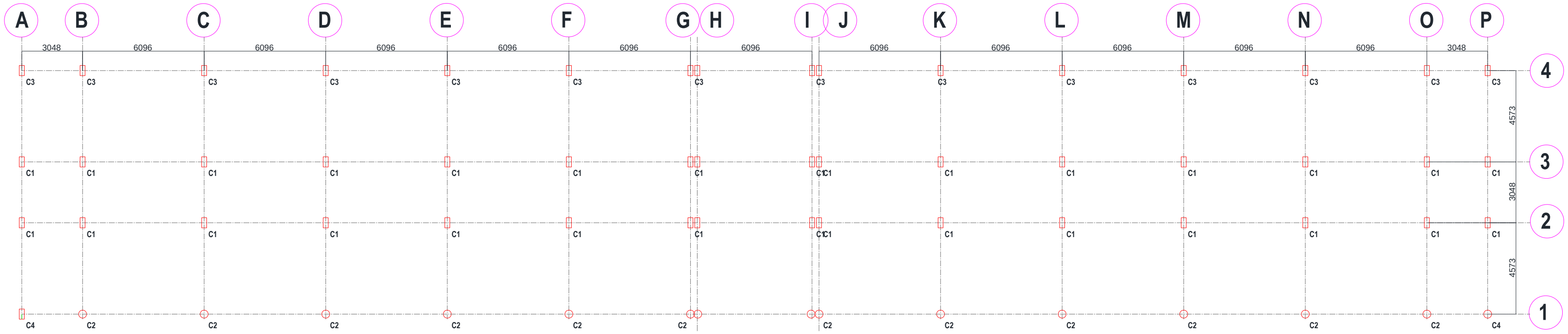
Dimension in inch. Feet (1 ft=30.48 cm, 1 inch=2.54 cm)

SL. NO.	COLUMN MARK	BELOW G.L./P.L.	GROUND FLOOR	1ST FLOOR	2ND FLOOR	3RD FLOOR	4TH FLOOR	5TH FLOOR	TIE
11	C11	13″ × 28″ 16-20 mm. ϕ	10″ × 25″ 16-20 mm. ϕ	10″ × 25″ 12-20 mm. ϕ	10″ × 25″ 8-20 mm. ϕ	10″ × 25″ 4-20 mm. ϕ + 4-16 mm. ϕ	10″ × 25″ 8-16 mm. ϕ	10″ × 25″ 8-16 mm. ϕ	10 mm. ϕ TIE @ 10″ C/C
12	C12	18″ × 18″ 14-22 mm. ϕ	15″ × 15″ 14-22 mm. ϕ	15″ × 15″ 10-22 mm. ϕ	15″ × 15″ 10-20 mm. ϕ	15″ × 15″ 6-20 mm. ϕ + 4-16 mm. ϕ	15″ × 15″ 6-20 mm. ϕ + 4-16 mm. ϕ	15″ × 15″ 6-20 mm. ϕ + 4-16 mm. ϕ	DO
13	C13	13″ × 18″ 8-22 mm. ϕ	10″ × 15″ 8-22 mm. ϕ	10″ × 15″ 8-20 mm. ϕ	10″ × 15″ 8-16 mm. ϕ	10″ × 15″ 6-16 mm. ϕ	10″ × 15″ 6-16 mm. ϕ	10″ × 15″ 6-16 mm. ϕ	DO
14	C14	13″ × 18″ 8-20 mm. ϕ	10″ × 15″ 8-20 mm. ϕ	10″ × 15″ 4-20 mm. ϕ + 4-16 mm. ϕ	10″ × 15″ 8-16 mm. ϕ	10″ × 15″ 6-16 mm. ϕ	10″ × 15″ 6-16 mm. ϕ	10″ × 15″ 6-16 mm. ϕ	DO
15	C15	13″ × 23″ 14-20 mm. ϕ	10″ × 20″ 14-20 mm. ϕ	10″ × 20″ 10-20 mm. ϕ	10″ × 20″ 10-16 mm. ϕ	10″ × 20″ 8-16 mm. ϕ	10″ × 20″ 8-16 mm. ϕ	10″ × 20″ 8-16 mm. ϕ	DO
16	C16 SAME AS C2	13″ × 33″ 18-25 mm. ϕ	10″ × 30″ 18-25 mm. ϕ	10″ × 30″ 18-22 mm. ϕ	CANCELLED 10″ 10-22 mm. ϕ + 8-20 mm. ϕ	10″ × 30″ 14-20 mm. ϕ	10″ × 30″ 10-20 mm. ϕ	10″ × 30″ 10-20 mm. ϕ	DO
17	C17 SAME AS C2	13″ × 33″ 16-22 mm. ϕ	10″ × 30″ 16-22 mm. ϕ	10″ × 30″ 12-22 mm. ϕ	CANCELLED 10″ 8-22 mm. ϕ	10″ × 30″ 8-22 mm. ϕ	10″ × 30″ 8-22 mm. ϕ	10″ × 30″ 8-22 mm. ϕ	DO
18	C18	13″ × 33″ 12-20 mm.	10″ × 30″ 12-20 mm.	10″ × 30″ 8-20 mm. ϕ	10″ × 30″ 6-20 mm. ϕ + 2-16 mm. ϕ	10″ × 30″ 6-20 mm. ϕ + 2-16 mm. ϕ	10″ × 30″ 6-20 mm. ϕ + 2-16 mm. ϕ	10″ × 30″ 6-20 mm. ϕ + 2-16 mm. ϕ	DO
19	C19	13″ × 23″ 12-20 mm. ϕ	10″ × 20″ 12-20 mm. ϕ	10″ × 20″ 10-20 mm. ϕ	10″ × 20″ 8-20 mm. ϕ	10″ × 20″ 8-16 mm. ϕ	10″ × 20″ 8-16 mm. ϕ	10″ × 20″ 8-16 mm. ϕ	DO
20	C20, C21,	13″ × 23″ 6-20 mm. ϕ	10″ × 20″ 6-20 mm. ϕ	10″ × 20″ 6-20 mm. ϕ					DO

Dimension in inch. Feet (1 ft=30.48 cm, 1 inch=2.54 cm)

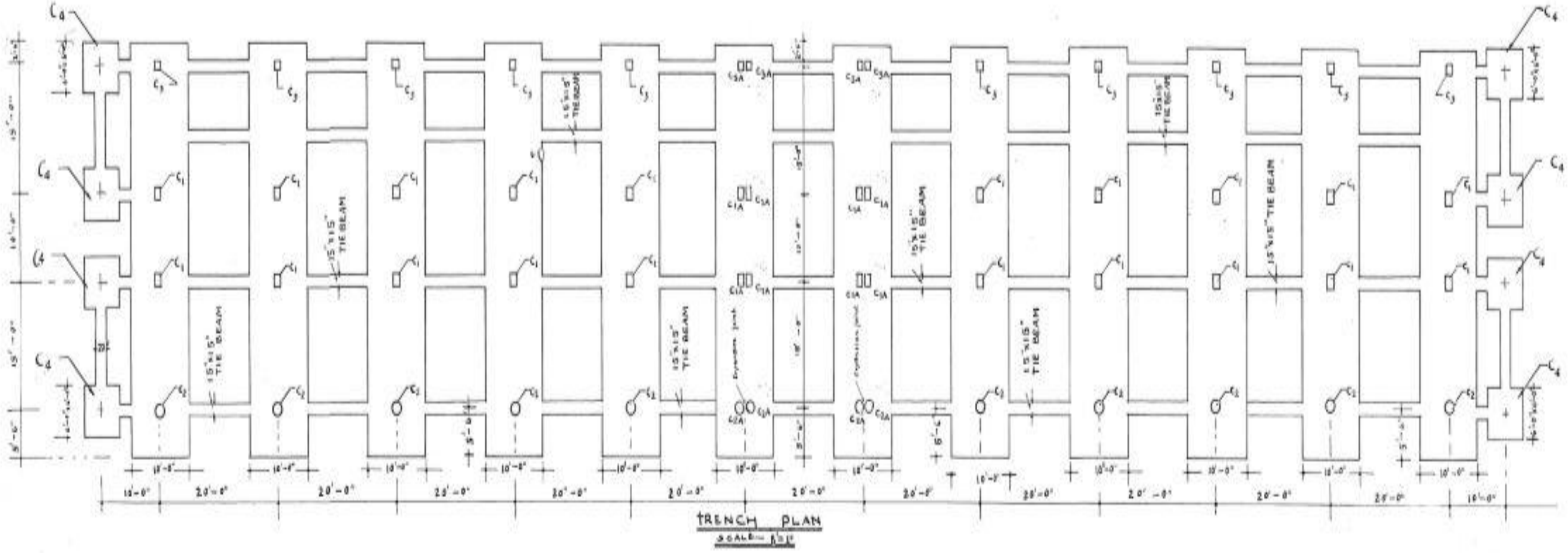
Building #2

Architectural Plan



Dimension in inch. Feet (1 ft=30.48 cm, 1 inch=2.54 cm)

Columns Layout:



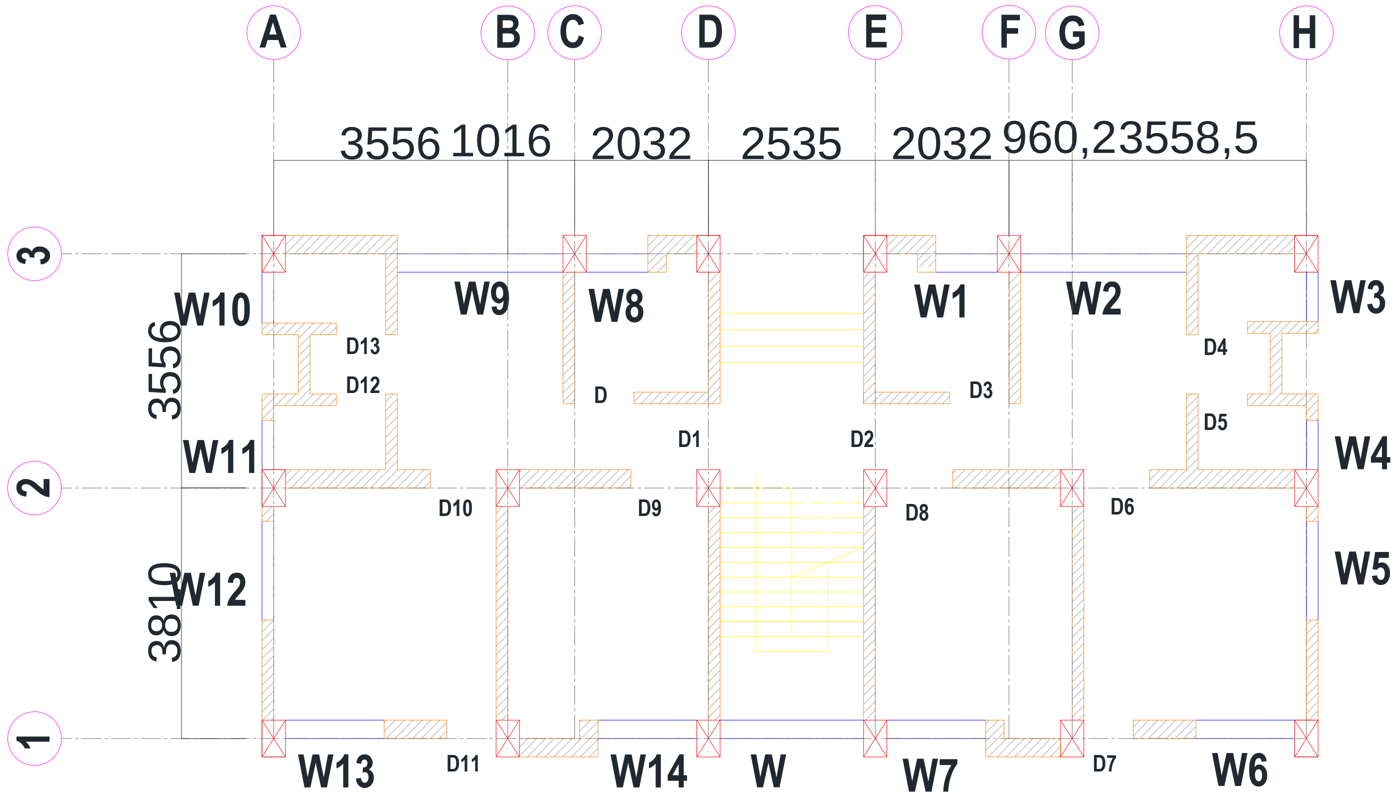
Schedule of Column

MARK	G.F.			F.F.			S.F.			T.F.			FTH F.		
	SIZE	REIN	LINK	SIZE	REIN	LINK	SIZE	REIN	LINK	SIZE	REIN	LINK	SIZE	REIN	LINK
C_1	18"x14"	10-7/8"φ	1/4"φ 3 NOS @ 12" c/c	16"x12"	8-7/8"φ	1/4"φ 2 NOS @ 12" c/c	12"x12"	8-3/4"φ	1/4"φ 2 NOS @ 12" c/c	12"x10"	6-3/4"φ	1/4"φ 2 NOS @ 10" c/c	10"x10"	4-3/4"φ	1/4"φ @ 10" c/c
C_2	18" DIA	12-7/8"φ	1/4"φ @ 10" c/c	14"x14"	12-7/8"φ	1/4"φ 3 NOS @ 12" c/c	12"x10"	6-3/4"φ	1/4"φ 2 NOS @ 12" c/c	10"x10"	4-3/4"φ	"	10"x10"	4-5/8"φ	"
C_3	14"x12"	8-7/8"φ	1/4"φ 2 NOS @ 12" c/c	12"x12"	8-3/4"φ	1/4"φ 2 NOS @ 12" c/c	12"x10"	"	"	10"x10"	"	"	10"x10"	"	"
C_4	13"x12"	4-3/4"φ	1/4"φ @ 10" c/c	10"x12"	4-5/8"φ	1/4"φ @ 12" c/c	10"x10"	4-5/8"φ	1/4"φ @ 10" c/c	10"x10"	4-5/8"φ	1/4"φ @ 10" c/c	10"x10"	4-5/8"φ	1/4"φ @ 10" c/c
C1A	12"x10"	8-3/4"φ	1/4"φ @ 10" c/c	10"x10"	4-3/4"φ	1/4"φ @ 10" c/c	10"x10"	4-5/8"φ	1/4"φ @ 10" c/c	10"x10"	4-5/8"φ	"	10"x10"	4-5/8"φ	"
C2A	14" DIA	6-3/4"φ	"	13" DIA	6-3/4"φ	"	12" DIA	6-5/8"φ	"	10" DIA	6-5/8"φ	"	10" DIA	6-1/2"φ	"
C3A	10"x10"	6-3/4"φ	"	10"x10"	4-3/4"φ	"	10"x10"	4-3/4"φ	"	10"x10"	4-5/8"φ	"	10"x10"	4-5/8"φ	"

Dimension in inch. Feet (1 ft=30.48 cm, 1 inch=2.54 cm)

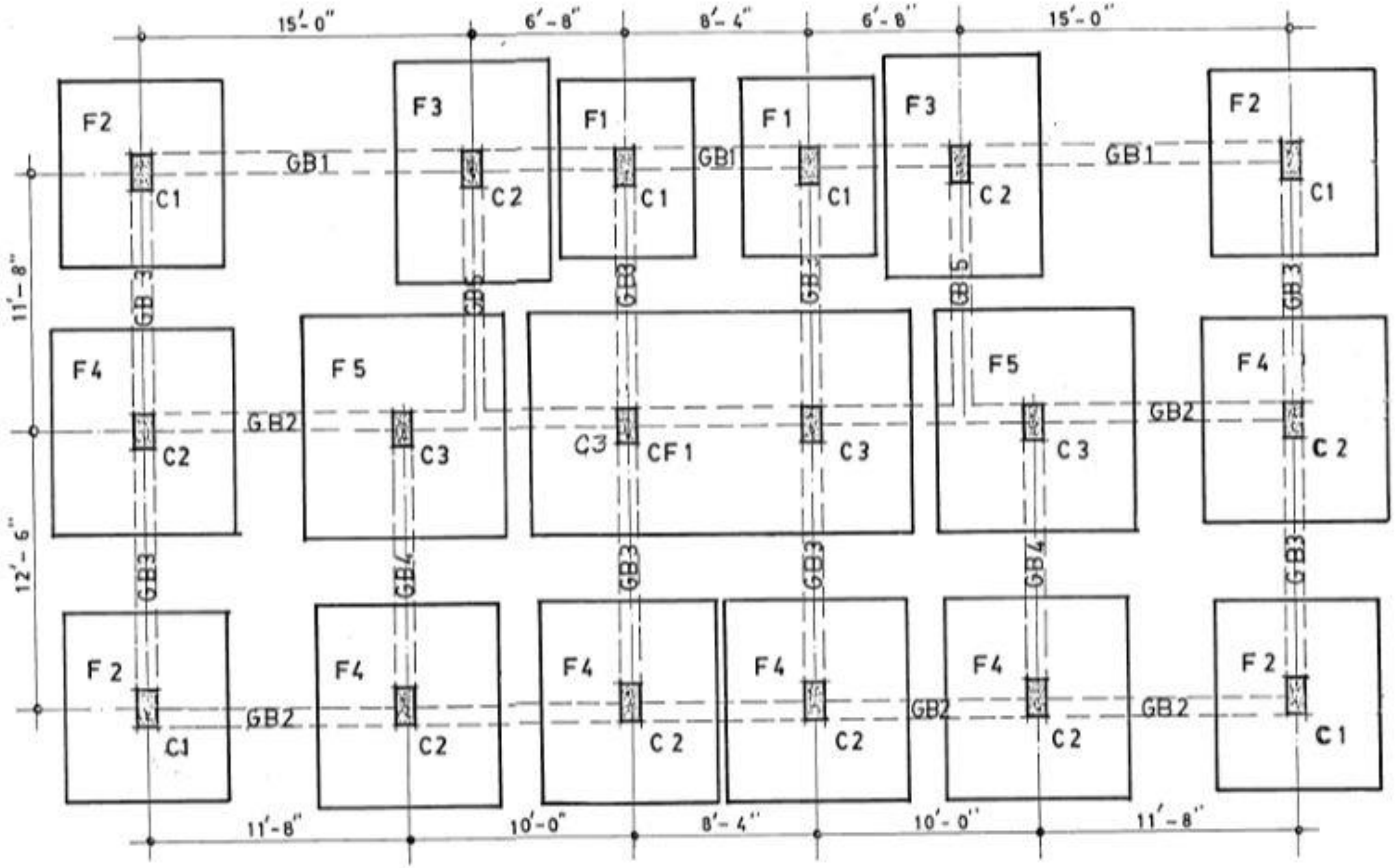
<u>Building # 5</u>

Architectural Plan



Dimension in inch. Feet (1 ft=30.48 cm, 1 inch=2.54 cm)

Columns Layout:

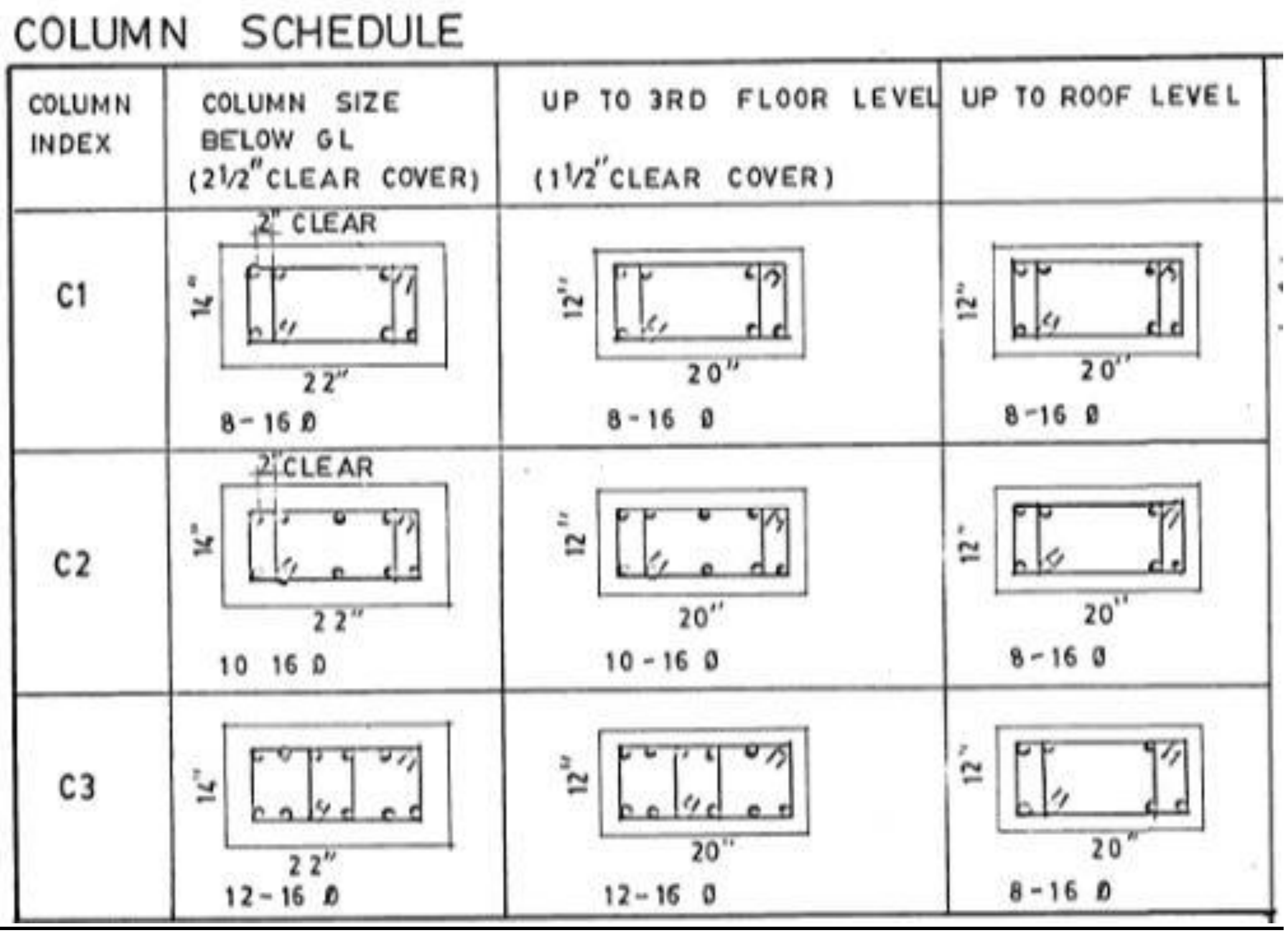


FOUNDATION OF TRENCH PLAN

SCALE: 3/16" = 1'-0"

Dimension in inch. Feet (1 ft=30.48 cm, 1 inch=2.54 cm)

Schedule of Column



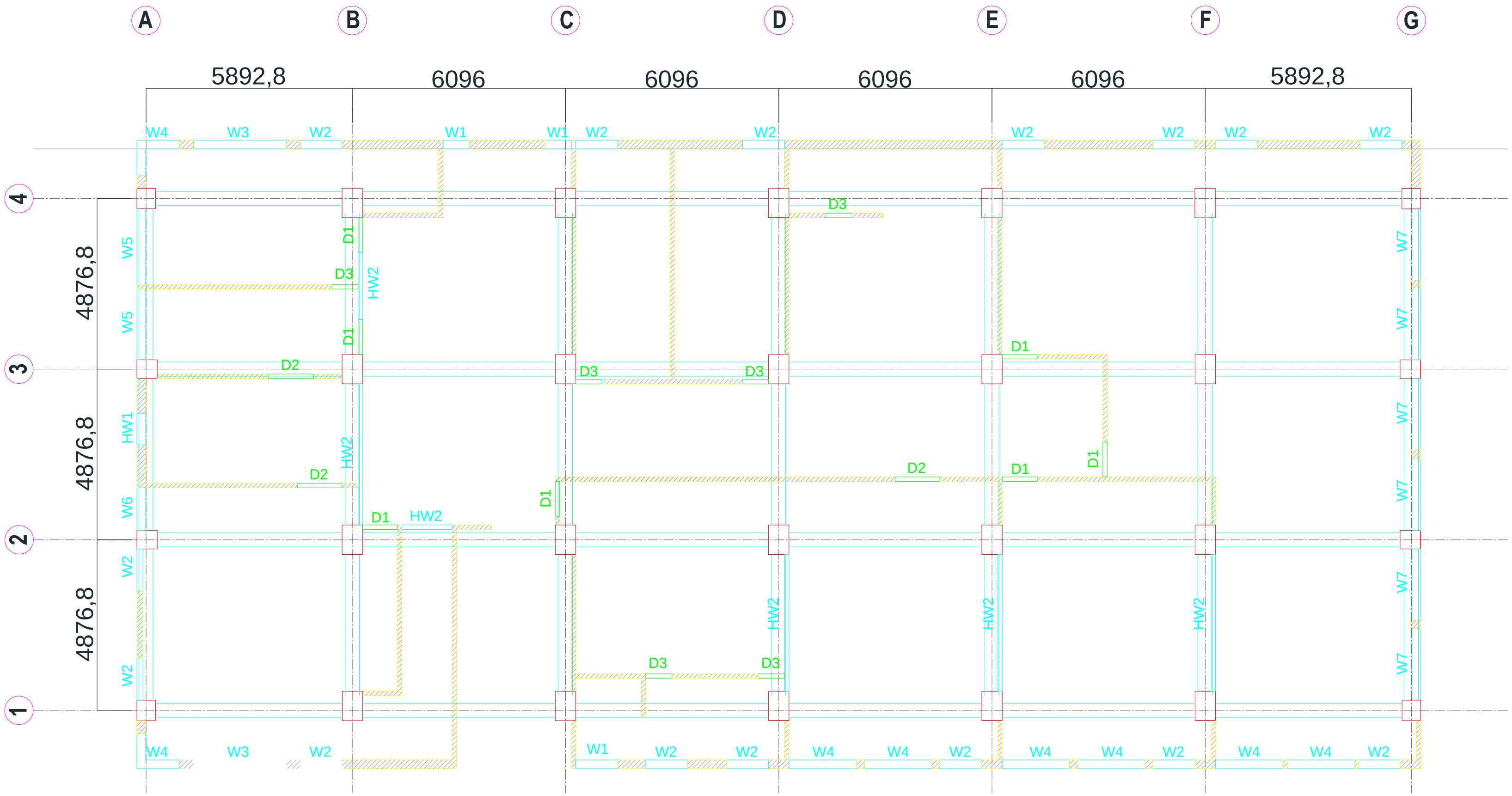
COLUMN SCHEDULE

COLUMN INDEX	COLUMN SIZE BELOW GL (2½" CLEAR COVER)	UP TO 3RD FLOOR LEVEL (1½" CLEAR COVER)	UP TO ROOF LEVEL
C1	2" CLEAR; 14" × 22"; 8 - 16 Ø	12" × 20"; 8 - 16 Ø	12" × 20"; 8 -16 Ø
C2	2" CLEAR; 14" × 22"; 10 16 Ø	12" × 20"; 10 - 16 Ø	12" × 20"; 8 - 16 Ø
C3	14" × 22"; 12 - 16 Ø	12" × 20"; 12 - 16 Ø	12" × 20"; 8 - 16 Ø

Dimension in inch. Feet (1 ft=30.48 cm, 1 inch=2.54 cm)

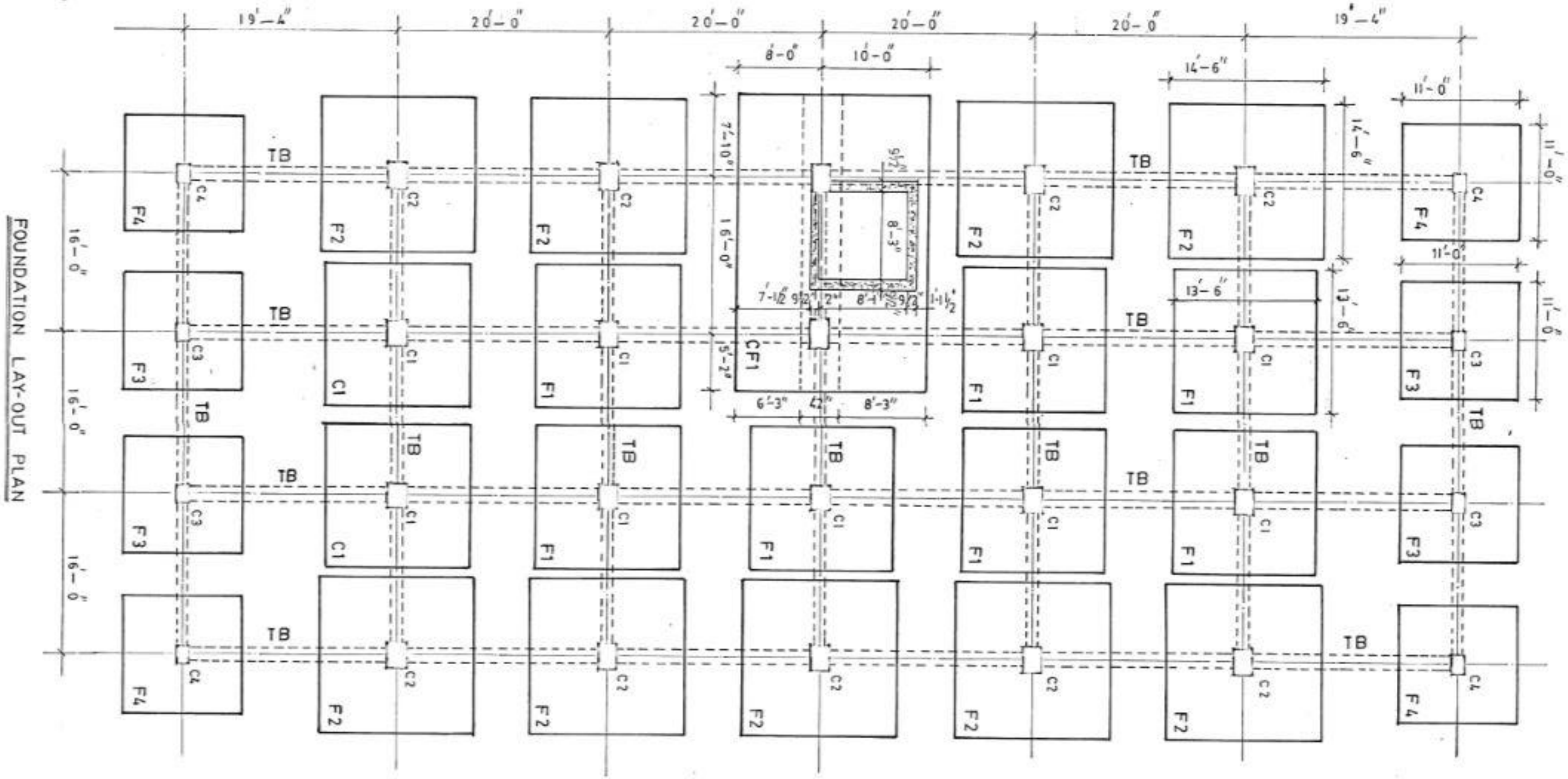
Building # 6

Architectural Plan



Dimension in inch. Feet (1 ft=30.48 cm, 1 inch=2.54 cm)

Columns Layout:



Dimension in inch. Feet (1 ft=30.48 cm, 1 inch=2.54 cm)

Schedule of Column

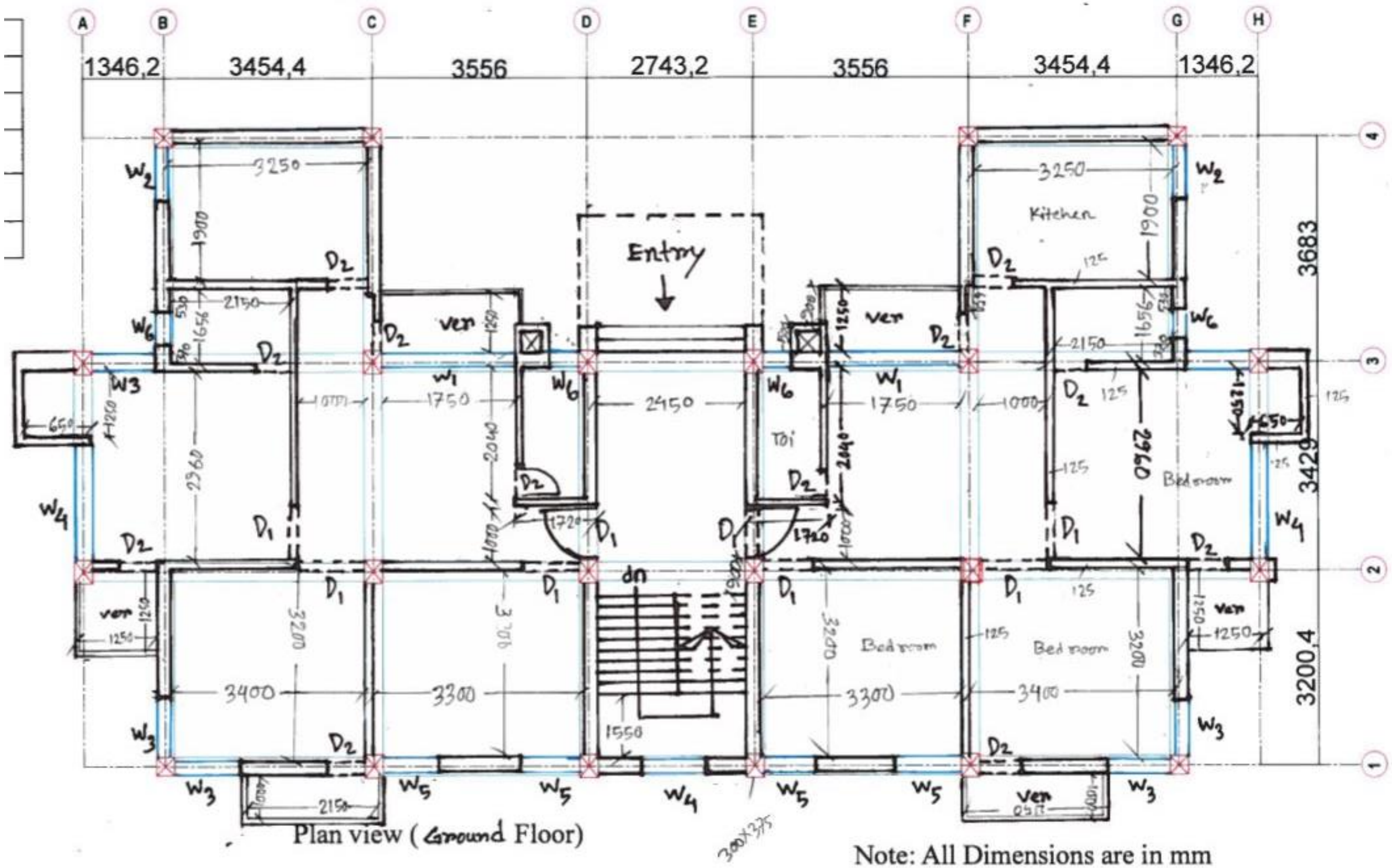
COLUMN SCHEDULE.

SL. NO.	FOOTING MARK.	COLUMN MARK.	ARRANGEMENTS OF COLUMN STEELS.						
			BELOW G.L.	GROUND FLOOR.	1ST FLOOR.	2ND FLOOR.	3RD FLOOR.	4TH FLOOR.	5TH FLOOR.
1.	F_1	C_1	19" + 9" × 23"; 4-7/8" Ø + 14-3/4" Ø; 2-3/4" Ø	16" + 9" × 20"; 4-7/8" Ø + 14-3/4" Ø; 2-3/4" Ø	16" + 9" × 20"; 8-3/4" Ø + 10-5/8" Ø; 2-3/4" Ø	16" + 9" × 20"; 14-5/8" Ø; 2-3/4" Ø	16" + 9" × 20"; 12-5/8" Ø; 2-3/4" Ø	SAME AS 3RD FLOOR	
2.	F_2	C_2	19" + 9" × 23"; 8-3/4" Ø + 10-5/8" Ø; 2-3/4" Ø	16" + 9" × 20"; 8-3/4" Ø + 10-5/8" Ø; 2-3/4" Ø	16" + 9" × 20"; 4-3/4" Ø + 10-5/8" Ø; 2-3/4" Ø	16" + 9" × 20"; 12-5/8" Ø; 2-3/4" Ø	SAME AS 2ND FLOOR		
3.	F_3	C_3	23" × 23"; 8-1" Ø + 8-7/8" Ø	20" × 20"; 8-1" Ø + 8-7/8" Ø	20" × 20"; 16-3/4" Ø	20" × 20"; 16-5/8" Ø	18" × 18"; 12-5/8" Ø	SAME AS 3RD FLOOR	
4.	F_4, F_5, F_6, CF_1, CF_2	C_4, C_5, C_6, C_8, C_{10}	23" × 23"; 20-1" Ø	20" × 20"; 20-1" Ø	20" × 20"; 10-1" Ø + 8-7/8" Ø	20" × 20"; 4-7/8" Ø + 12-3/4" Ø	18" × 18"; 4-3/4" Ø + 12-5/8" Ø	18" × 18"; 12-5/8" Ø	SAME AS 4TH FLOOR
5.	F_7	C_7	25" × 25"; 12-1" Ø + 10-7/8" Ø	22" × 22"; 12-1" Ø + 10-7/8" Ø	20" × 20"; 10-1" Ø + 8-7/8" Ø	20" × 20"; 4-7/8" Ø + 12-3/4" Ø	18" × 18"; 4-3/4" Ø + 12-5/8" Ø	18" × 18"; 12-5/8" Ø	SAME AS 4TH FLOOR
6.	CF_2	C_{11}	13" × 23"; 12-3/4" Ø	10" × 20"; 12-3/4" Ø	10" × 20"; 12-5/8" Ø	10" × 20"; 10-5/8" Ø	10" × 20"; 8-5/8" Ø	SAME AS 3RD FLOOR	
7.	CF_1	C_9	13" × 23"; 8-5/8" Ø	10" × 20"; 8-5/8" Ø	—	—	—	—	—

Dimension in inch. Feet (1 ft=30.48 cm, 1 inch=2.54 cm)

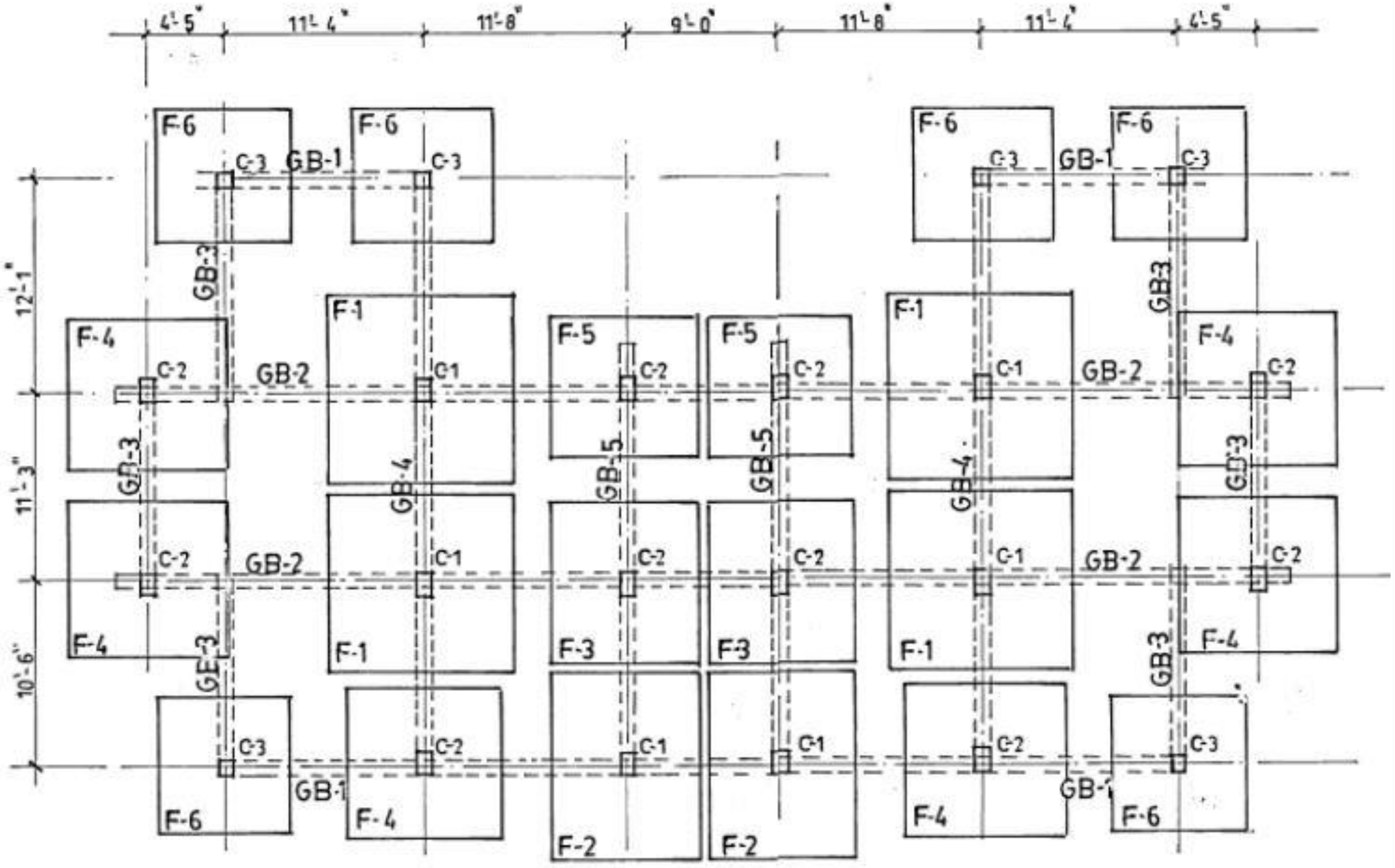
Building # 7

Architectural Plan



Plan view (Ground Floor)

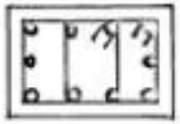
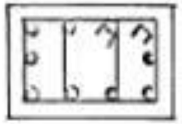
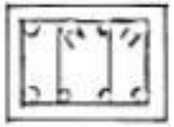
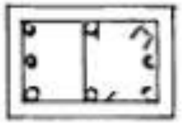
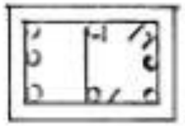
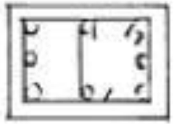
Columns Layout:



Dimension in inch. Feet (1 ft=30.48 cm, 1 inch=2.54 cm)

Schedule of Column

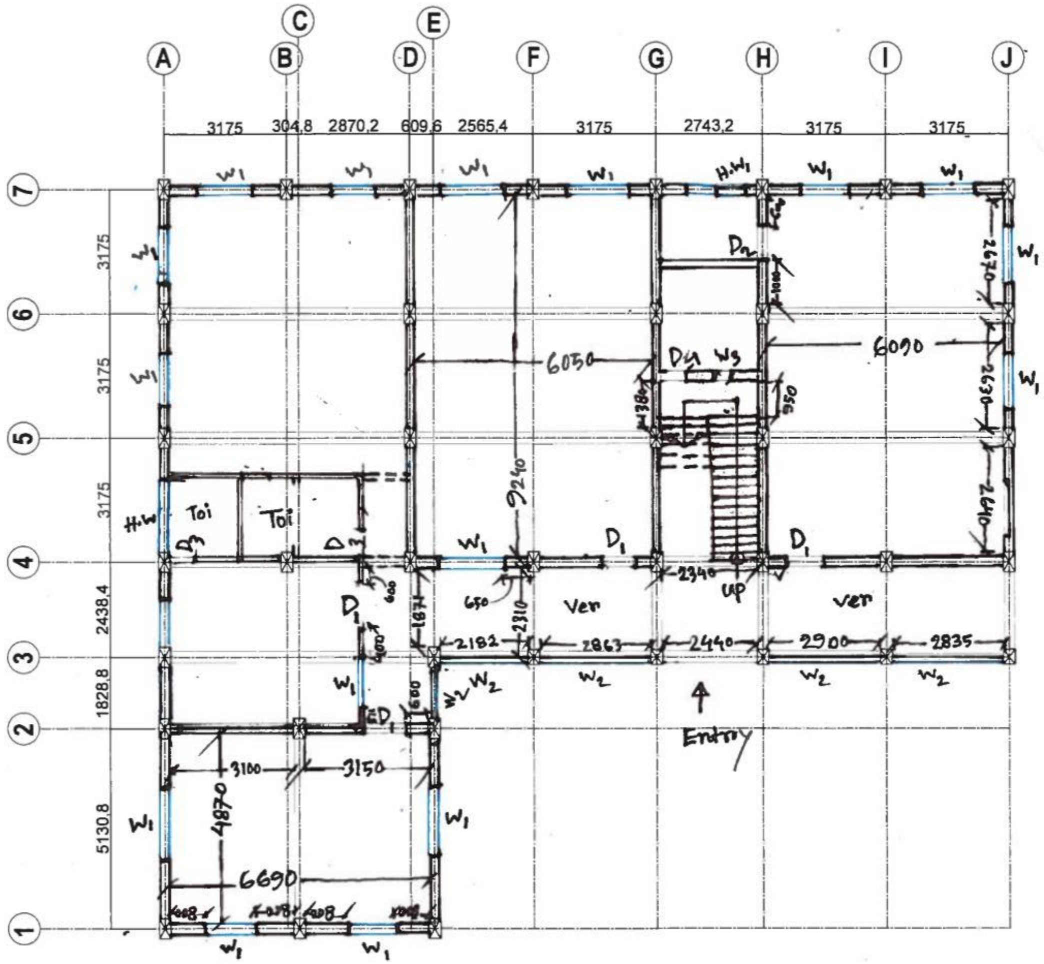
COLUMN SCHEDULE:-

SL NO	COLUMN SIZE		COLUMN REINFORCEMENT		
	BELOW GL/PL	ABOVE GL/PL.	UP TO 2ND. FLOOR LEVEL	UP TO 4TH. FLOOR LEVEL	UP TO ROOF LEVEL.
C-1	15"X18"	12"X15"	 10-20 mm φ	 10-16mm φ	 8-16mm φ
C-2	15"X18"	12"X15"	 8-20mm φ	 8-16 mm φ	 8-16mm φ
C-3	15"X15"	12"X12"	 8-16mm φ	 6-16mm φ	 6-16mm φ

Dimension in inch. Feet (1 ft=30.48 cm, 1 inch=2.54 cm)

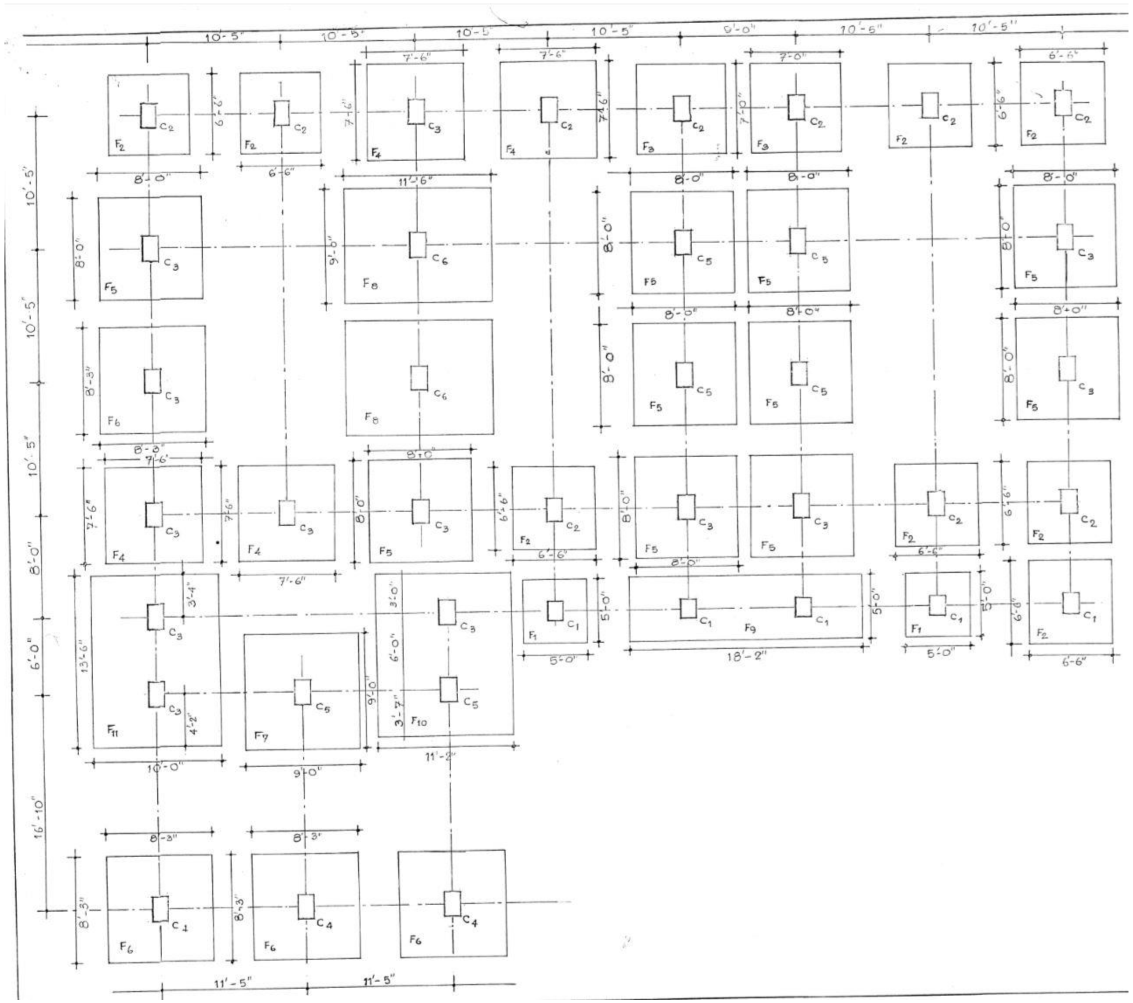
Building # 8

Architectural Plan



Dimension in inch. Feet (1 ft=30.48 cm, 1 inch=2.54 cm)

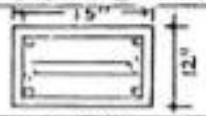
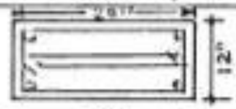
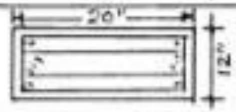
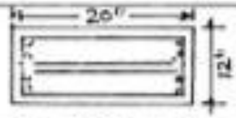
Columns Layout:



Dimension in inch. Feet (1 ft=30.48 cm, 1 inch=2.54 cm)

Schedule of Column

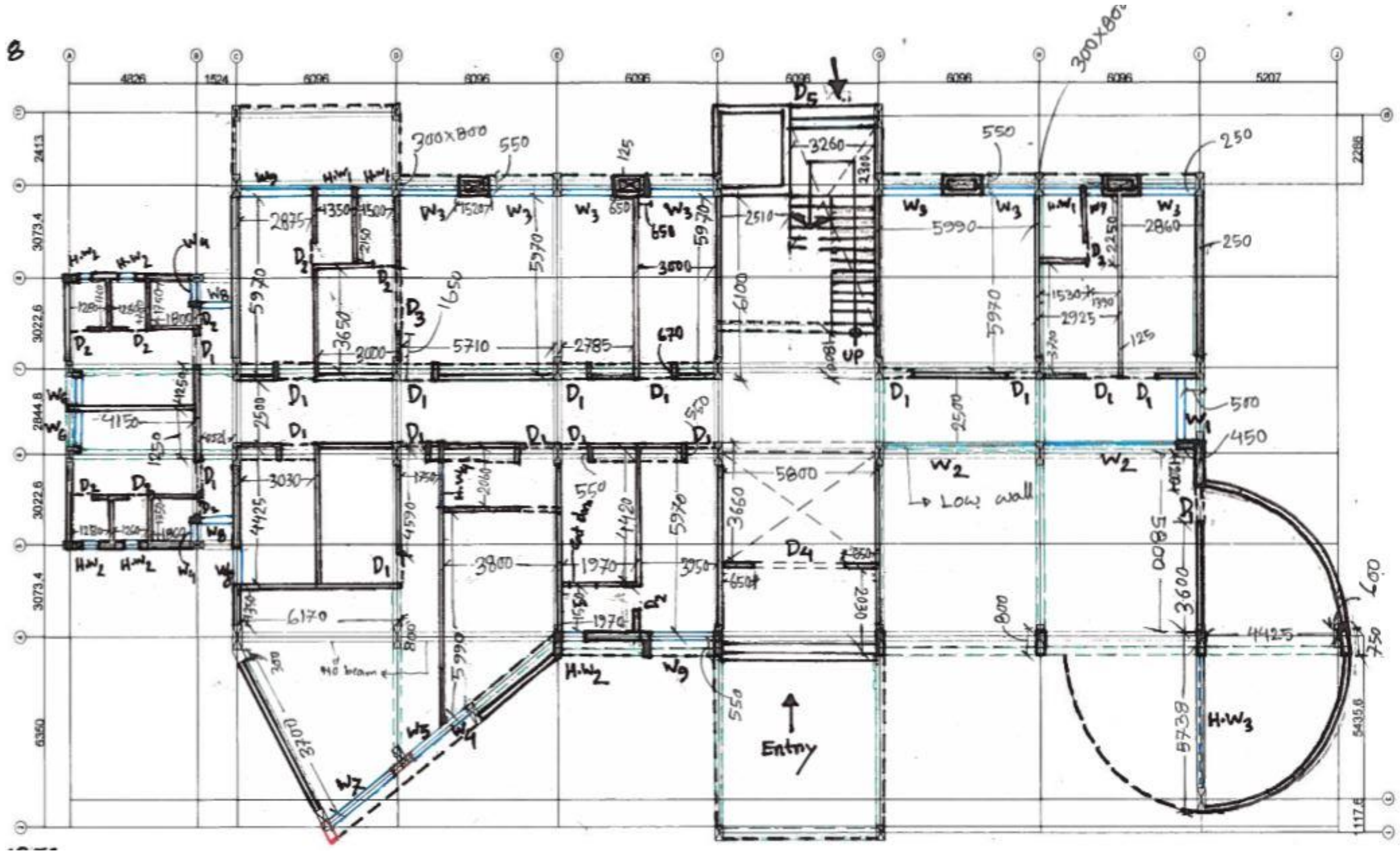
COLUMN SCHEDULE

SL.NO	TYPE	SIZE		VERTICAL REINF.	TIE BAR	SEC. OF COL. ABOVE GROUND LEVEL.
		ABOVE GL	BELOW GL			
1.	C_1	12"X15"	15"X18"	6-7/8"ϕ	3/8"ϕ@10"c/c	
2.	C_2	12"X20"	15"X23"	6-7/8"ϕ	3/8"ϕ@10"c/c	
3.	C_3	12"X20"	15"X23"	8-7/8"ϕ	3/8"ϕ@10"c/c	
4.	C_4	12"X20"	15"X23"	10-7/8"ϕ	3/8"ϕ@10"c/c	
5.	C_5	12"X20"	15"X23"	10-1"ϕ	3/8"ϕ@10"c/c	
6.	C_6	12"X20"	15"X23"	10-1"ϕ 2-5/8"ϕ	3/8"ϕ@10"c/c	

<u>Building # 9</u>

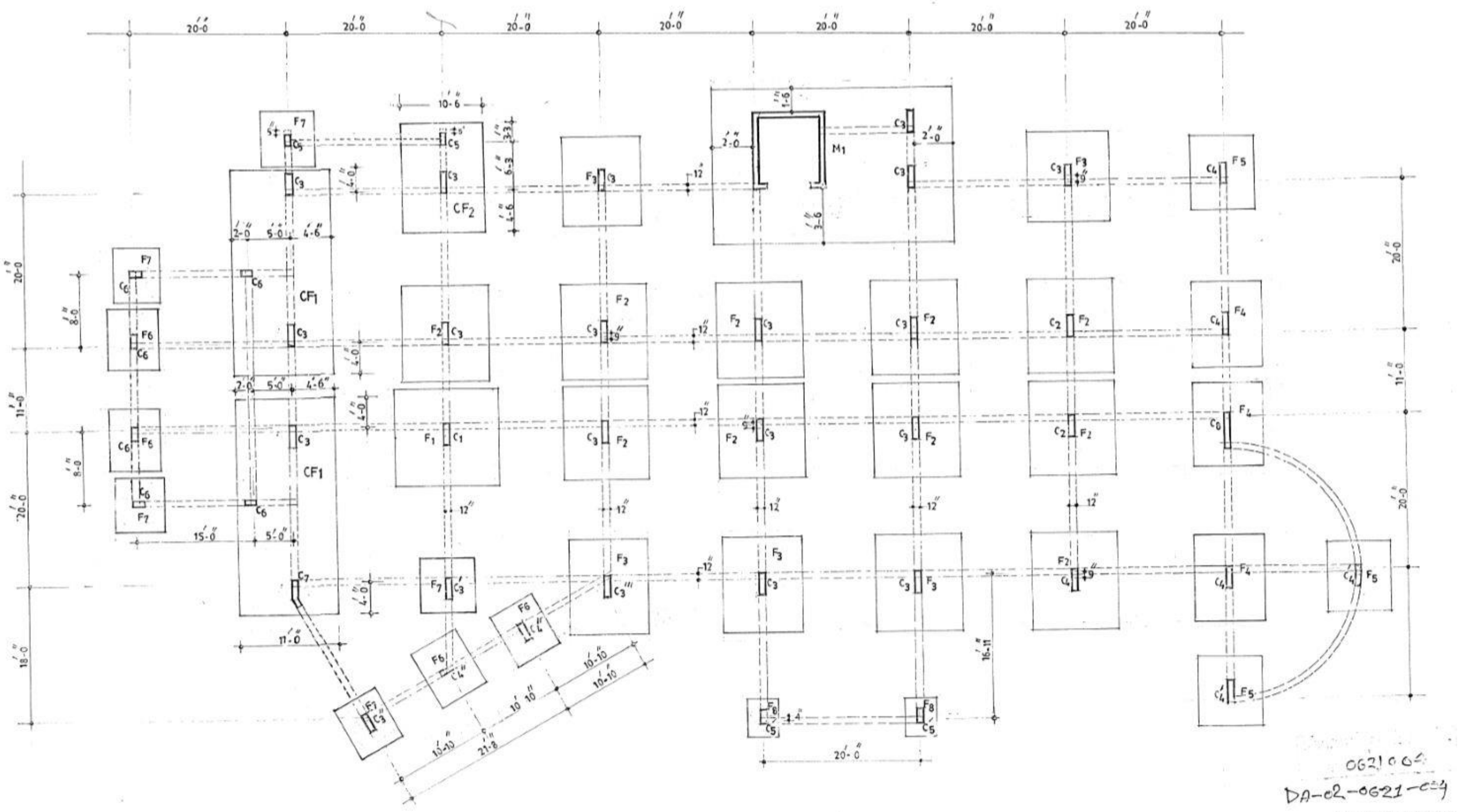
Dimension in inch. Feet (1 ft=30.48 cm, 1 inch=2.54 cm)

Architectural Plan



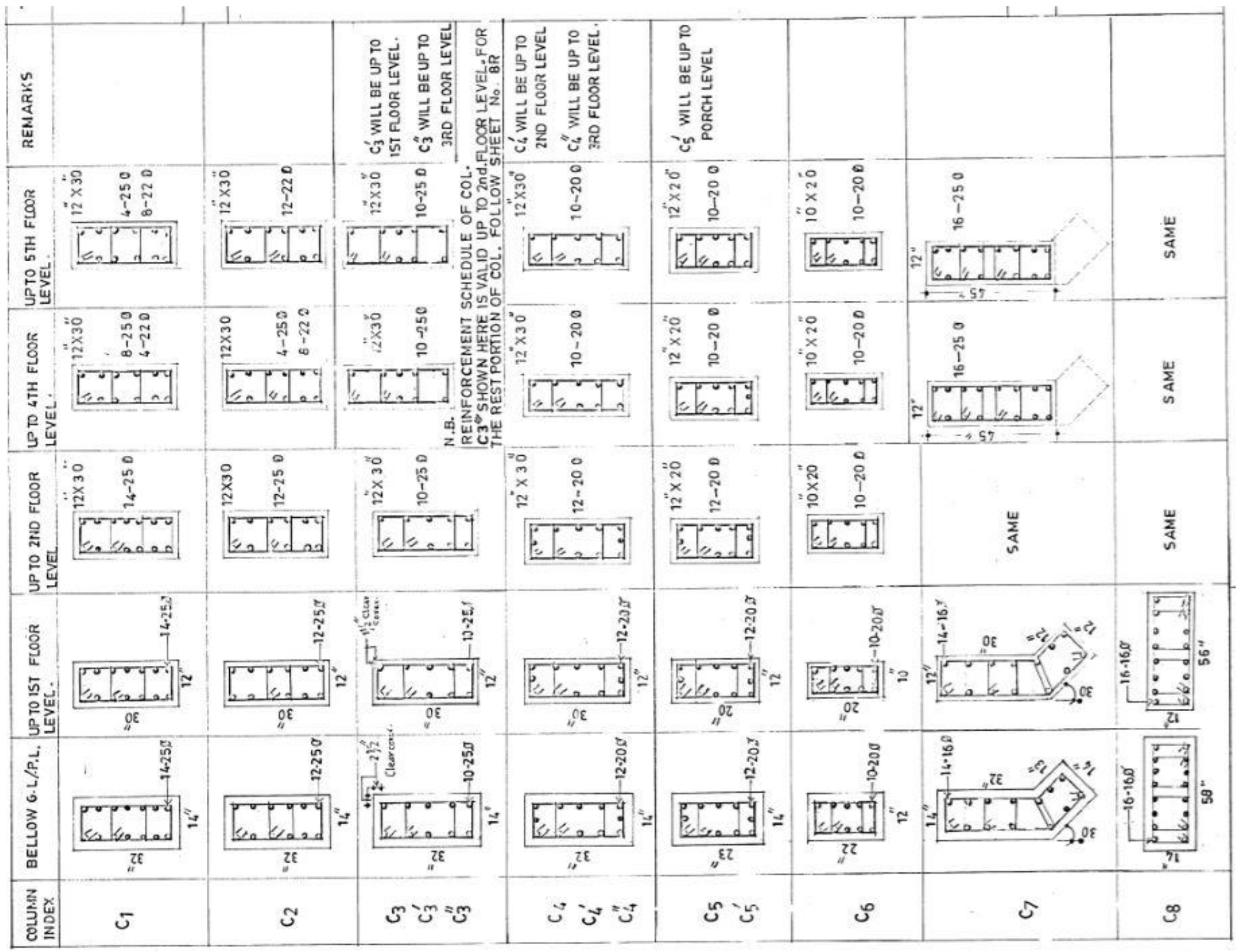
Columns Layout:

Dimension in inch. Feet (1 ft=30.48 cm, 1 inch=2.54 cm)



Schedule of Column

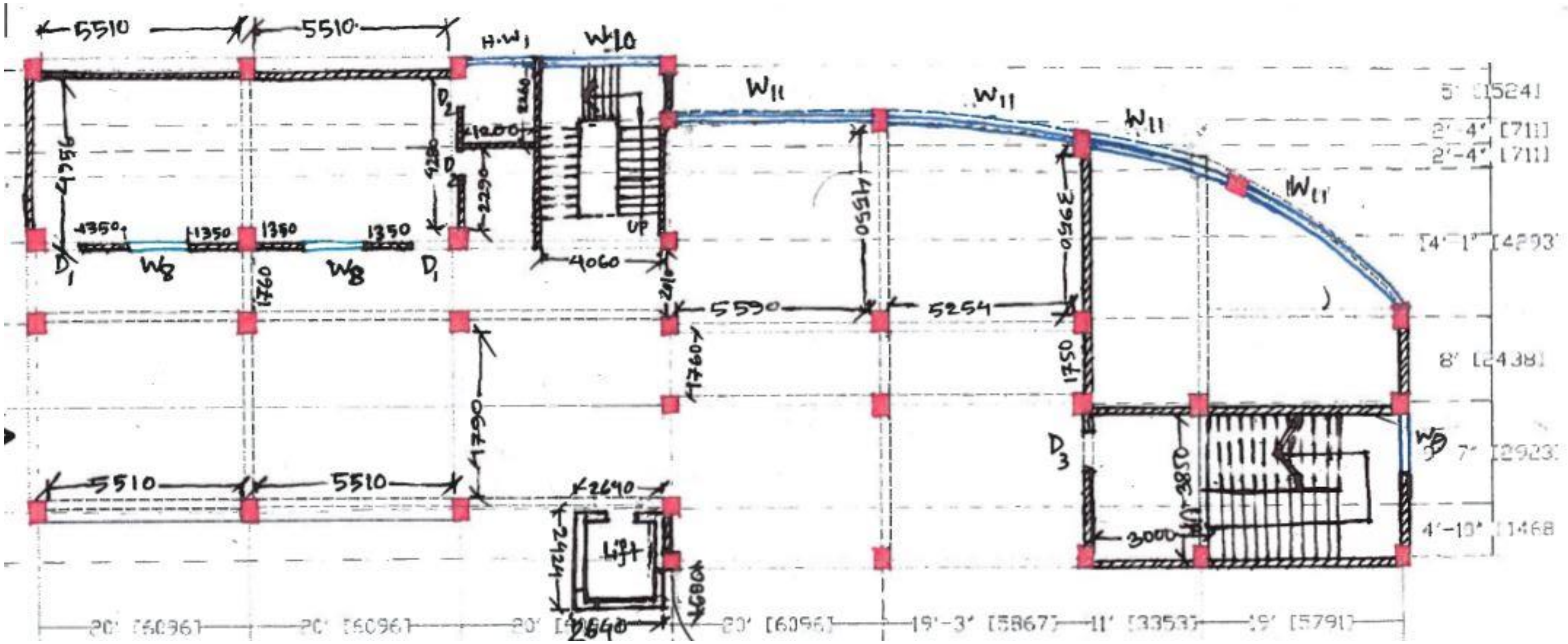
Dimension in inch. Feet (1 ft=30.48 cm, 1 inch=2.54 cm)



Building # 10

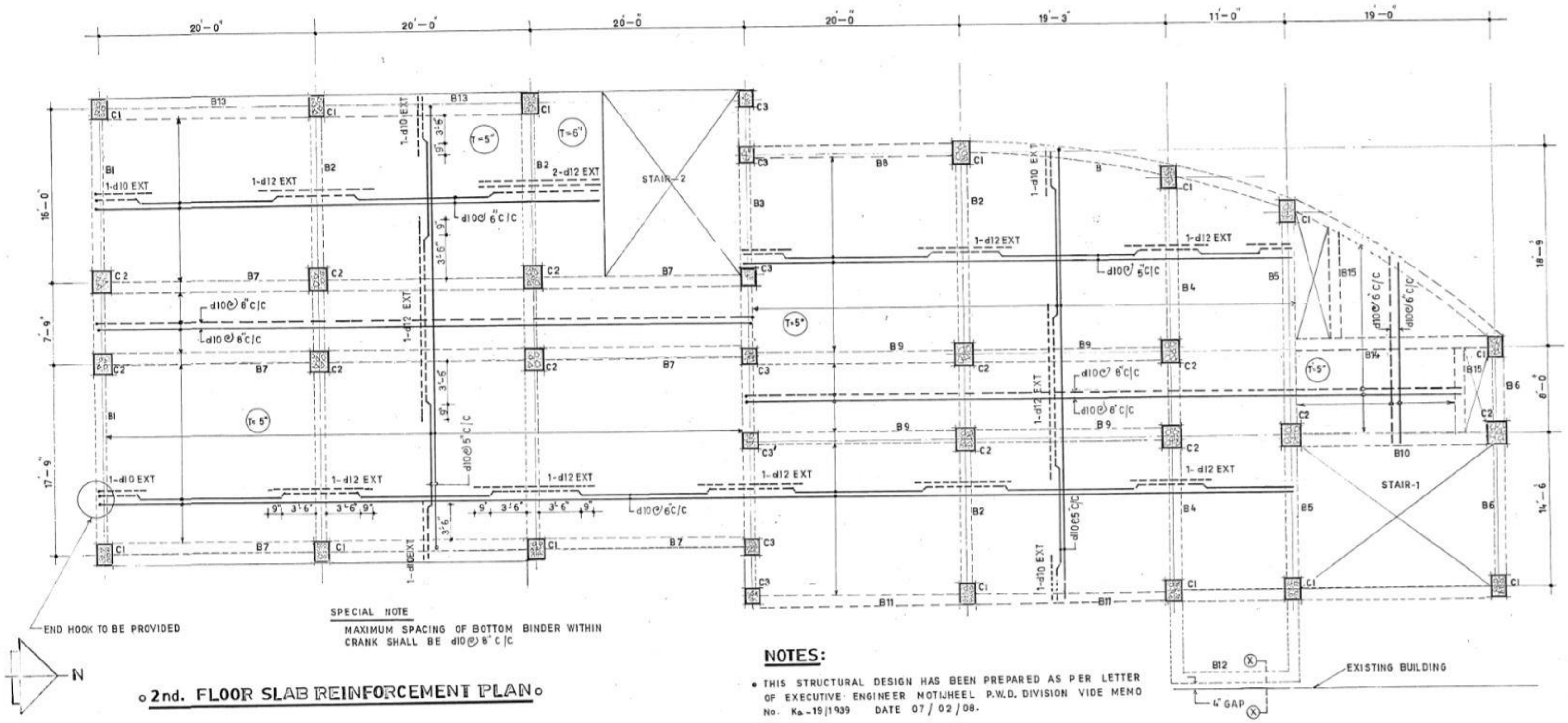
Dimension in inch. Feet (1 ft=30.48 cm, 1 inch=2.54 cm)

Architectural Plan



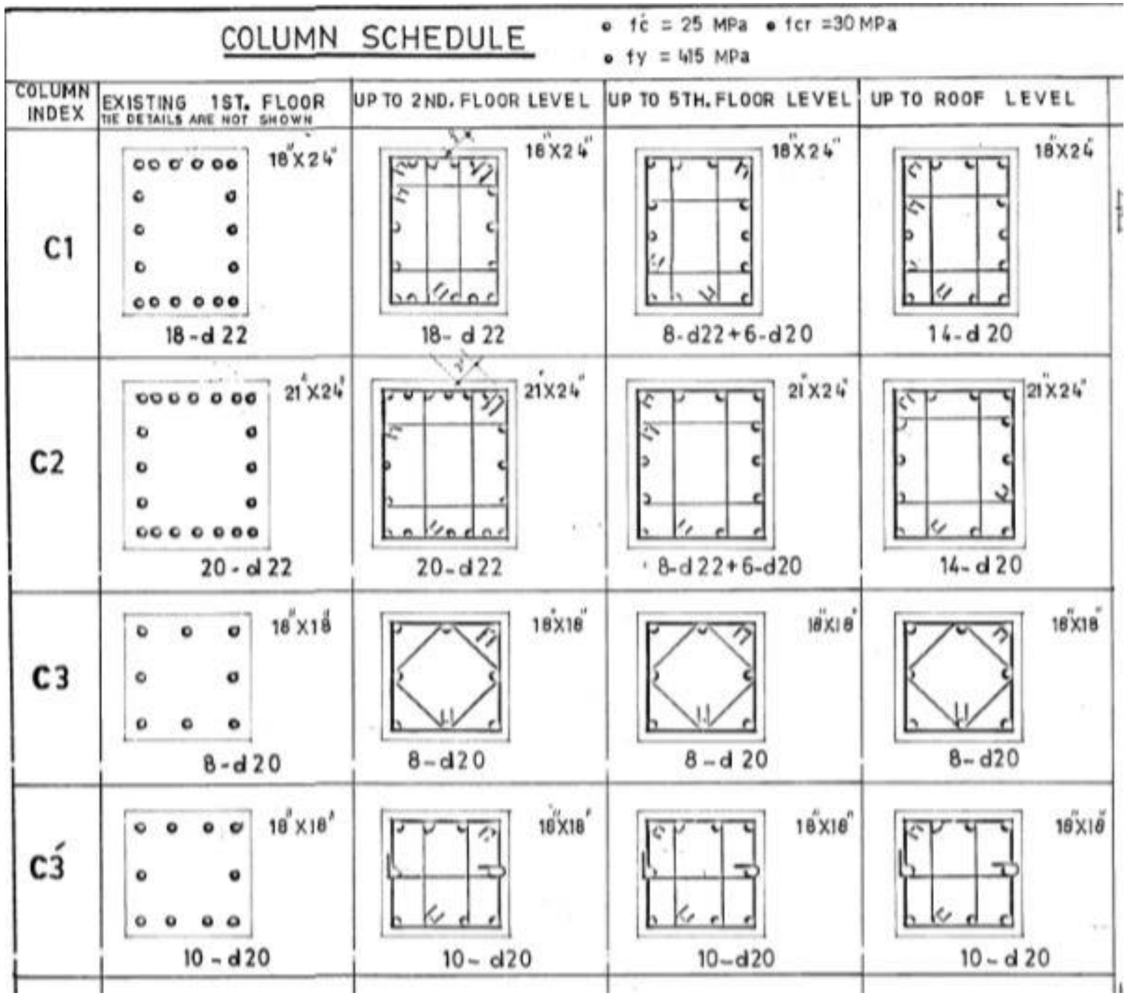
Columns Layout:

Dimension in inch. Feet (1 ft=30.48 cm, 1 inch=2.54 cm)



Schedule of Column

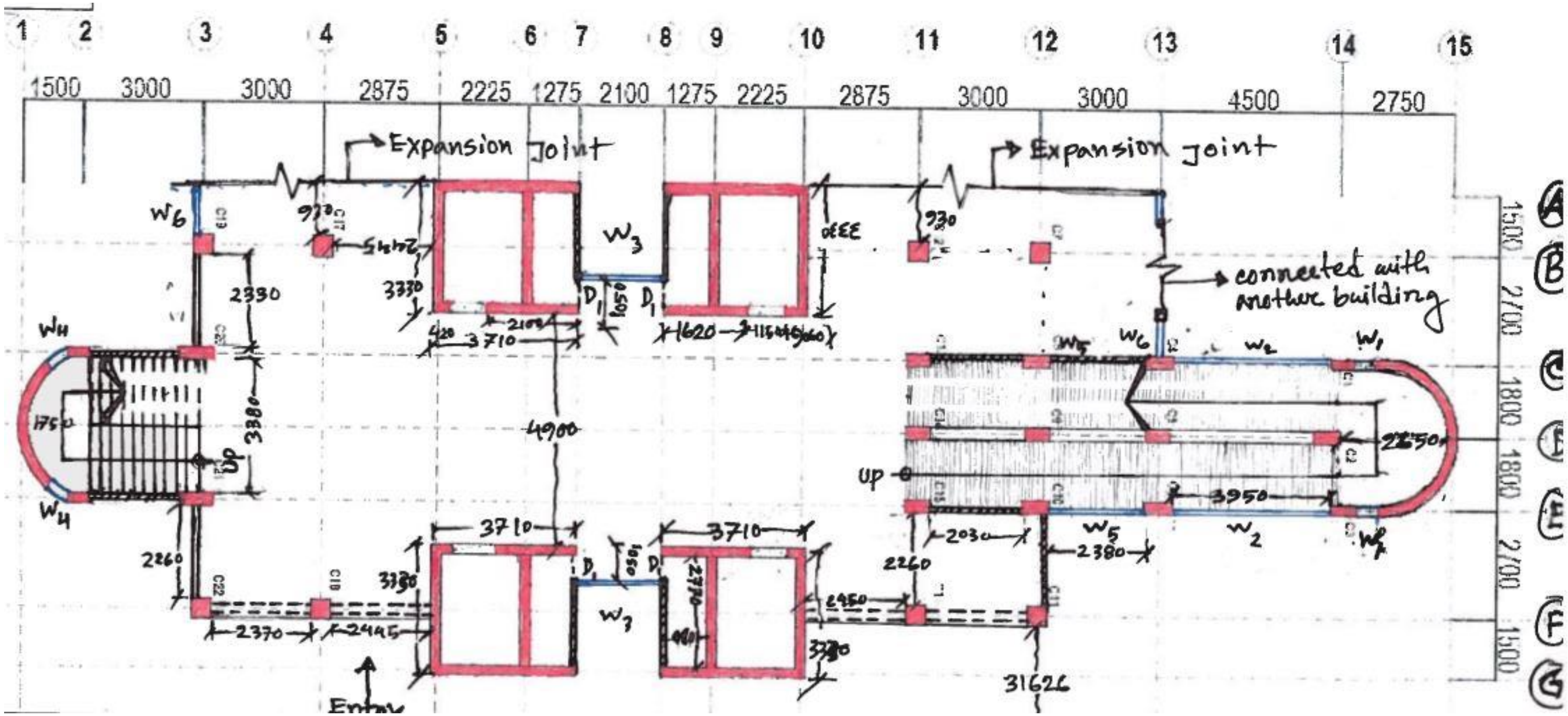
Dimension in inch. Feet (1 ft=30.48 cm, 1 inch=2.54 cm)



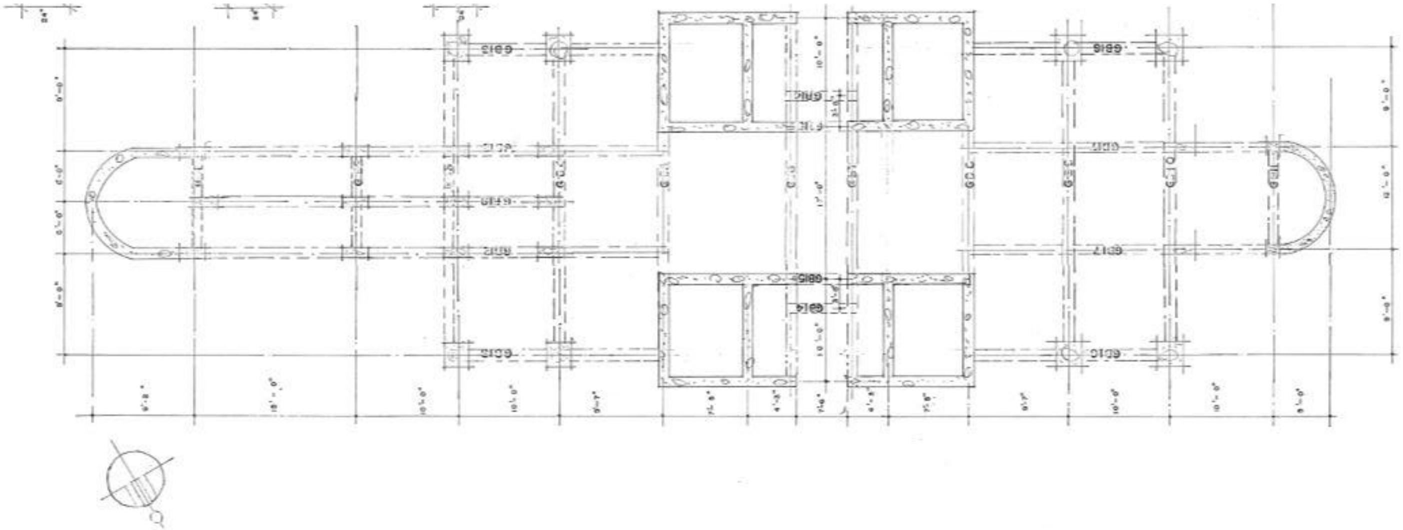
Dimension in inch. Feet (1 ft=30.48 cm, 1 inch=2.54 cm)

Building # 11

Architectural Plan

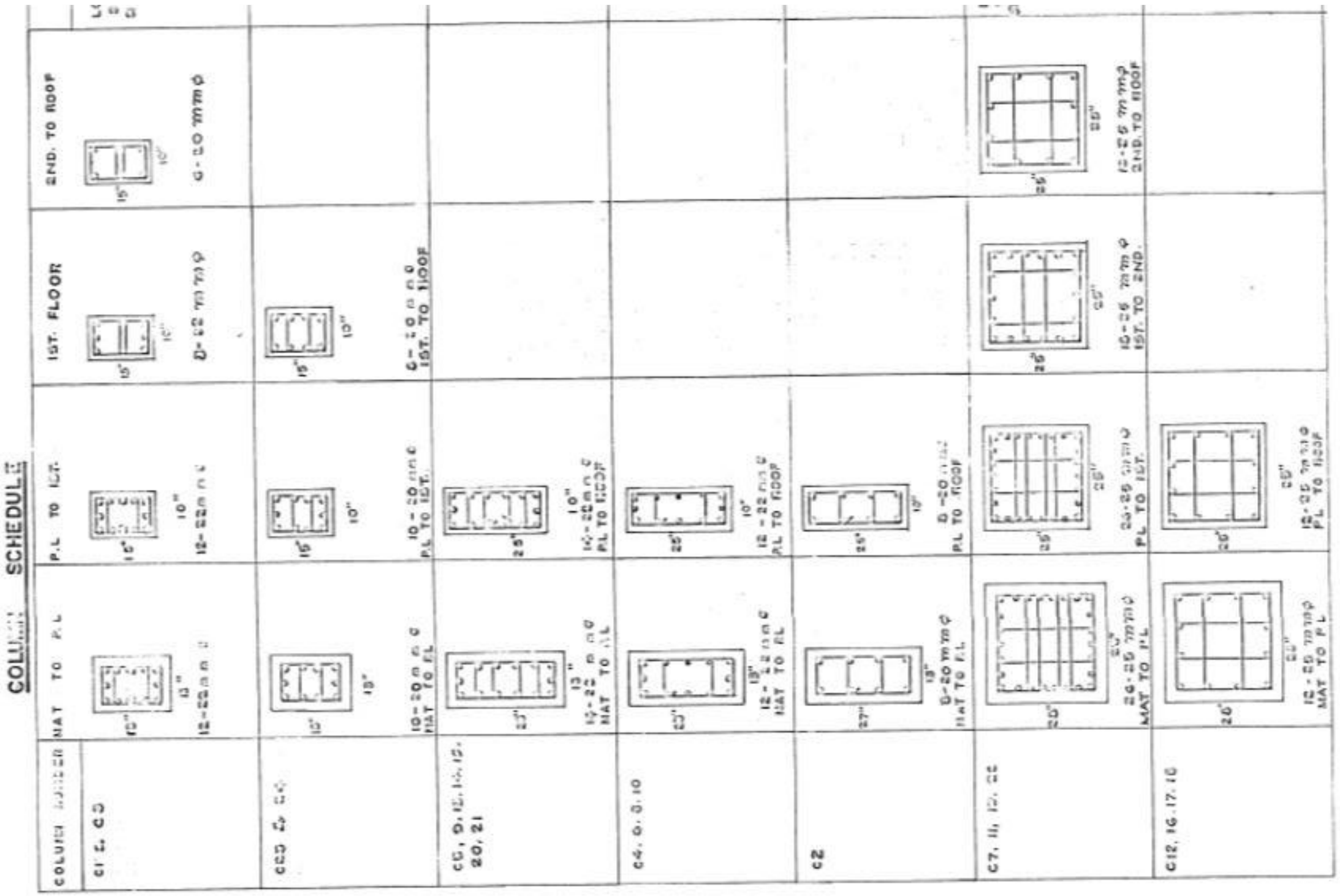


Columns Layout:



Schedule of Column

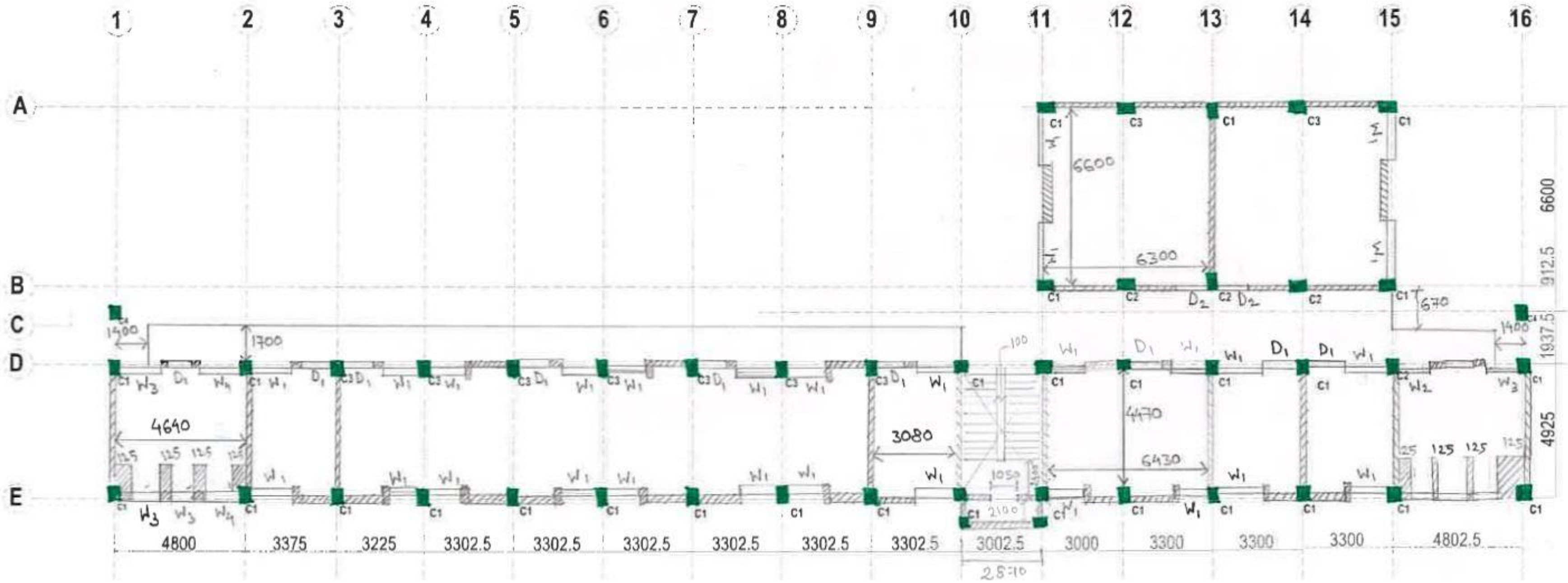
Dimension in inch. Feet (1 ft=30.48 cm, 1 inch=2.54 cm)



Building # 12

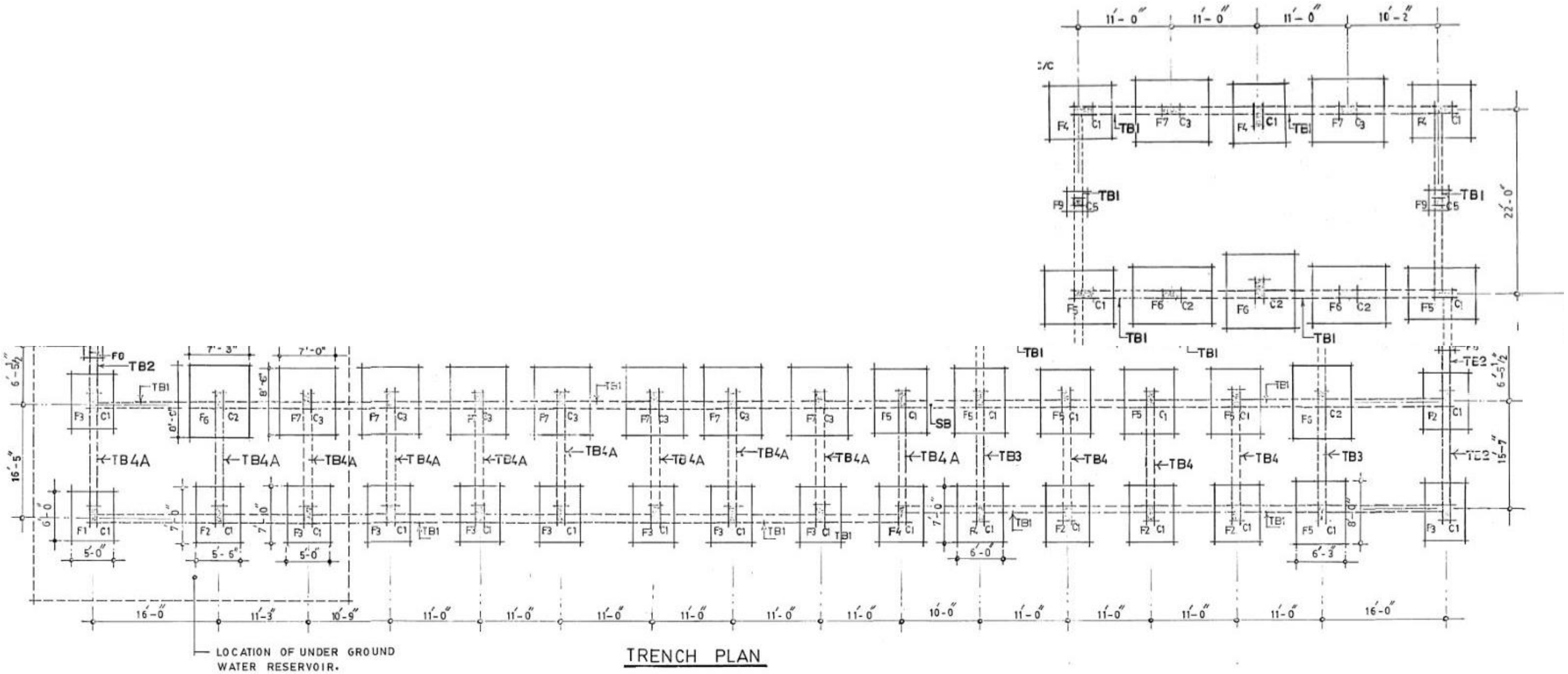
Dimension in inch. Feet (1 ft=30.48 cm, 1 inch=2.54 cm)

Architectural Plan



Columns Layout:

Dimension in inch. Feet (1 ft=30.48 cm, 1 inch=2.54 cm)



Schedule of Column

Dimension in inch. Feet (1 ft=30.48 cm, 1 inch=2.54 cm)

COLUMN SCHEDULE.

COLUMN TITLE	COLUMN SIZE AND BARS		2ND & 3RD FLOOR	4TH & 5TH FLOOR	COLUMN TIE	REMARKS (NO OF COL)
	BELOW G.L	GROUND & 1ST FLOOR				
C1	11" X 21"	10" × 20" 6-16 Ø	10" × 20" 6-16 Ø	10" × 20" 6-16 Ø	10 Ø AT 5" TO 10" C/C.	28
C2	11" X 21"	10" × 20" 10-20 Ø	10" × 20" 6-20 Ø + 4-16 Ø	10" × 20" 4-20 Ø + 6-16	10 Ø AT 5" TO 10" C/C.	5
C3	11" X 21"	10" × 20" 8-20 Ø	10" × 20" 6-20 Ø + 2-16 Ø	10" × 20" 4-16 Ø + 4-20 Ø	10 Ø AT 5" TO 10" C/C.	9
C4	11" X 16"	10" × 15" 4-16 Ø	15" 4-16 Ø	15" 4-16 Ø	10 Ø AT 5" TO 10" C/C.	2
C5	11" X 11"	11" × 11" 4-16 Ø	-	-	10 Ø AT 10" C/C.	2

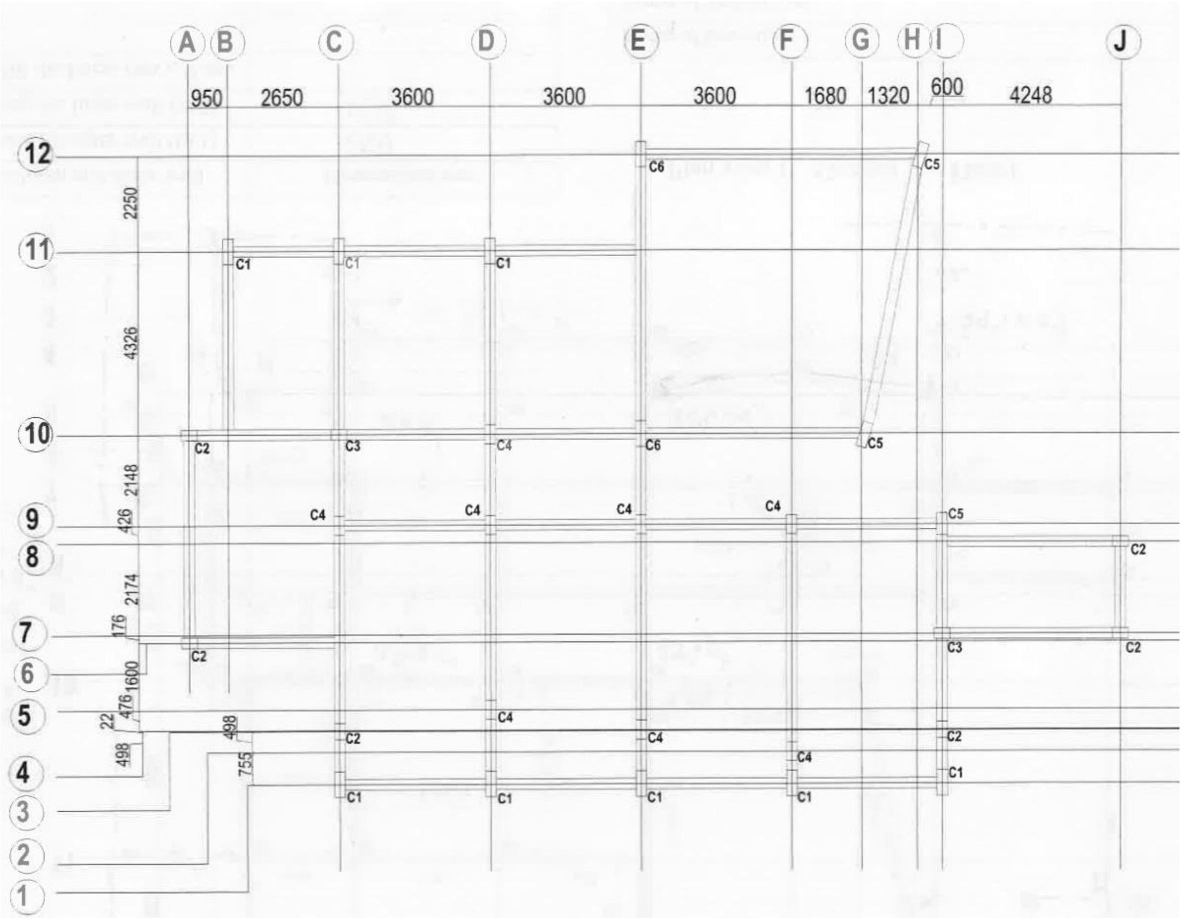
TIE BEAM

C-5 WILL BE UP TO (BELOW G.L.)

Dimension in inch. Feet (1 ft=30.48 cm, 1 inch=2.54 cm)

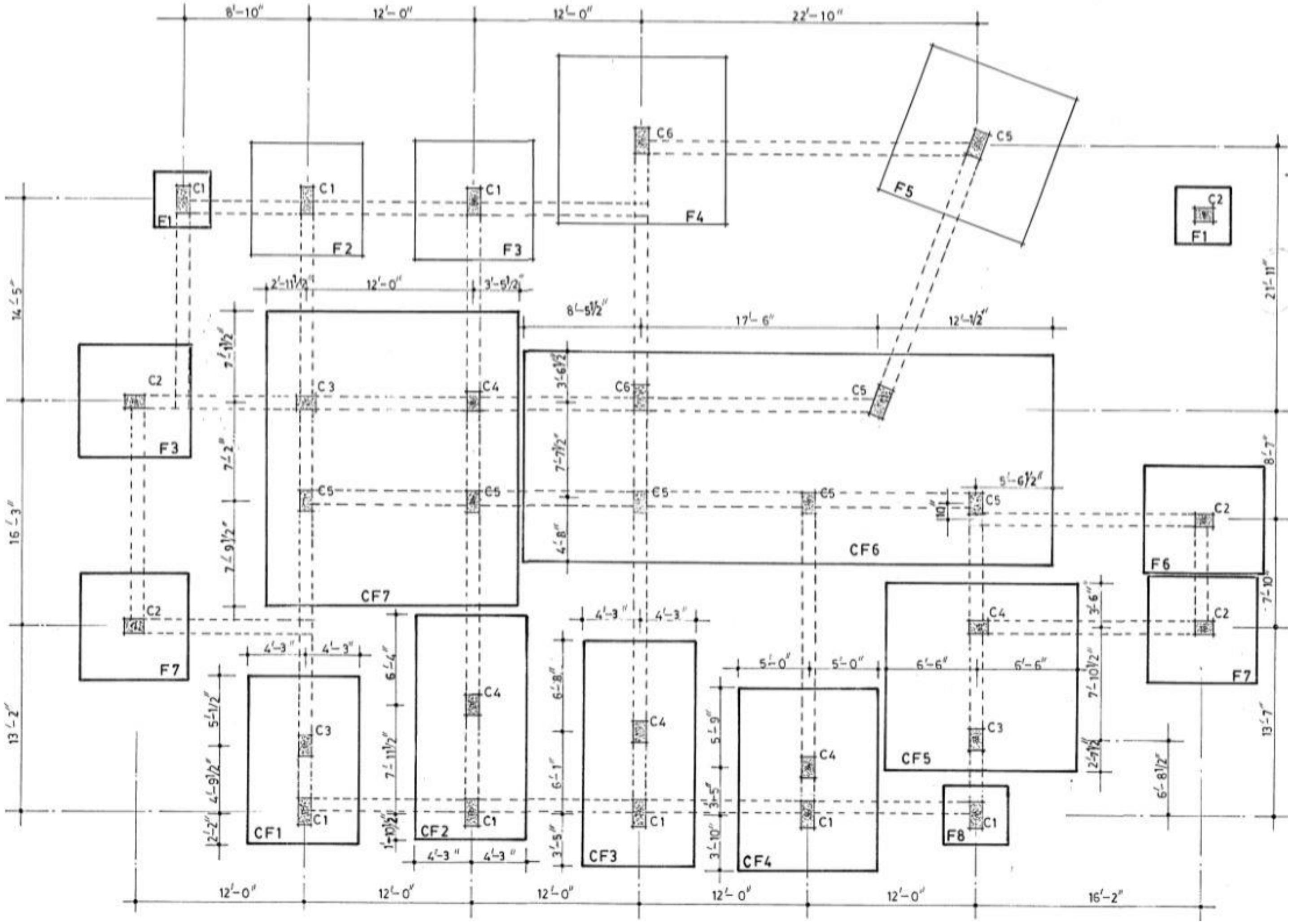
Building # 13

Architectural Plan



Dimension in inch. Feet (1 ft=30.48 cm, 1 inch=2.54 cm)

Columns Layout:



Dimension in inch. Feet (1 ft=30.48 cm, 1 inch=2.54 cm)

Schedule of Column

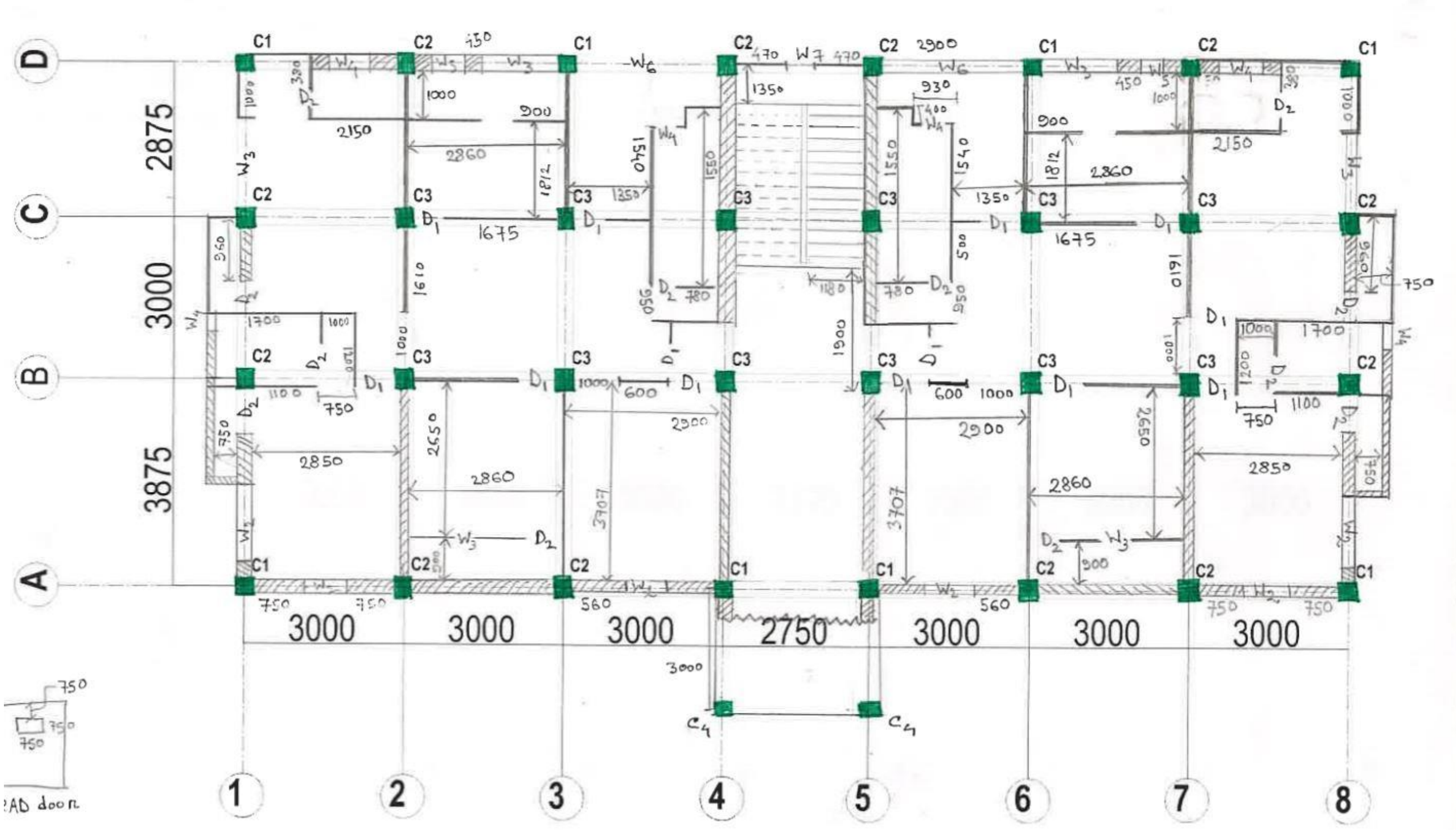
COLUMN SCHEDULE

COLUMN INDEX	COLUMN DIMENSION		COLUMN REINFORCEMENT		COLUMN TIE SPACING 'H' BEING THE COLUMN HEIGHT		
	BELOW F.G.L.	ABOVE F.G.L.	UP TO 2ND FLOOR	3RD & 4TH FLOOR	UP TO H/5 FROM FLOOR So	MIDSPAN S1	UP TO H/5 BELOW ROOF SLAB So
C1	27"X13"	24"X10"	8-16 ϕ	8-16 ϕ	10ϕ TIE @ 5" C/C	10ϕ TIE @ 10" C/C	10ϕ TIE @ 5" C/C
C2	18"X13"	15"X10"	6-16 ϕ	6-16 ϕ	DO	DO	DO
C3	18"X13"	15"X10"	10-16 ϕ	8-16 ϕ	DO	DO	DO
C4	18"X13"	15"X10"	10-20 ϕ	4-20ϕ+4-16ϕ	DO	DO	DO
C5	21"X13"	18"X10"	12-20 ϕ	8-20 ϕ	DO	DO	DO
C6	24"X13"	21"X10"	14-20 ϕ	8-20 ϕ	DO	DO	DO

Dimension in inch. Feet (1 ft=30.48 cm, 1 inch=2.54 cm)

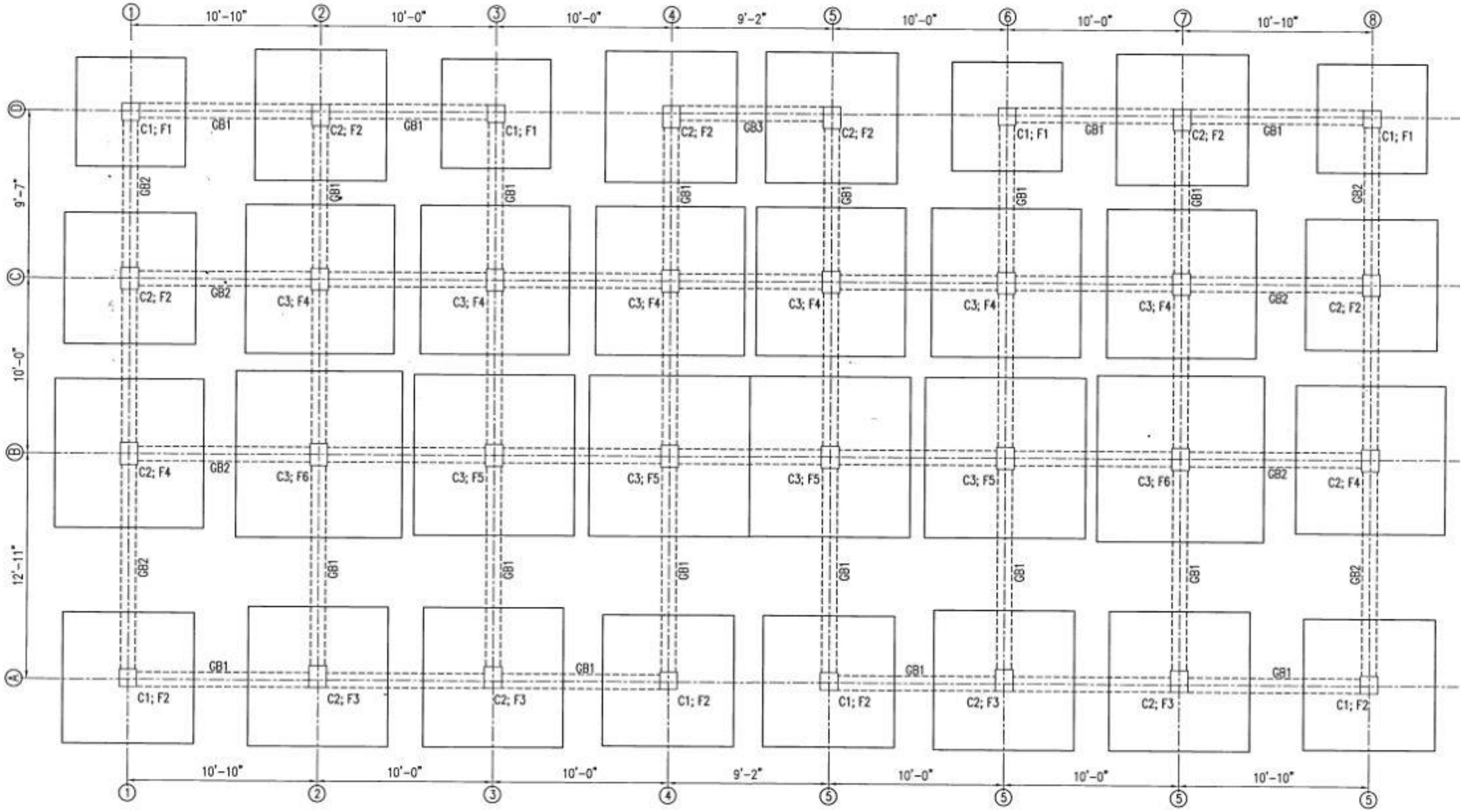
Building # 14

Architectural Plan



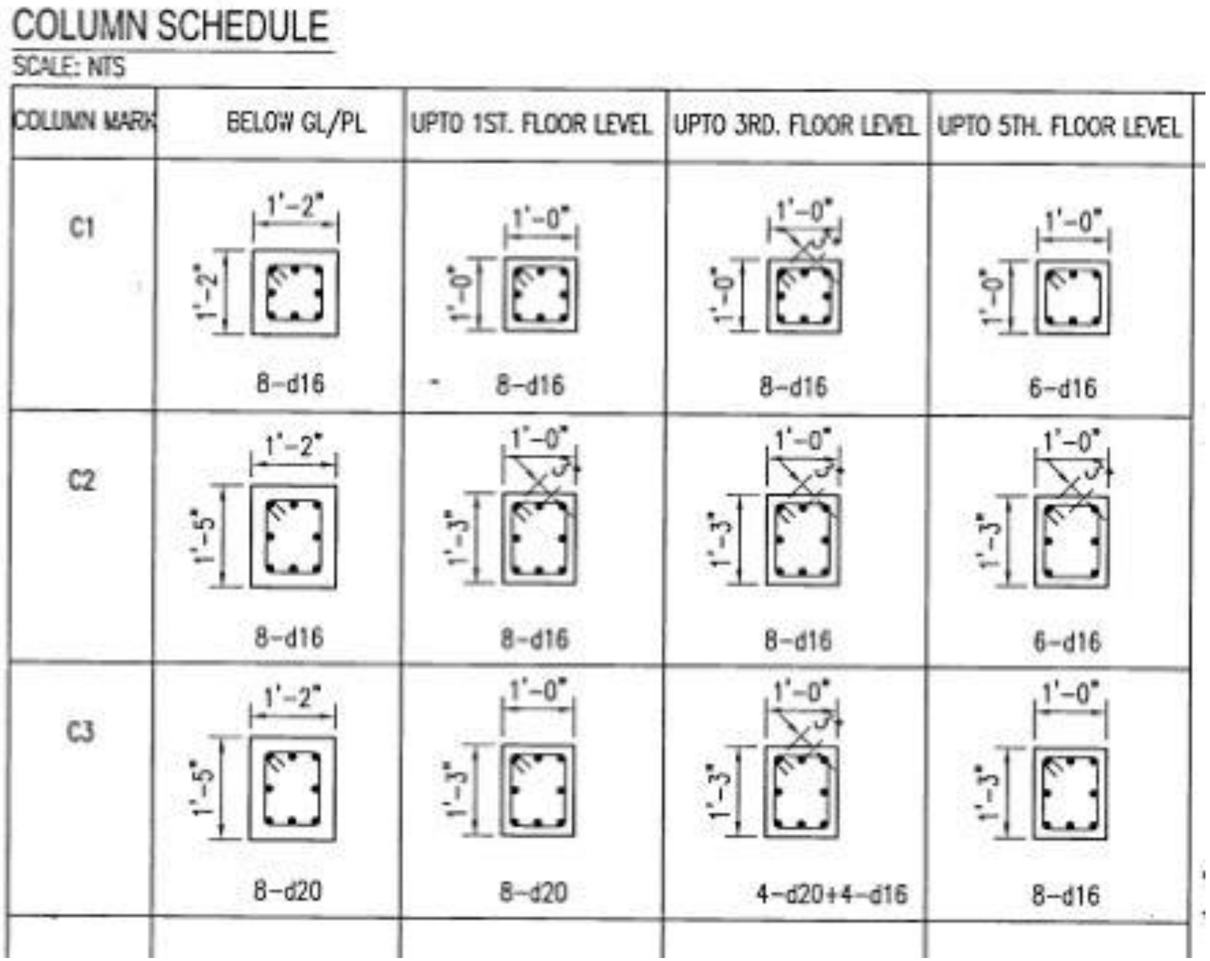
Dimension in inch. Feet (1 ft=30.48 cm, 1 inch=2.54 cm)

Columns Layout:



Dimension in inch. Feet (1 ft=30.48 cm, 1 inch=2.54 cm)

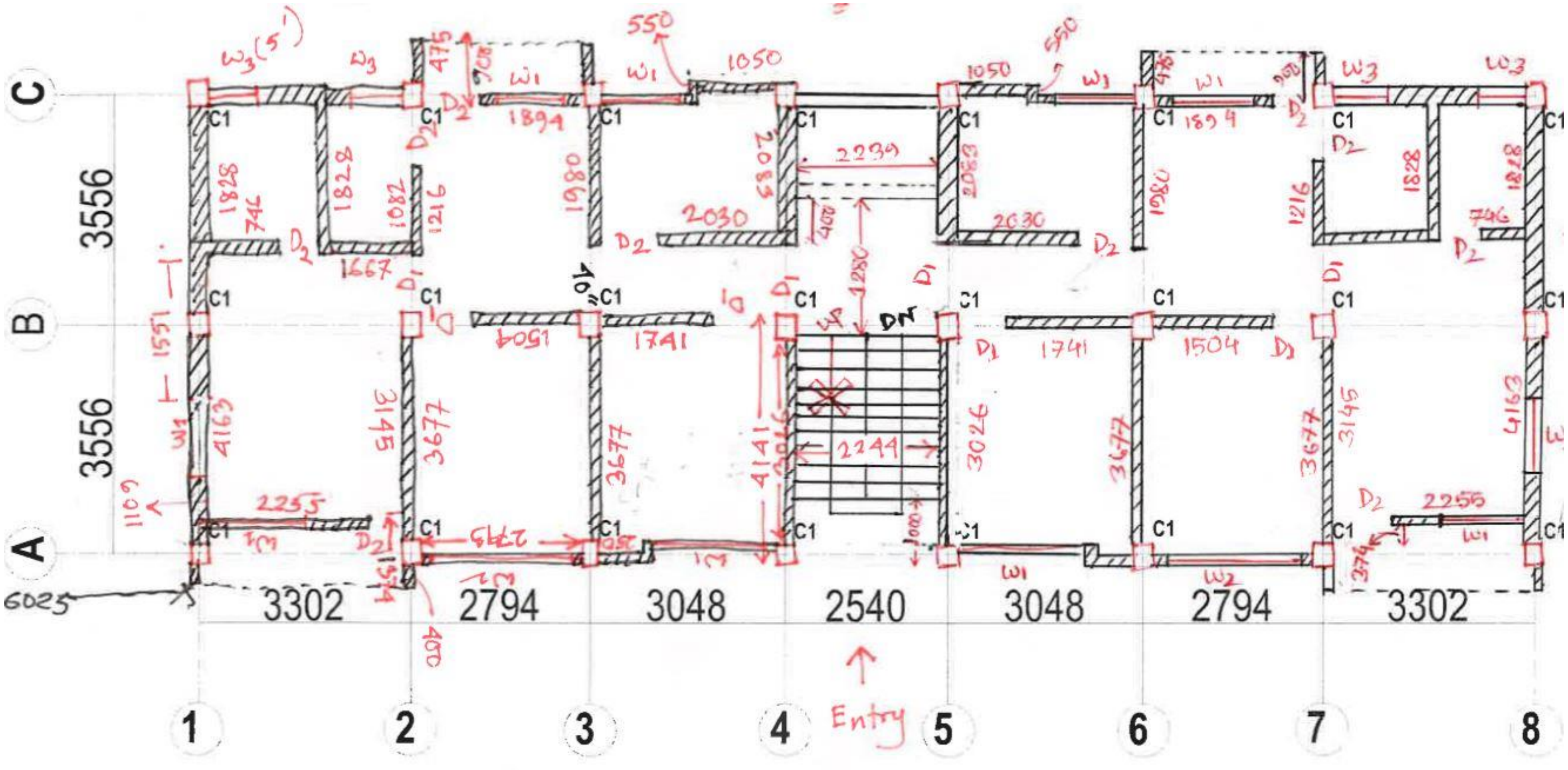
Schedule of Column



Dimension in inch. Feet (1 ft=30.48 cm, 1 inch=2.54 cm)

Building # 15

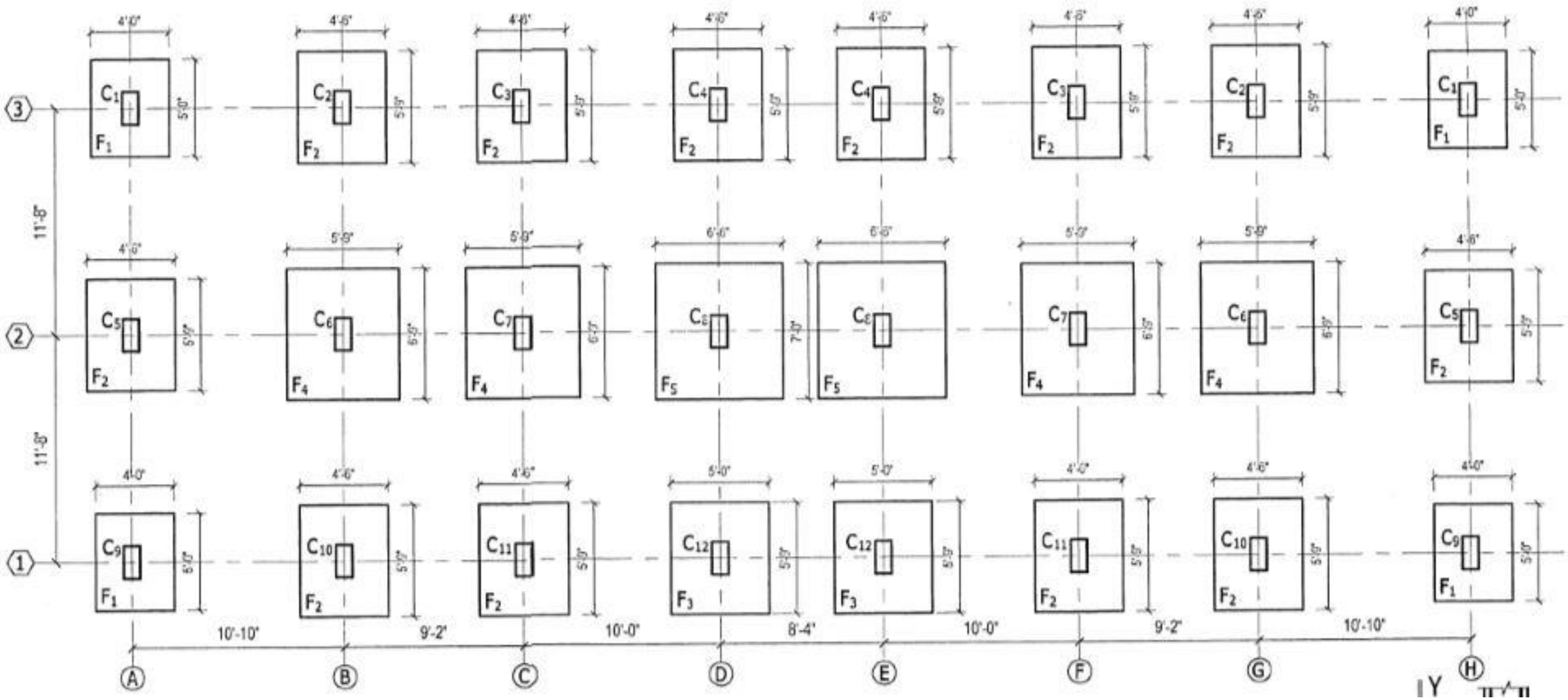
Architectural Plan



Columns Layout:

Dimension in inch. Feet (1 ft=30.48 cm, 1 inch=2.54 cm)

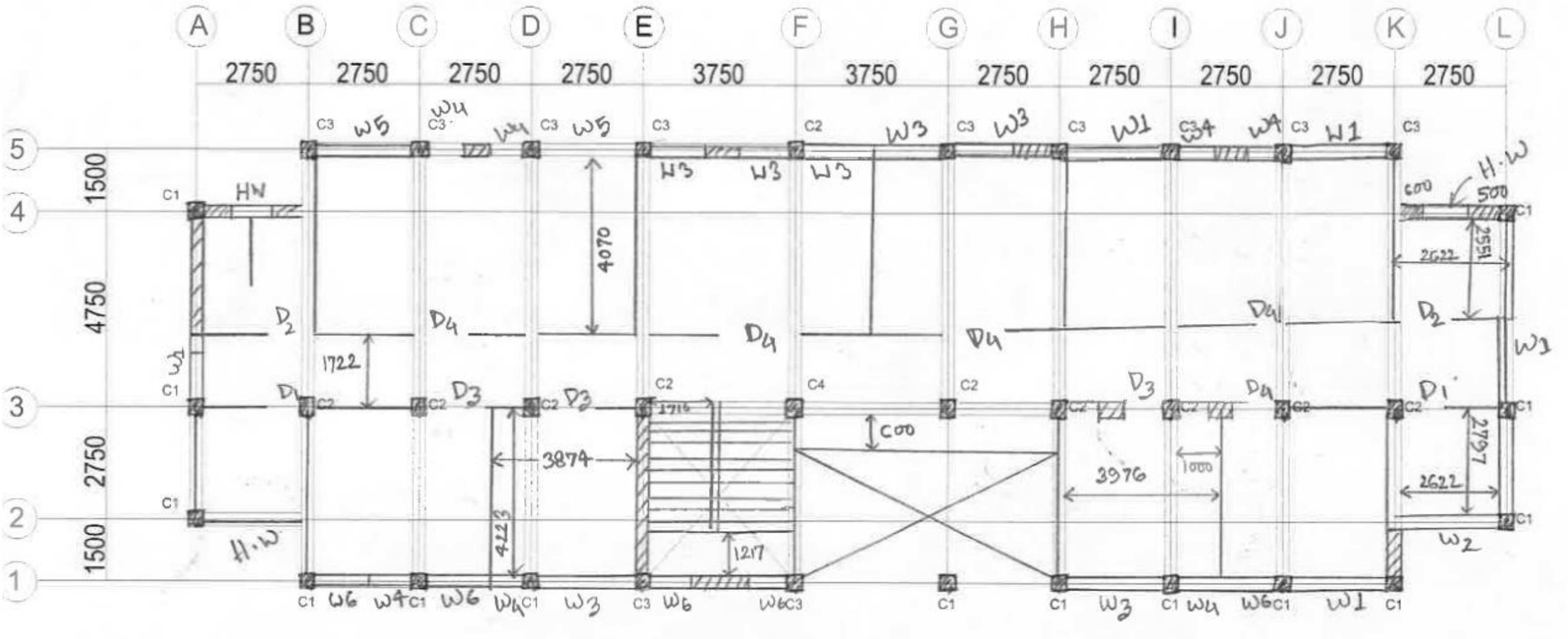
Schedule of Column



Dimension in inch. Feet (1 ft=30.48 cm, 1 inch=2.54 cm)

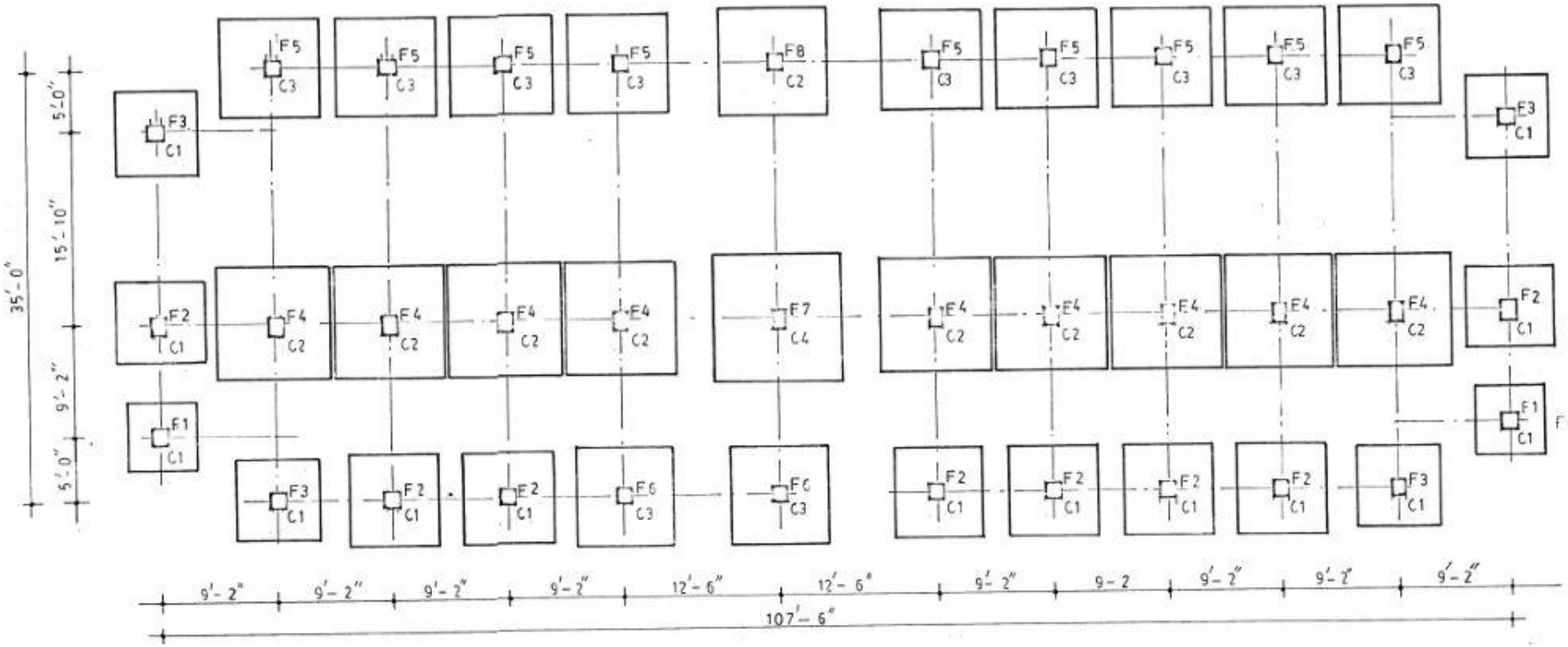
Building # 16

Architectural Plan



Dimension in inch. Feet (1 ft=30.48 cm, 1 inch=2.54 cm)

Columns Layout:



Dimension in inch. Feet (1 ft=30.48 cm, 1 inch=2.54 cm)

Schedule of Column

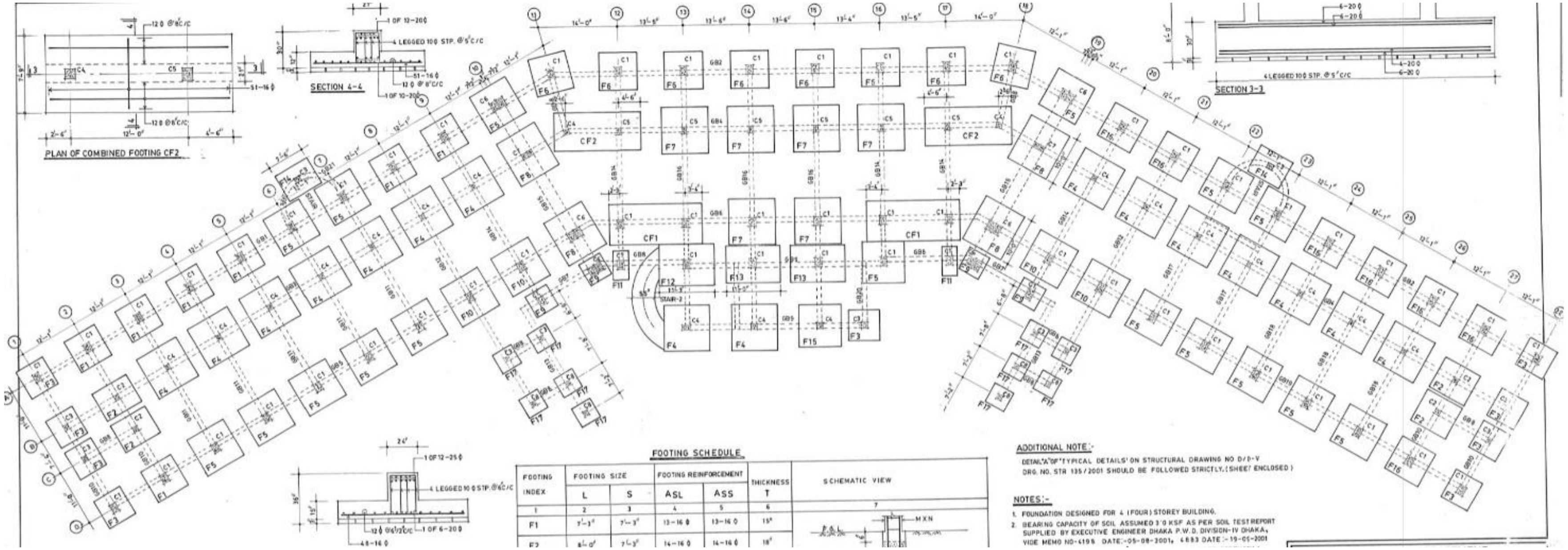
COLUMN AND FOOTING NO.	FOOTING SIZE IN ft. (a X b)	FOOTING THICKNESS IN INCH		COLUMN SIZE IN INCH		COLUMN ROD
		T	t	BELOW DECK SLAB	ABOVE DECK SLAB	
C1 F1	5′-6″ X 5′-6″	12″	9″	15″ X 15″	12″ X 12″	4 - 16 Ø; 10 Ø AT 250 C/C; 75 CLEAR COVER; 15″; 15″
C1 F2	7′-0″ X 7′-0″	15″	9″	15″ X 15″	12″ X 12″	4 - 16 Ø; 10 Ø AT 250 C/C; 75 CLEAR COVER; 15″; 15″
C1 F3	6′-6″ X 6′-6″	12″	9″	15″ X 15″	12″ X 12″	4 - 16 Ø; 10 Ø AT 250 C/C; 75 CLEAR COVER; 15″; 15″
C2 F4	9′-0″ X 9′-0″	18″	12″	15″ X 18″	12″ X 15″	6 - 19 Ø; 10 Ø AT 250 C/C; 75 CLEAR COVER; 15″; 18″
C3 F5	8′-0″ X 8′-0″	15″	9″	15″ X 15″	12″ X 12″	4 - 19 Ø; 10 Ø AT 250 C/C; 75 CLEAR COVER; 15″; 15″
C3 F6	7′-9″ X 7′-9″	15″	9″	15″ X 15″	12″ X 12″	4 - 19 Ø; 10 Ø AT 250 C/C; 75 CLEAR COVER; 15″; 15″
C4 F7	10′-0″ X 10′-0″	18″	12″	15″ X 18″	12″ X 15″	8 - 19 Ø; 10 Ø AT 250 C/C; 75 CLEAR COVER; 15″; 18″
C2 F8	8′-6″ X 8′-6″	15″	9″	15″ X 18″	12″ X 15″	6 - 19 Ø; 10 Ø AT 250 C/C; 75 CLEAR COVER; 15″; 15″

Dimension in inch. Feet (1 ft=30.48 cm, 1 inch=2.54 cm)

<u>Building # 17</u>

Architectural Plan

Columns Layout:



Dimension in inch. Feet (1 ft=30.48 cm, 1 inch=2.54 cm)

Schedule of Column

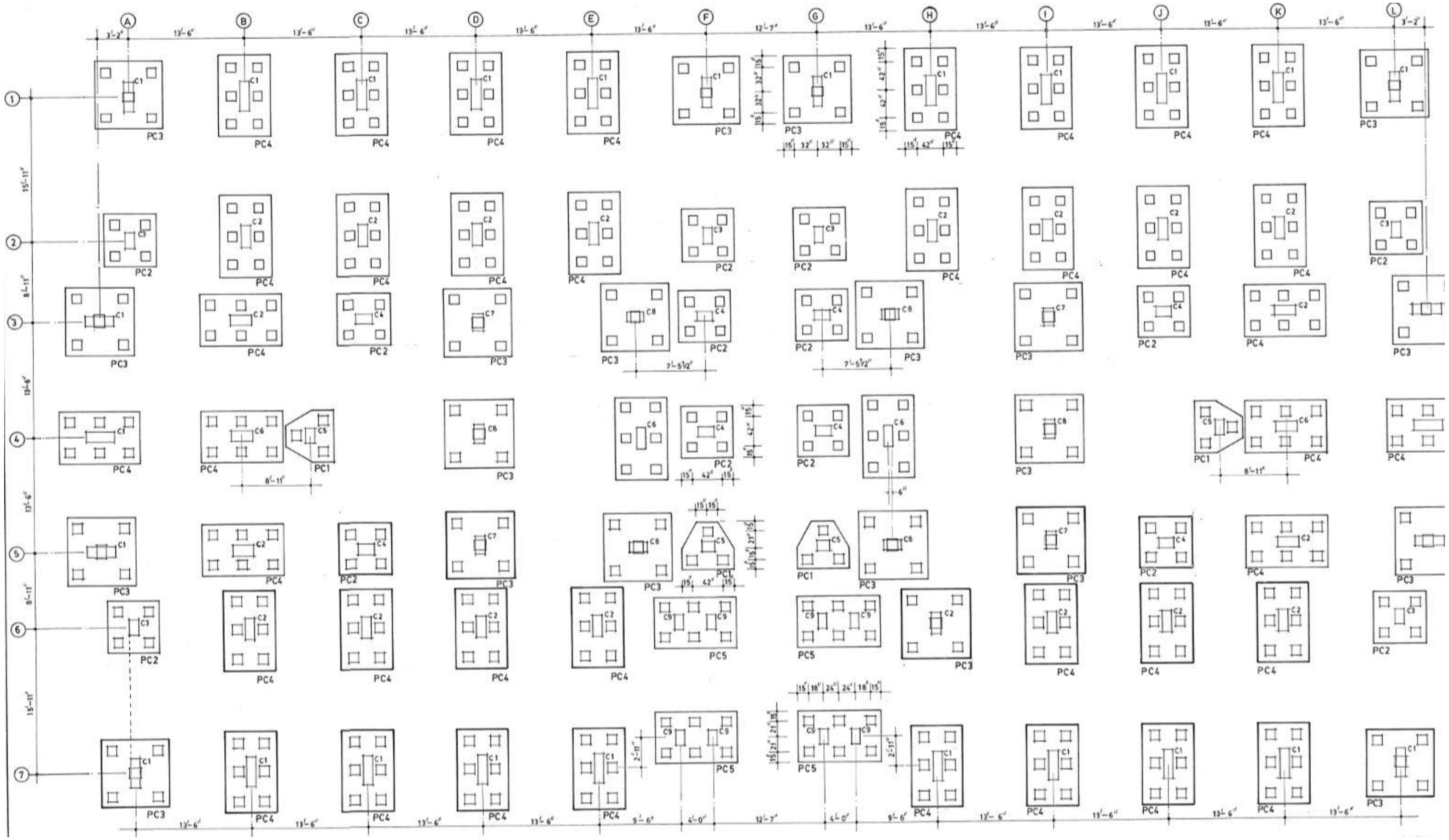
COLUMN INDEX	COLUMN DIMENSION: BELOW F.G.L. (m x n)	COLUMN DIMENSION: ABOVE F.G.L. (M+N)	COLUMN REINFORCEMENT: UP TO GROUND FLOOR ROOF	COLUMN REINFORCEMENT: 1ST FLOOR	COLUMN REINFORCEMENT: 2ND FLOOR AND 3RD FLOOR
C1	18" X 23"	15" X 20"	10–16 φ	10–16 φ	10–16 φ
C2	15" X 15"	12" X 12"	8–16 φ	8–16 φ	6–16 φ
C3	15" X 15"	12" X 12"	6–16 φ	6–16 φ	6–16 φ
C4	15" X 15"	12" X 12"	8–25 φ	8–25 φ	6–25 φ
C5	15" X 18"	12" X 15"	12–20 φ	12–20 φ	8–20 φ
C6	34" x 23"; 10–16 φ + 10–16 φ	15" + 8" + 15" x 20"; 10–16 φ, 10–16 φ	10–16 φ, 10–16 φ	10–16 φ, 10–16 φ	10–16 φ, 10–16 φ
C7	28" x 15"; 6–16 φ + 6–16 φ	12" + 8" + 12" x 12"; 6–16 φ, 6–16 φ	6–16 φ, 6–16 φ	6–16 φ, 6–16 φ	6–16 φ, 6–16 φ
C8	15" X 15"	12" X 12"	6–16 φ	6–16 φ	—

Dimension in inch. Feet (1 ft=30.48 cm, 1 inch=2.54 cm)

Building # 18

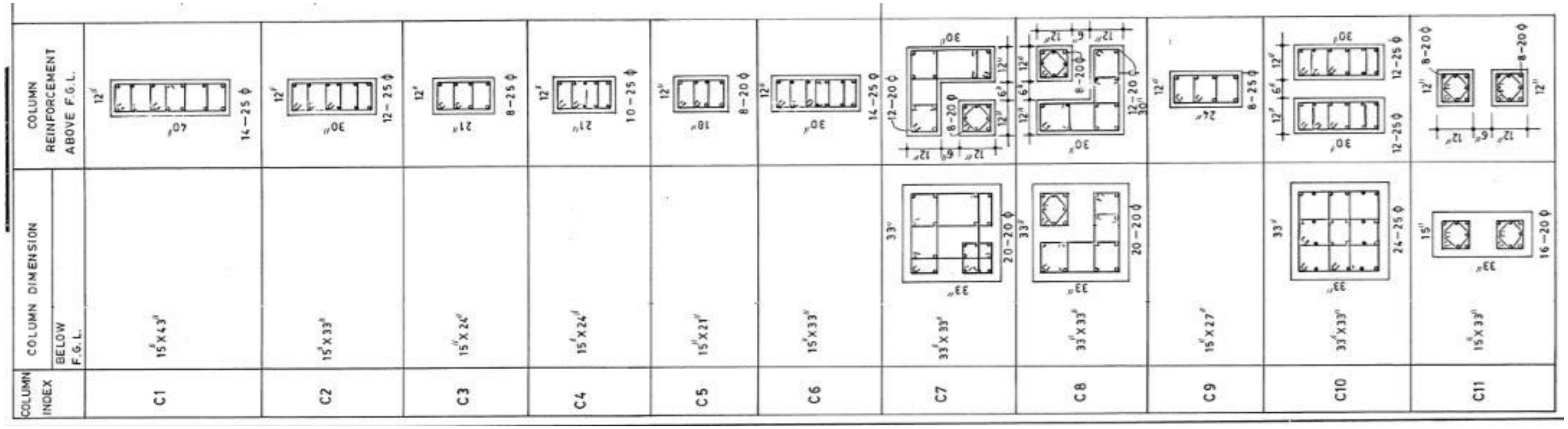
Architectural Plan

Columns Layout:



Dimension in inch. Feet (1 ft=30.48 cm, 1 inch=2.54 cm)

Schedule of Column

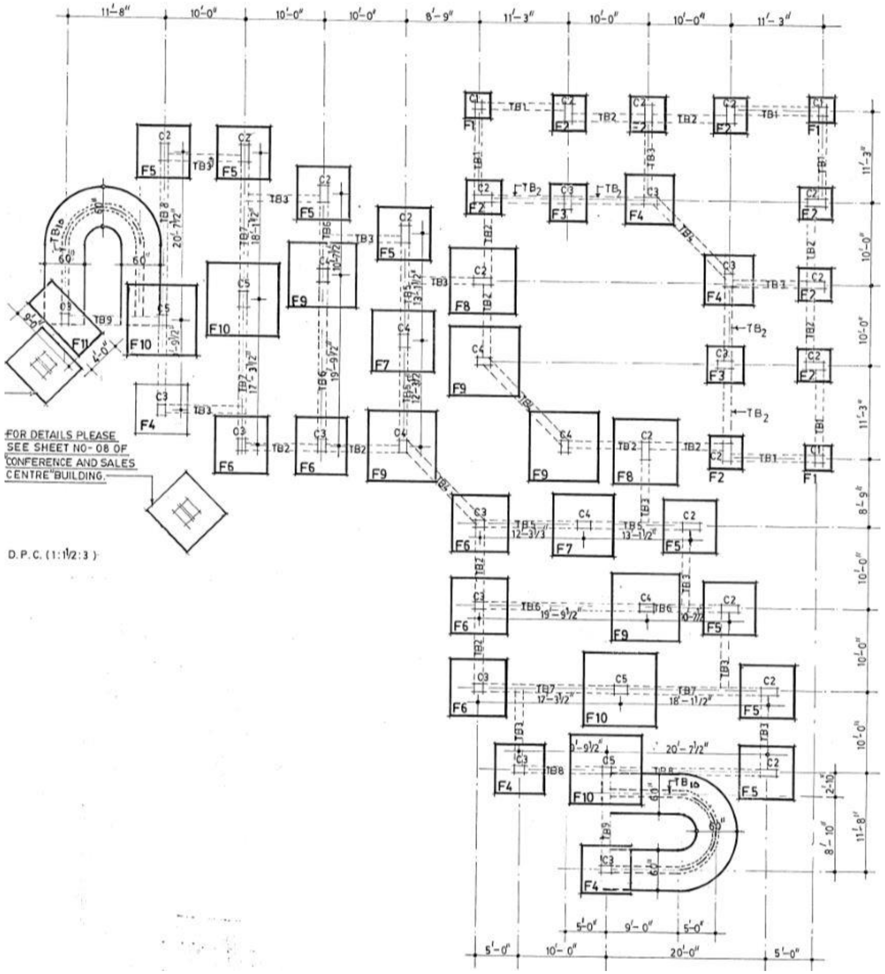


Building # 19

Architectural Plan

Dimension in inch. Feet (1 ft=30.48 cm, 1 inch=2.54 cm)

Columns Layout:



Dimension in inch. Feet (1 ft=30.48 cm, 1 inch=2.54 cm)

Schedule of Column

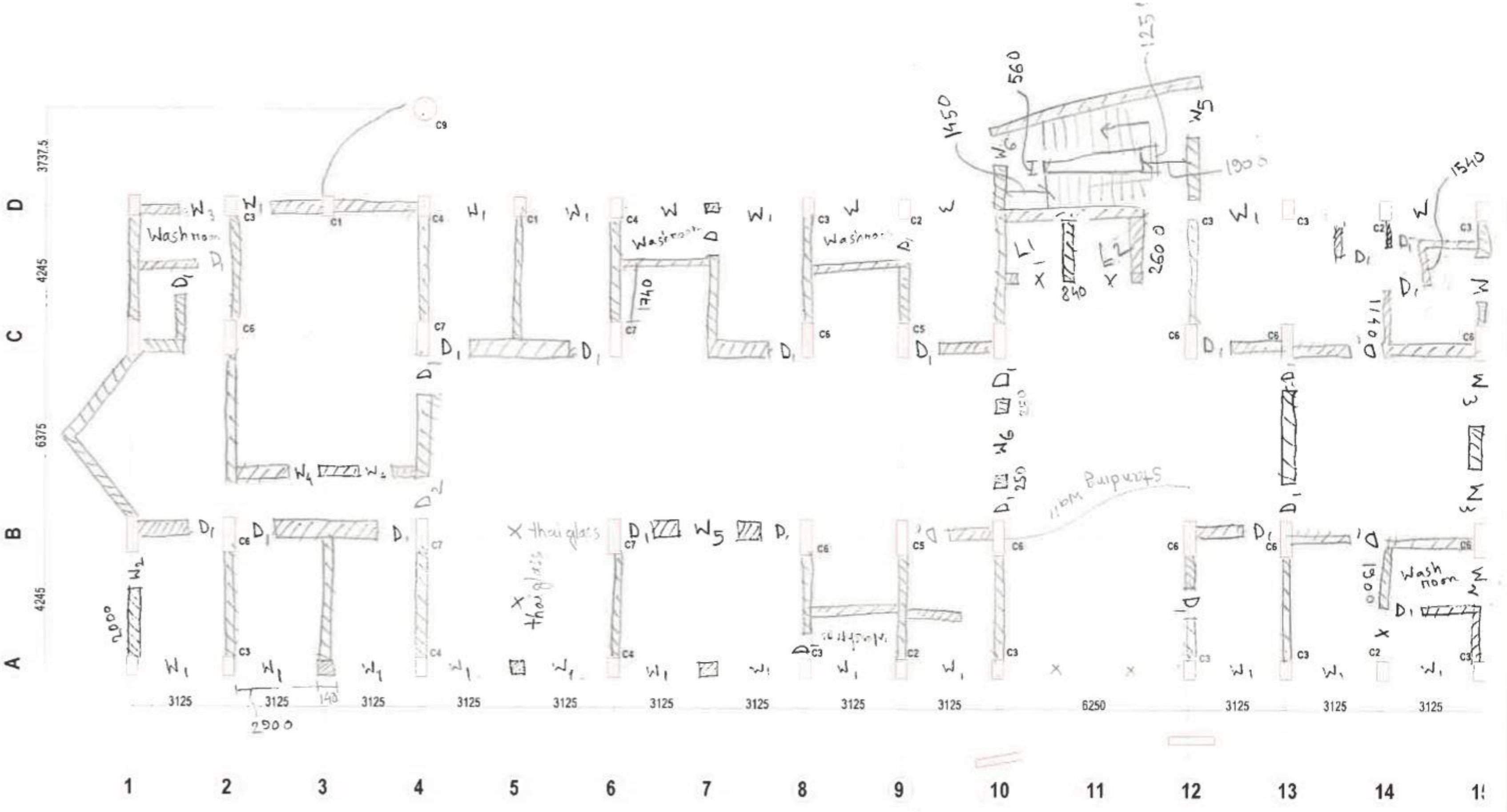
COLUMN SCHEDULE:-

SL. NO.	COLUMN INDEX	FLOOR WISE REINFORCEMENT OF COLUMNS (MAIN RODS)						
		UPTO P.L.	GROUND FLOOR	1ST FLOOR	2ND FLOOR	3RD FLOOR	4TH FLOOR	5TH FLOOR
1	C1	4-16mm.ϕ	4-16mm.ϕ	SAME AS IN GROUND FLOOR	SAME AS IN GROUND FLOOR	SAME AS IN GROUND FLOOR	SAME AS IN GROUND FLOOR	SAME AS IN GROUND FLOOR
2	C2	8-16mm.ϕ	8-16mm ϕ	SAME AS IN GROUND FLOOR	SAME AS IN GROUND FLOOR	SAME AS IN GROUND FLOOR	SAME AS IN GROUND FLOOR	SAME AS IN GROUND FLOOR
3	C3	6-16mm. ϕ	6-16mm. ϕ	SAME AS IN GROUND FLOOR	SAME AS IN GROUND FLOOR	SAME AS IN GROUND FLOOR	SAME AS IN GROUND FLOOR	SAME AS IN GROUND FLOOR
4	C4	2-20mm. ϕ 10-16mm. ϕ	2-20mm. ϕ 10-16mm. ϕ	8-15mm ϕ	6-16mm. ϕ	SAME AS IN 2ND FLOOR	SAME AS IN 2ND FLOOR	SAME AS IN 2ND FLOOR
5	C5	12-20mm. ϕ	12-20mm. ϕ	12-16 mm. ϕ	12-16mm. ϕ	8-16mm. ϕ	6-16mm. ϕ	SAME AS IN 4TH FLOOR

Dimension in inch. Feet (1 ft=30.48 cm, 1 inch=2.54 cm)

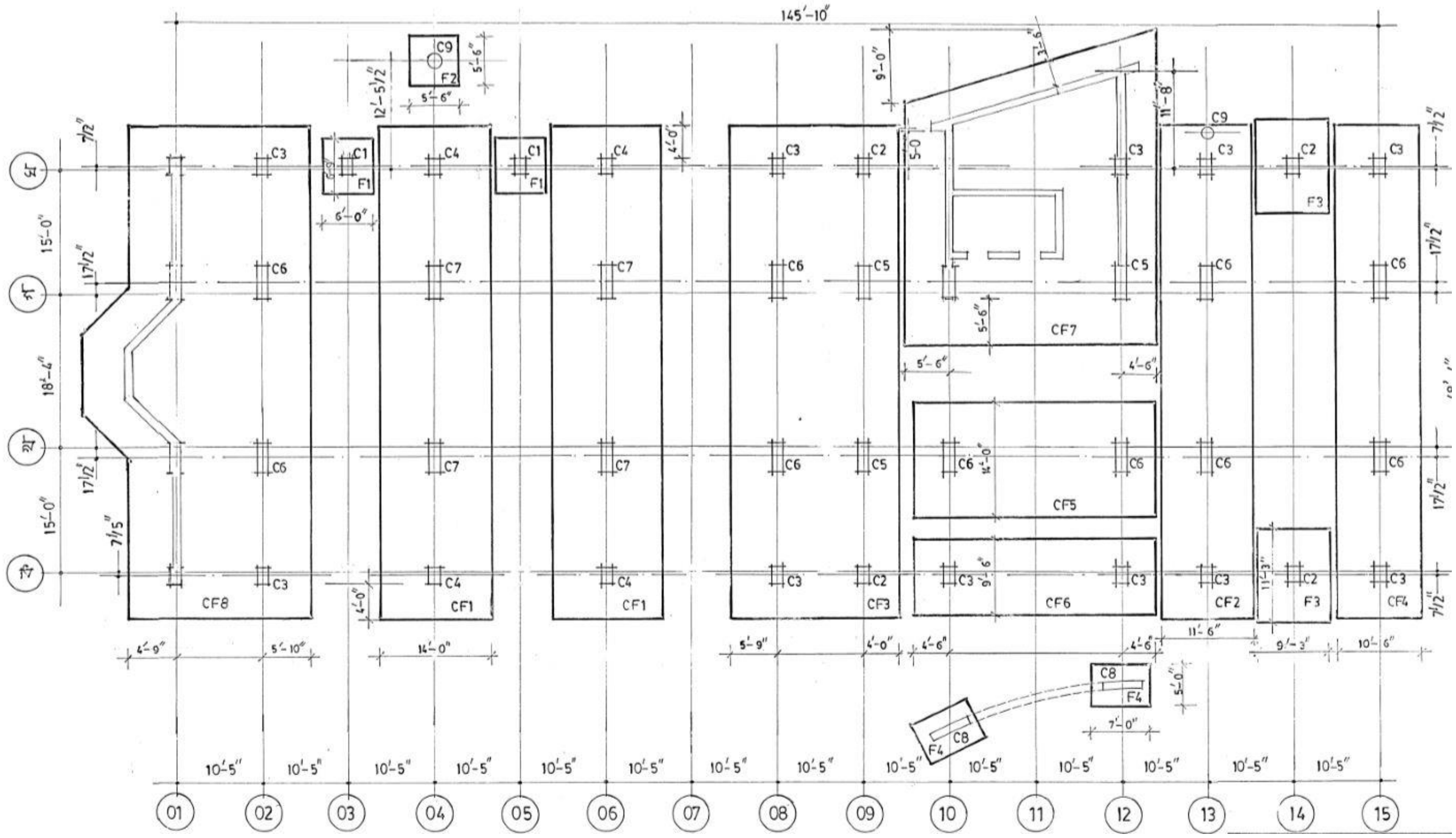
Building # 20

Architectural Plan



Dimension in inch. Feet (1 ft=30.48 cm, 1 inch=2.54 cm)

Columns Layout:



Dimension in inch. Feet (1 ft=30.48 cm, 1 inch=2.54 cm)

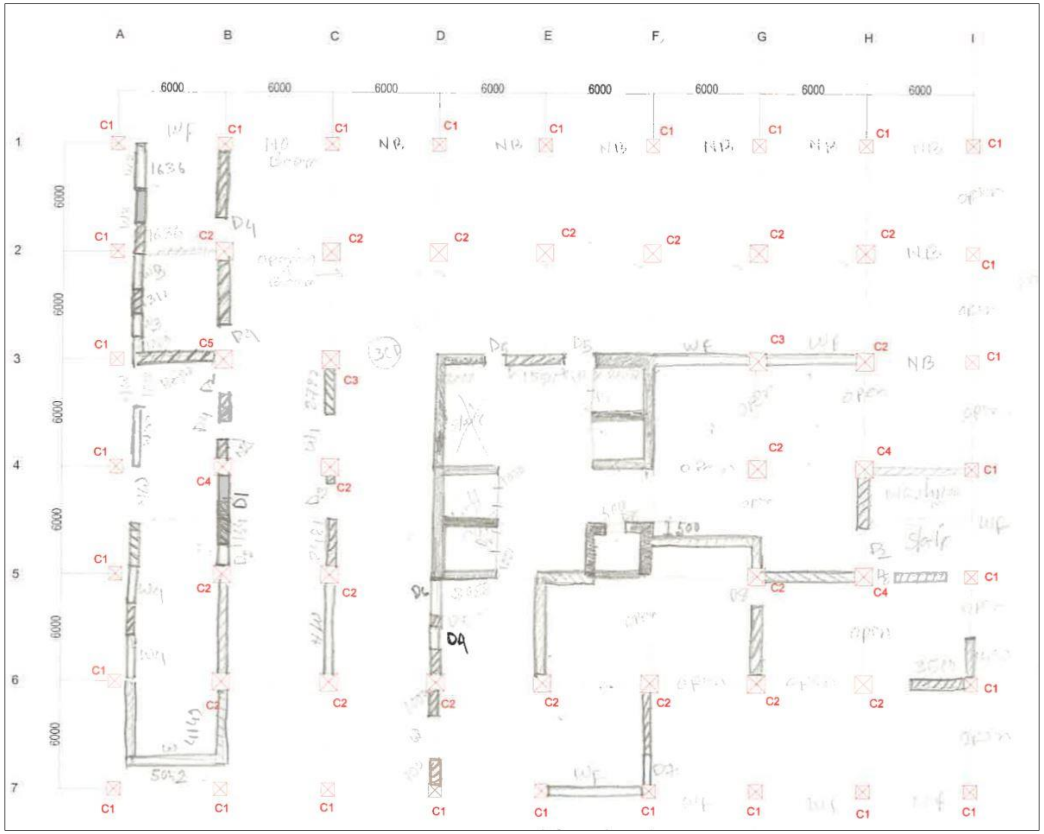
COLUMN SCHEDULE

COLUMN MARK	COLUMN SECTIONS AT FLOOR LEVEL				
	SECTION BELOW GL/PL	SEC. UPTO 3RD FLOOR	SEC. UPTO 6TH FLOOR	SEC. UPTO 8TH FLOOR	SEC. UPTO 10TH FLOOR
C1	3" 3"; 18"; 28"; 12 – 16 Ø	25"; 15"; 12 – 16 Ø	C1 Shall not extened beyond 2nd floor slab.		
C2	3"3" 3"3"; 18"; 28"; 12 – 20 Ø + 4-16 Ø	25"; 15"; 12-20 Ø + 4 – 16 Ø	25"; 15"; 8-20 Ø +4-16 Ø		
C3	3"3" 3"3"; 18"; 28"; 12 – 25 Ø	25"; 15"; 12 – 25 Ø	25"; 15"; 8-25 Ø+ 4-15 Ø		
C4	3"3" 3"3"; 18"; 28"; 20 – 25 Ø	25"; 15"; 20 – 25 Ø	25"; 15"; 16-25 Ø		
C5	3"3"7" 7"3"3"; 18"; 48"; 20 – 20 Ø	45"; 15"; 20 – 20 Ø	45"; 15"; 12 – 20 Ø+ 4-16 Ø		
C6	3"3" 3"3"; 18"; 48"; 16 – 25 Ø	45"; 15"; 16 – 25 Ø	45"; 15"; 8 – 25 Ø+ 8-16 Ø		
C7	3"3"3"3" 3"3"3"3"; 18"; 48"; 24 – 25 Ø	45"; 15"; 24 – 25 Ø	45"; 15"; 16 – 25 Ø		
C8	63"; 13"; 20 – 15 Ø	60"; 10"; 20 – 16 Ø	C8 Shall not extened beyond 2nd floor slab.		
C9	18" Ø; 8 – 16 Ø	15" Ø; 8 – 16 Ø			

Dimension in inch. Feet (1 ft=30.48 cm, 1 inch=2.54 cm)

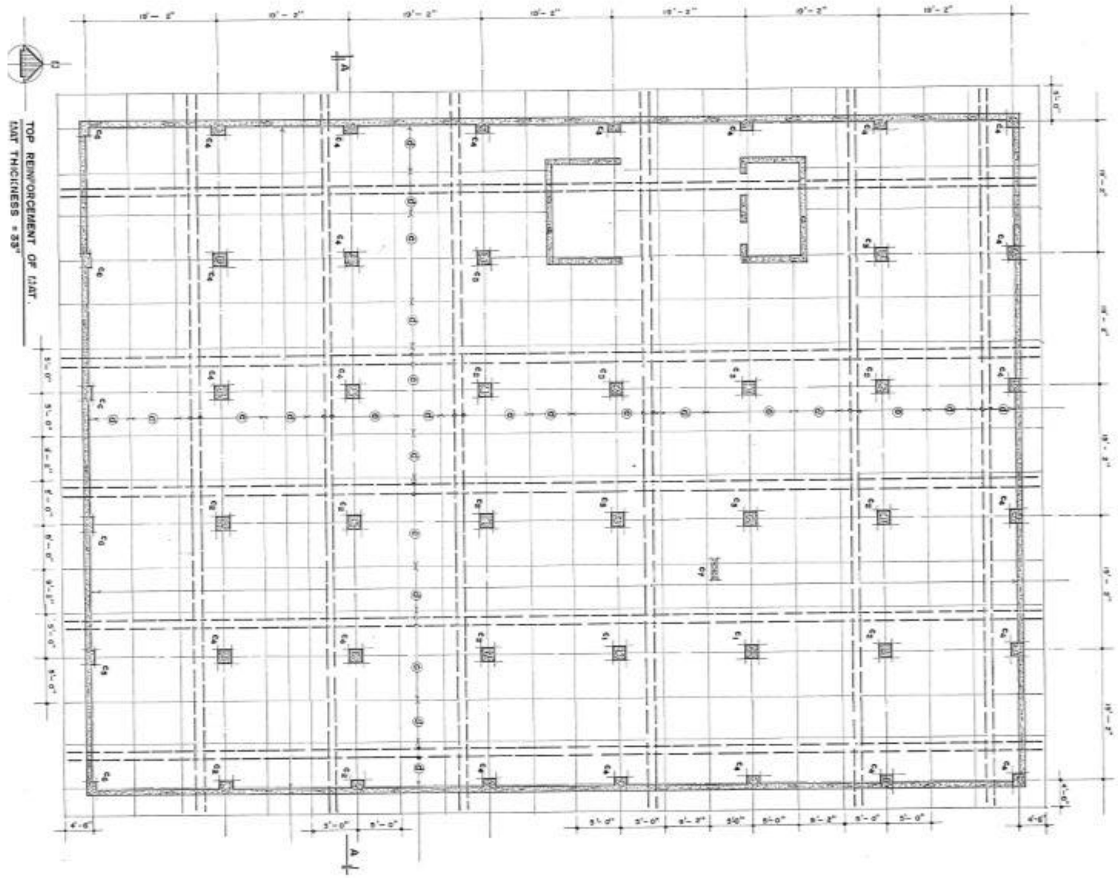
Building # 21

Architectural Plan



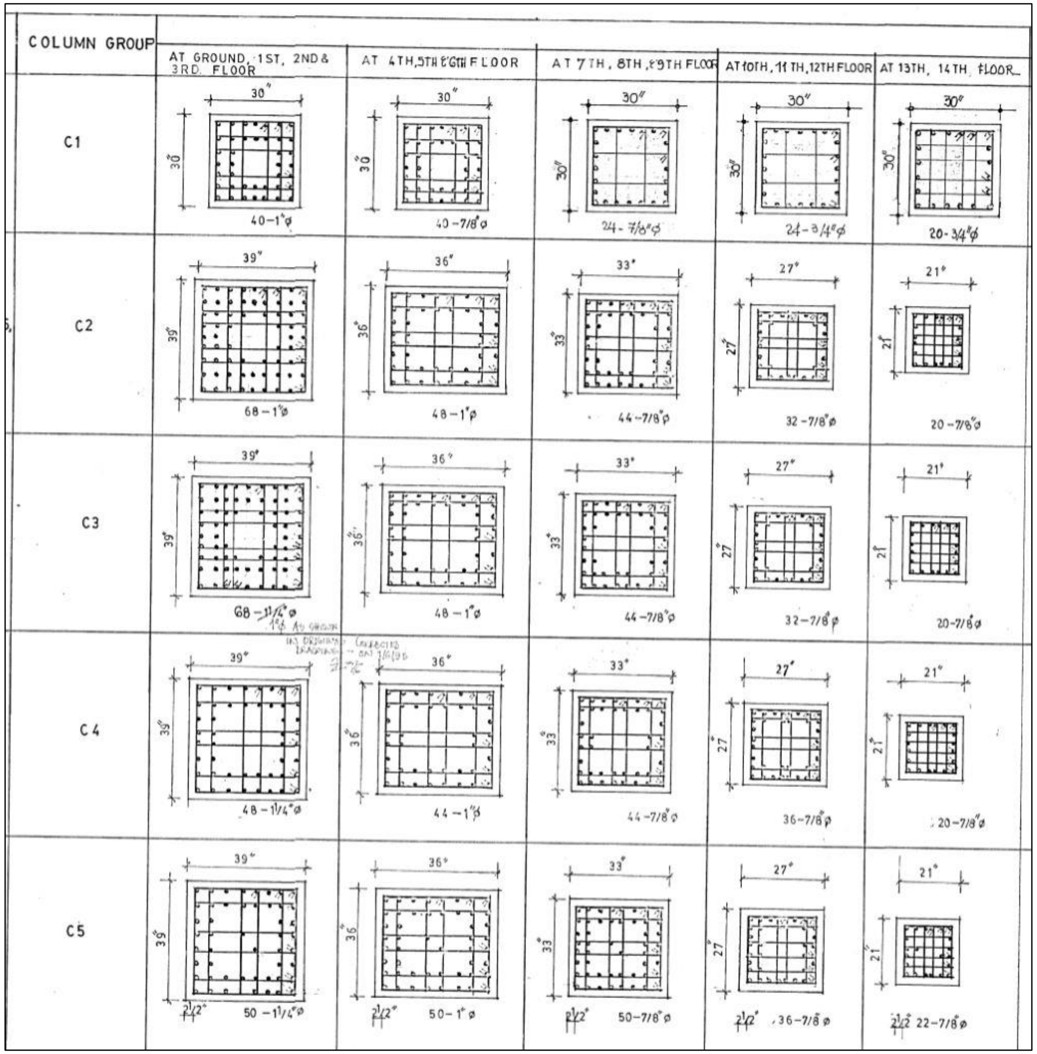
Dimension in inch. Feet (1 ft=30.48 cm, 1 inch=2.54 cm)

Column layout



Dimension in inch. Feet (1 ft=30.48 cm, 1 inch=2.54 cm)

Schedule of Column

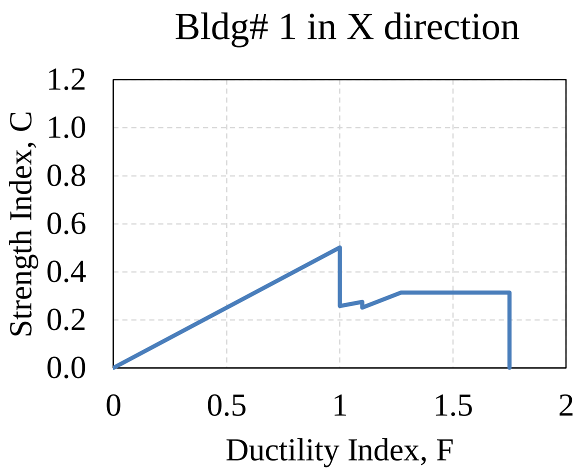


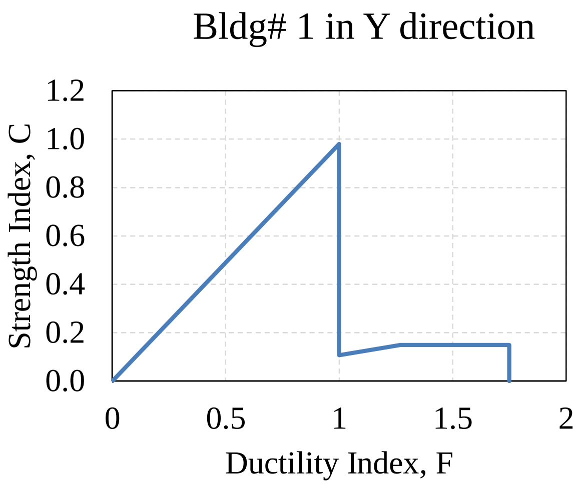
Dimension in inch. Feet (1 ft=30.48 cm, 1 inch=2.54 cm)

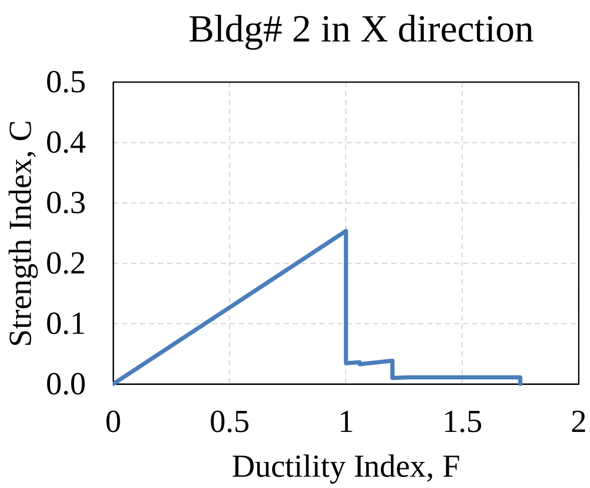
Dimension in inch. Feet (1 ft=30.48 cm, 1 inch=2.54 cm)

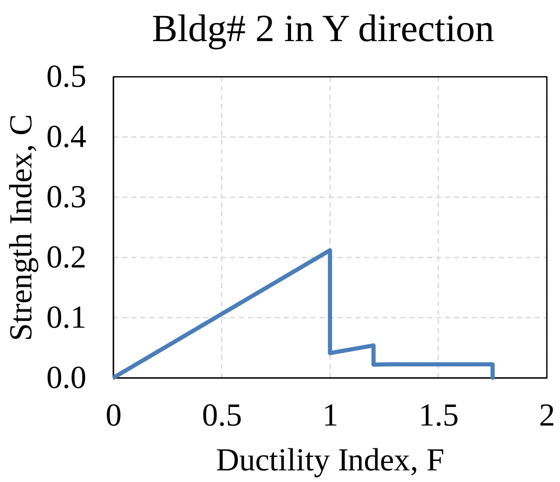
Appendix C

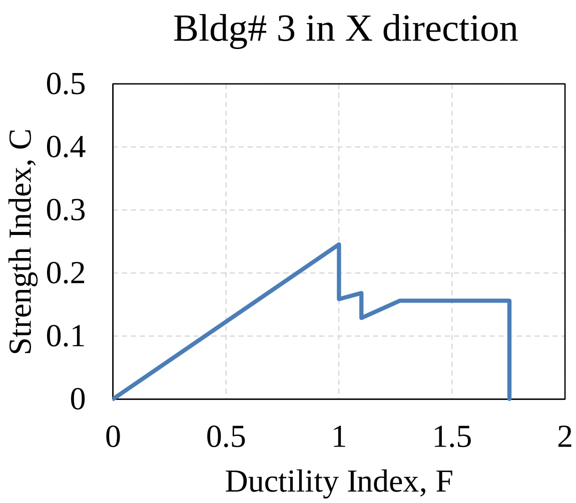
This appendix shows Force-deformation relationship of investigated RC buildings in Bangladesh

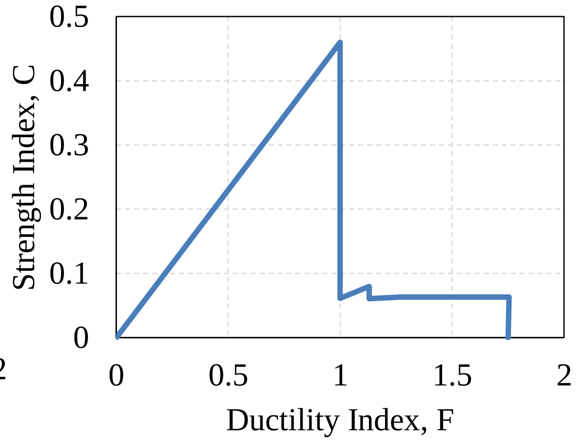


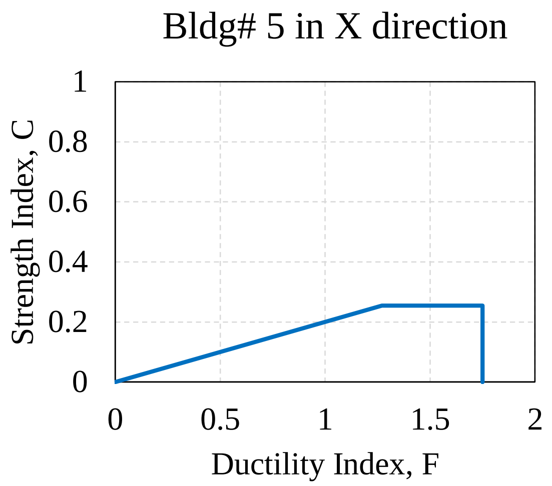











Bldg# 5 in X direction
Strength Index, C
Ductility Index, F
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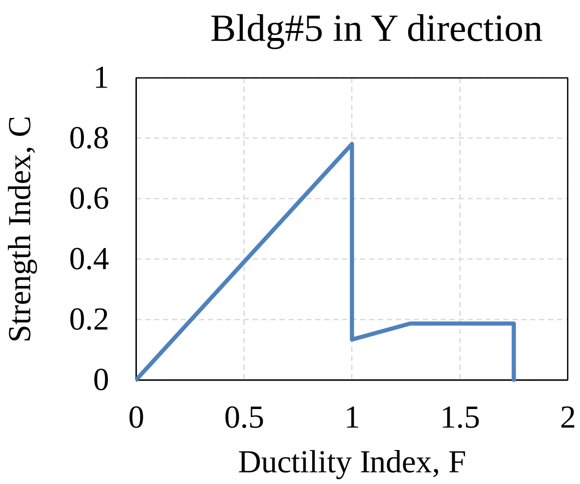
0.6
0.8
1
0
0.5
1
1.5
2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Ductility Index, F
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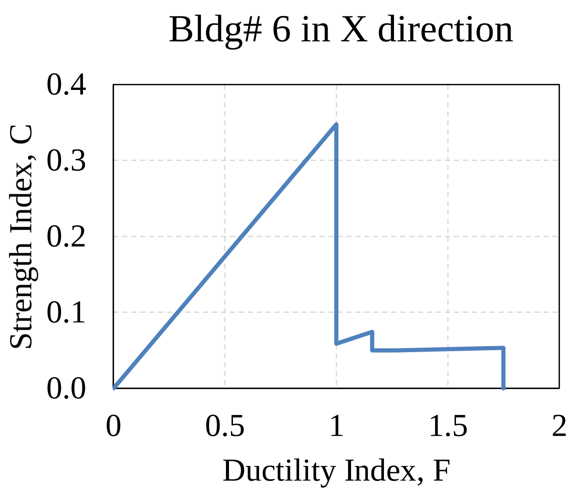
1.5
2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Ductility Index, F
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0.5
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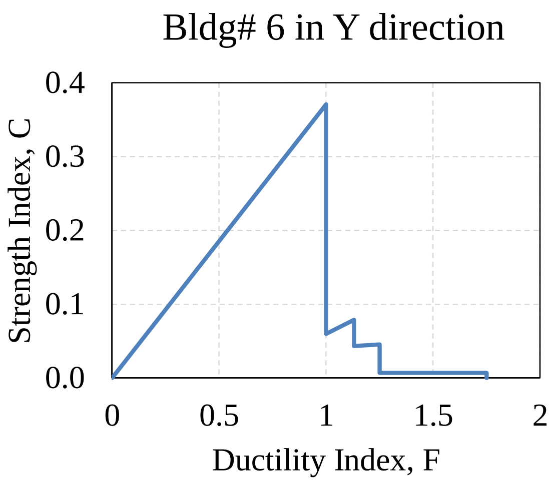
1.5
2


Bldg# 6 in Y direction
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Ductility Index, F
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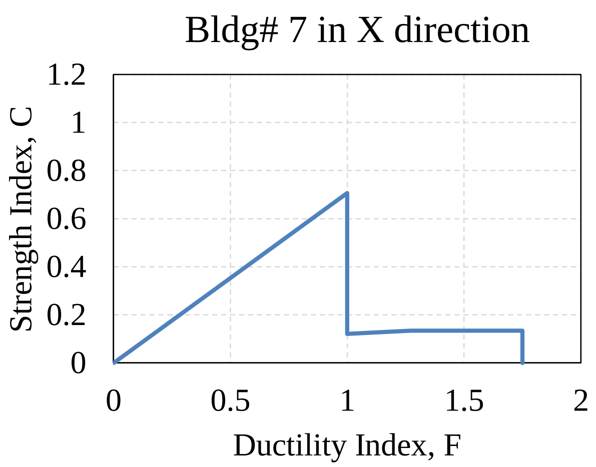
0.3
0.4
0
0.5
1
1.5
2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Ductility Index, F
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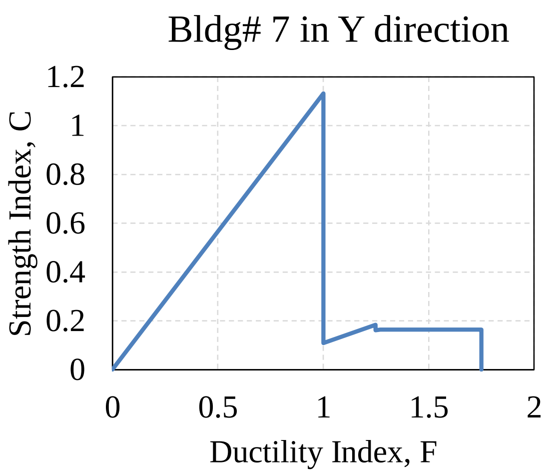
1
1.5
2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Ductility Index, F
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1.2
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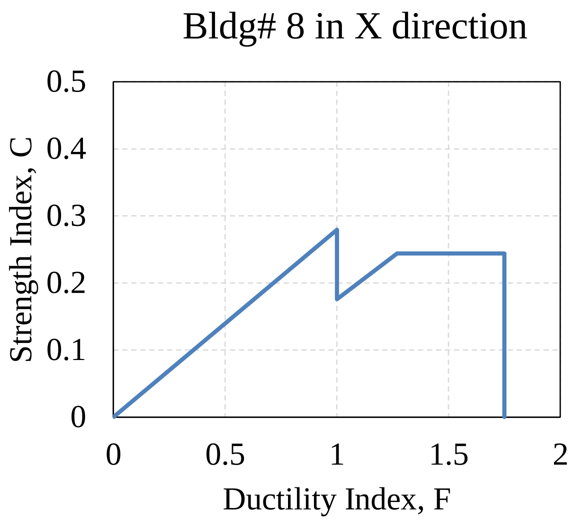
0.5
1
1.5
2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0.3
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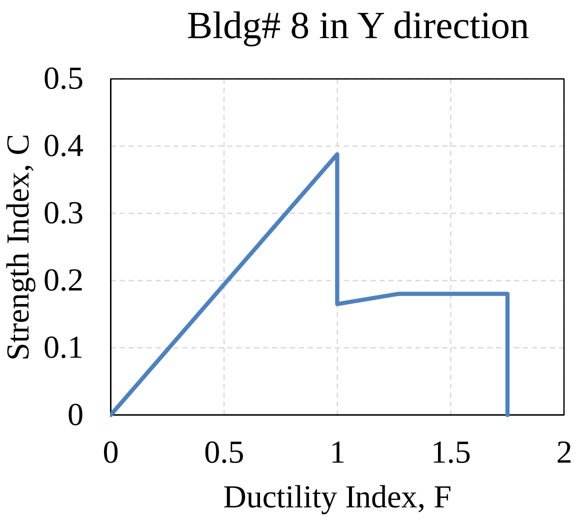
0
0.5
1
1.5
2
Ductility Index, F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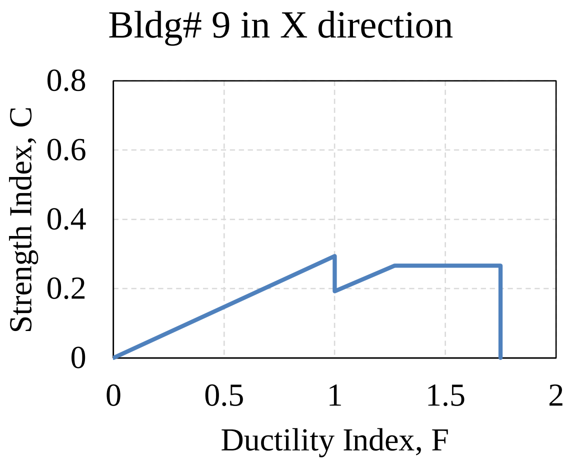
1.5
2
Ductility Index, F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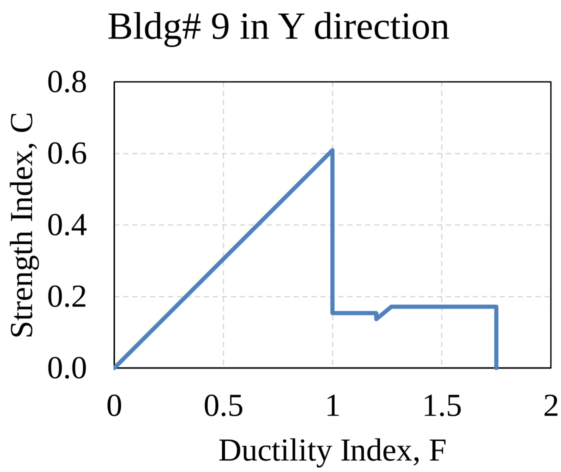
2
Ductility Index, F


Bldg# 9 in Y direction
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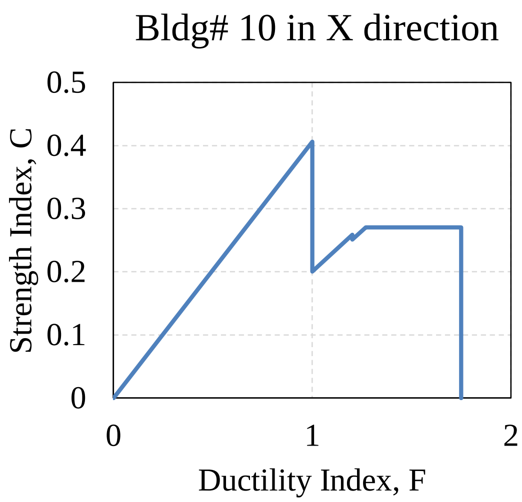
1
1.5
2
Ductility Index, F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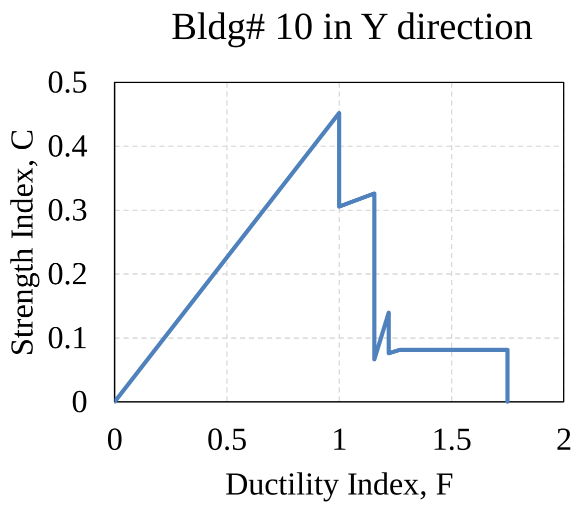
0
1
2
Ductility Index, F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0
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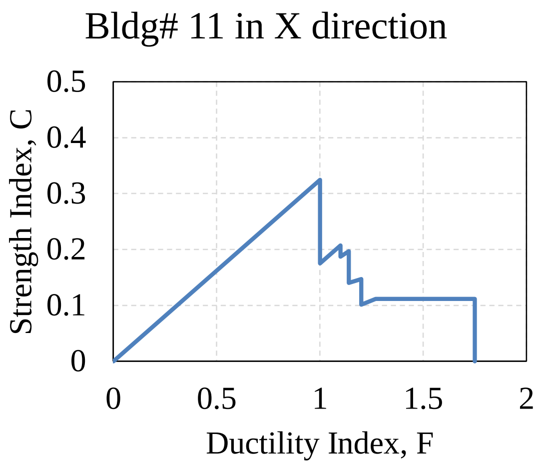
1.5
2
Ductility Index, F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Ductility Index, F
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1.5
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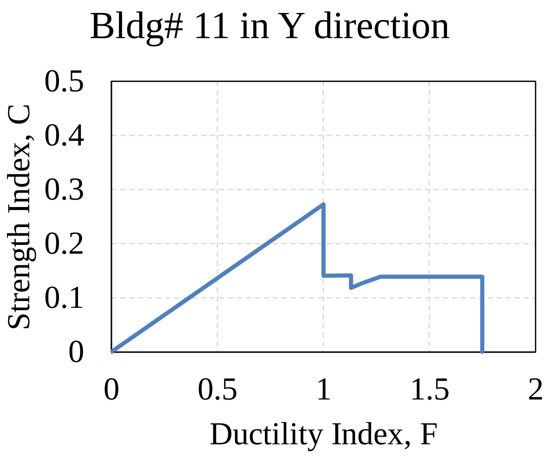
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Ductility Index, F
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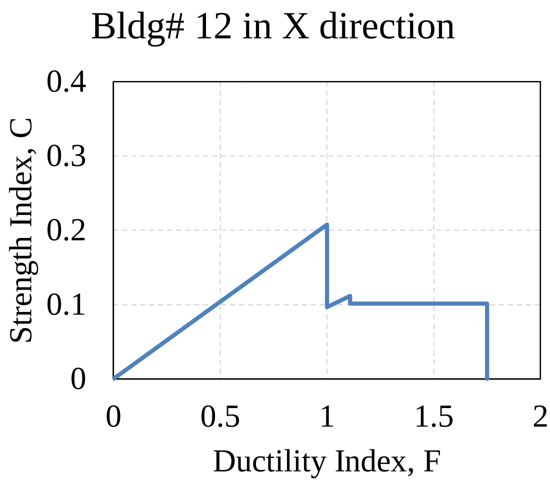
2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Ductility Index, F
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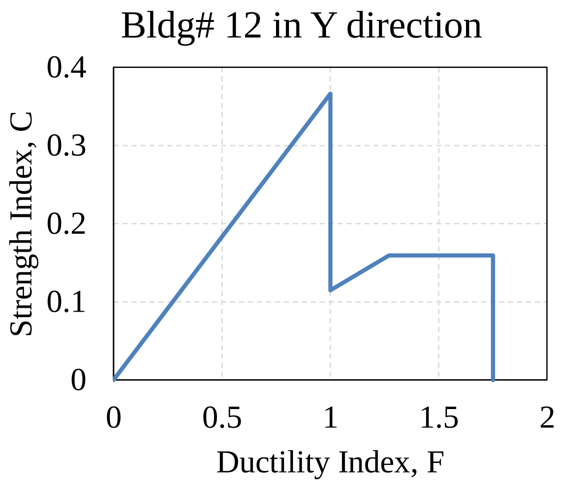
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Ductility Index, F
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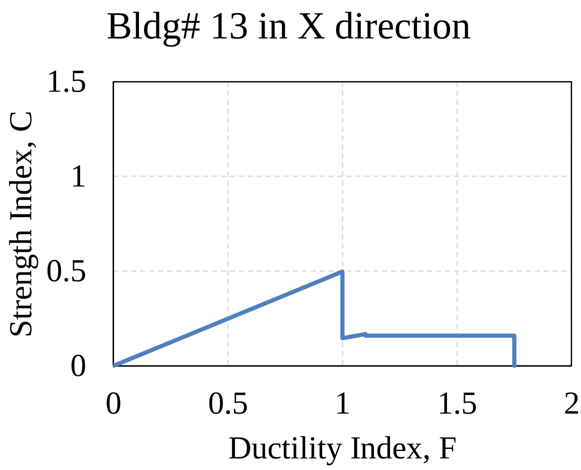
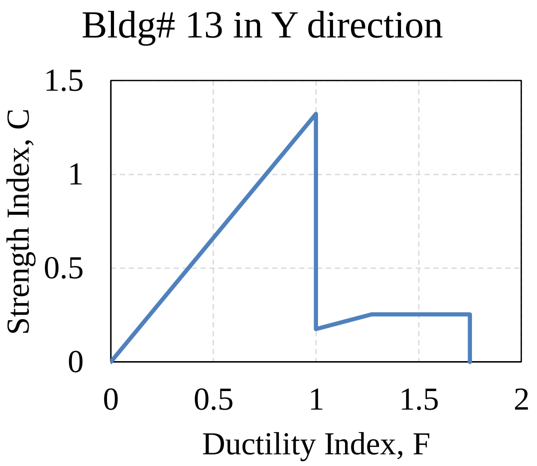
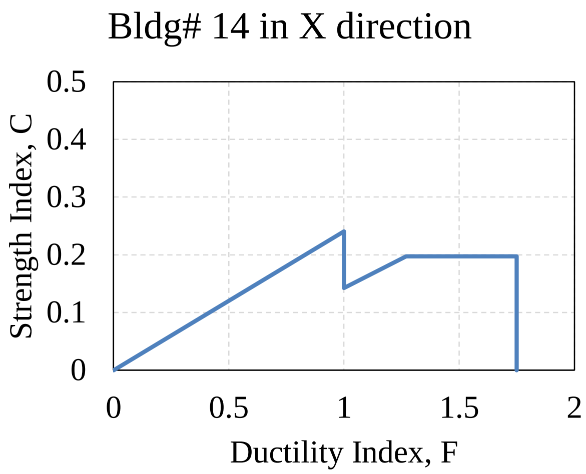
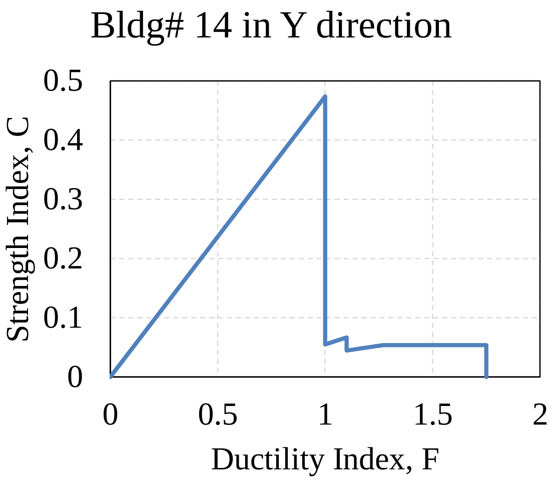
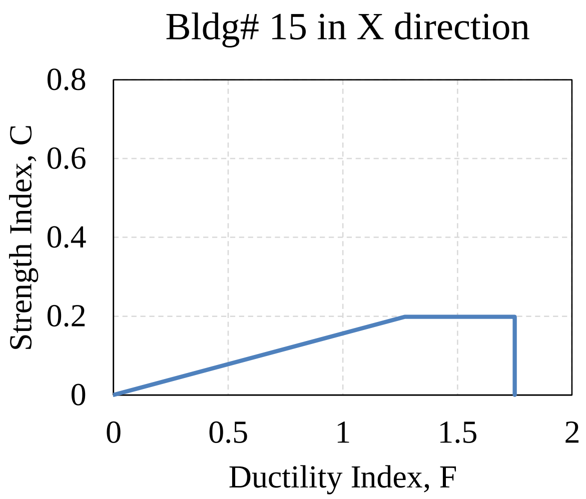
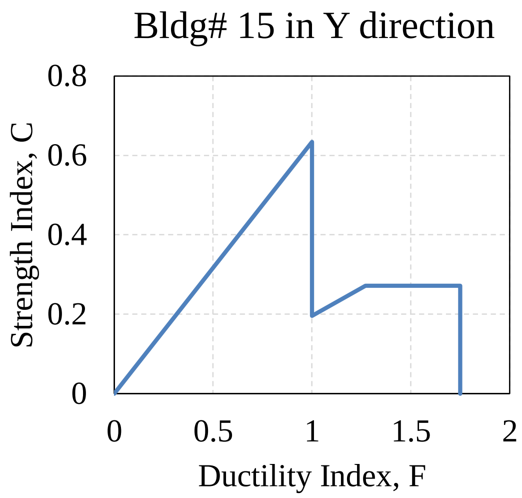

Bldg# 13 in X direction
Strength Index, C
Ductility Index, F
0
0.5
1
1.5
0
0.5
1
1.5
2

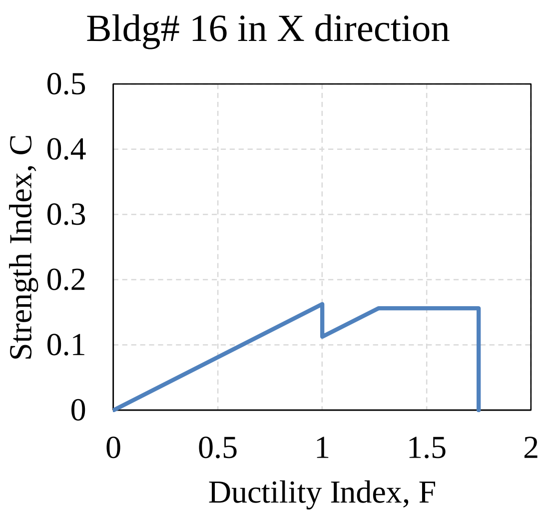

Bldg# 13 in Y direction
Strength Index, C
Ductility Index, F
0
0.5
1
1.5
0
0.5
1
1.5
2

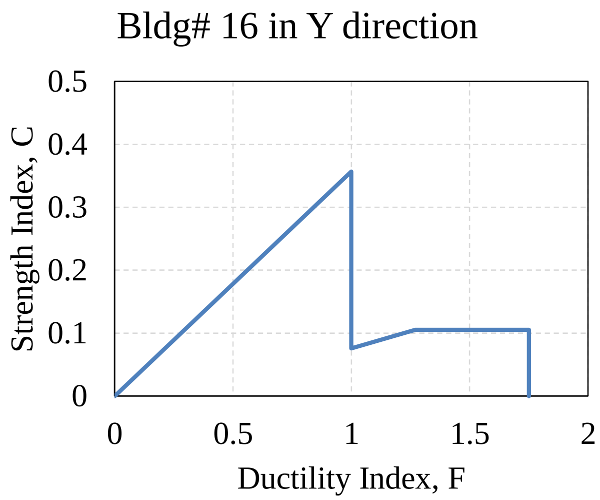

Bldg# 14 in X direction
Strength Index, C
0.5
0.4
0.3
0.2
0.1
0
0
0.5
1
1.5
2
Ductility Index, F

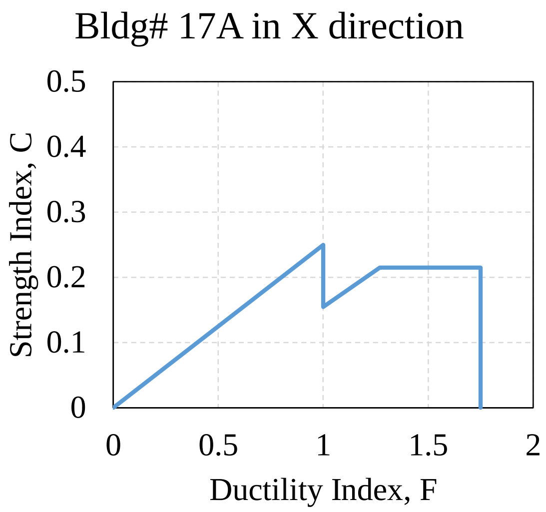

Bldg# 14 in Y direction
Strength Index, C
0.5
0.4
0.3
0.2
0.1
0
0
0.5
1
1.5
2
Ductility Index, F

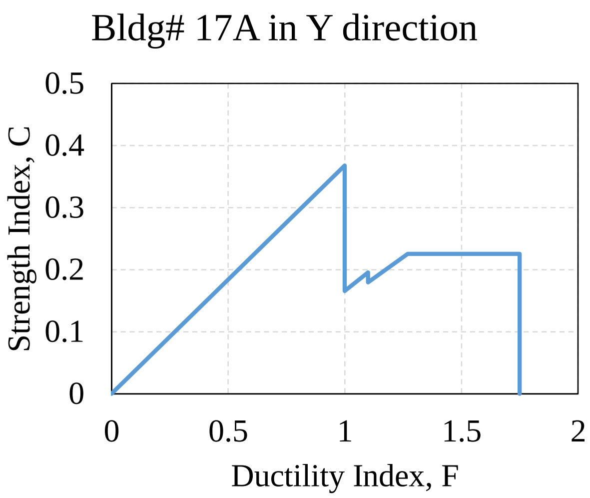

Bldg# 15 in X direction
Strength Index, C
0.8
0.6
0.4
0.2
0
0
0.5
1
1.5
2
Ductility Index, F

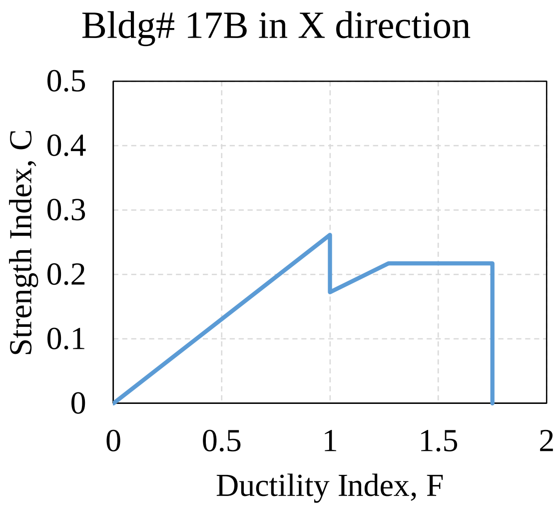

Bldg# 15 in Y direction
Strength Index, C
0.8
0.6
0.4
0.2
0
0
0.5
1
1.5
2
Ductility Index, F

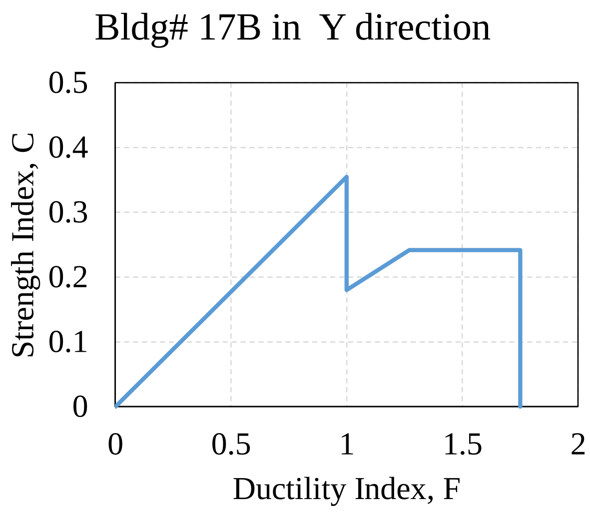

Bldg# 16 in X direction
Strength Index, C
0.5
0.4
0.3
0.2
0.1
0
0
0.5
1
1.5
2
Ductility Index, F

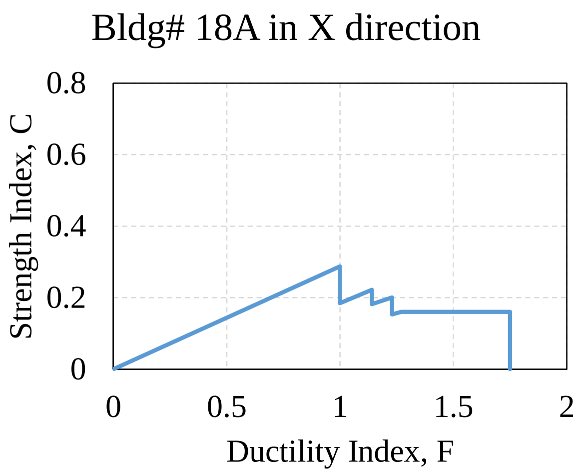

Bldg# 16 in Y direction
Strength Index, C
0.5
0.4
0.3
0.2
0.1
0
0
0.5
1
1.5
2
Ductility Index, F

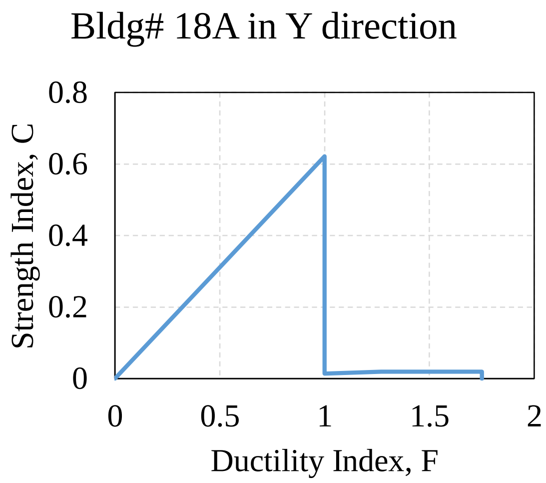

Bldg# 17A in X direction
Strength Index, C
Ductility Index, F
0
0.1
0.2
0.3
0.4
0.5
0
0.5
1
1.5
2

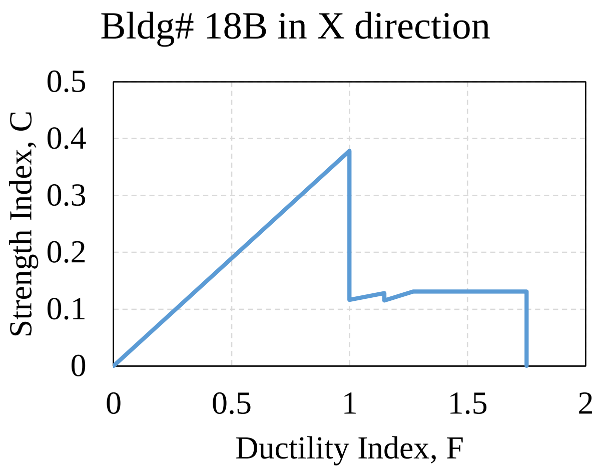

Bldg# 17A in Y direction
Strength Index, C
Ductility Index, F
0
0.1
0.2
0.3
0.4
0.5
0
0.5
1
1.5
2

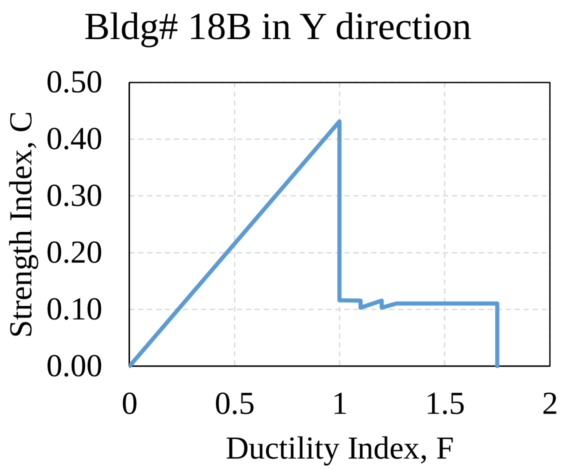

Bldg# 17B in X direction
Strength Index, C
Ductility Index, F
0
0.1
0.2
0.3
0.4
0.5
0
0.5
1
1.5
2

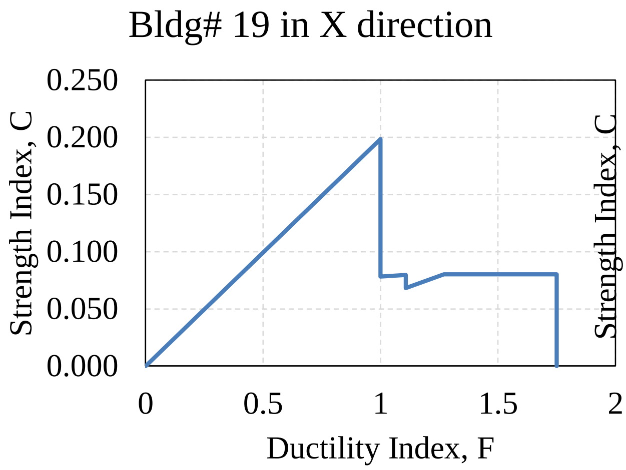

Bldg# 17B in Y direction
Strength Index, C
Ductility Index, F
0
0.1
0.2
0.3
0.4
0.5
0
0.5
1
1.5
2

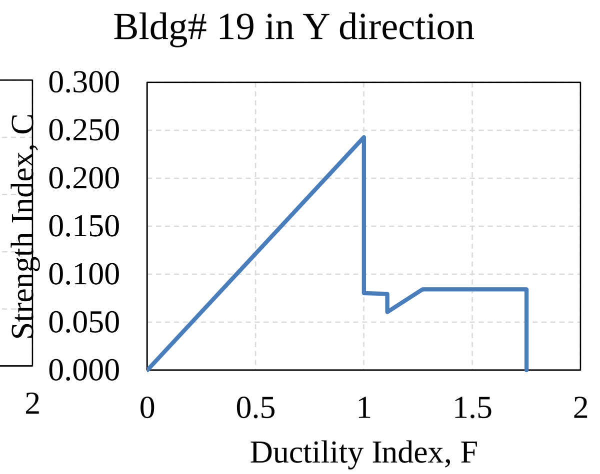

Bldg# 18A in X direction
Strength Index, C
Ductility Index, F
0
0.2
0.4
0.6
0.8
0
0.5
1
1.5
2

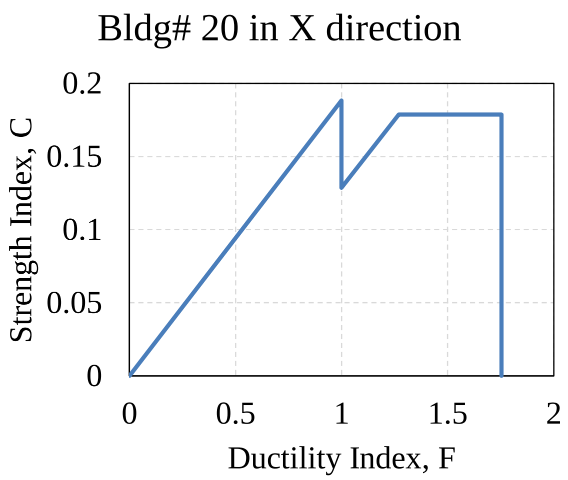

Bldg# 18A in Y direction
Strength Index, C
Ductility Index, F
0
0.2
0.4
0.6
0.8
0
0.5
1
1.5
2

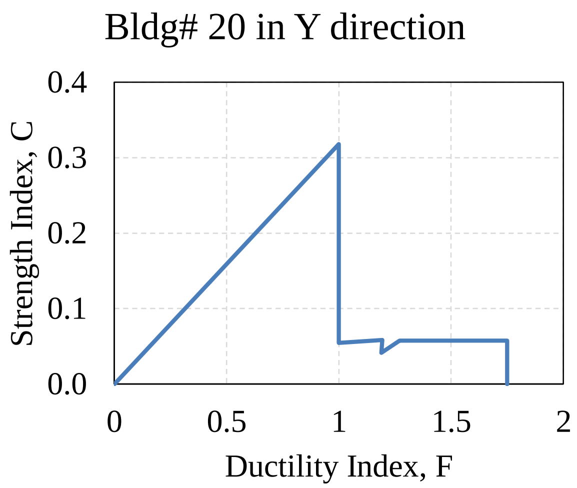

Bldg# 18B in X direction
Strength Index, C
0.5
0.4
0.3
0.2
0.1
0
0
0.5
1
1.5
2
Ductility Index, F

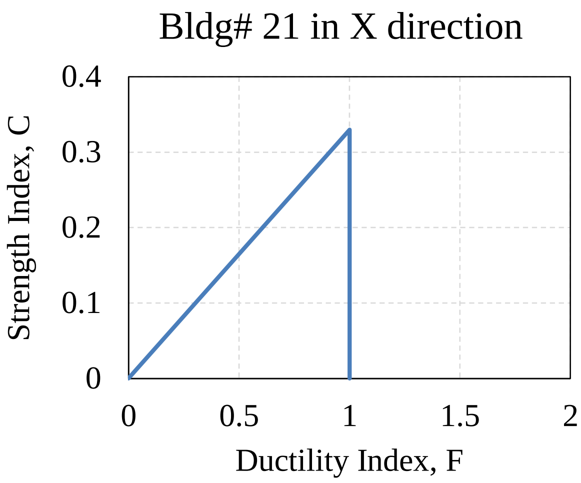

Bldg# 18B in Y direction
Strength Index, C
0.50
0.40
0.30
0.20
0.10
0.00
0
0.5
1
1.5
2
Ductility Index, F


Bldg# 19 in X direction
Strength Index, C
0.250
0.200
0.150
0.100
0.050
0.000
0
0.5
1
1.5
2
Ductility Index, F


Bldg# 19 in Y direction
Strength Index, C
0.300
0.250
0.200
0.150
0.100
0.050
0.000
0
0.5
1
1.5
2
Ductility Index, F


Bldg# 20 in X direction
Strength Index, C
0.2
0.15
0.1
0.05
0
0
0.5
1
1.5
2
Ductility Index, F


Bldg# 20 in Y direction
Strength Index, C
0.4
0.3
0.2
0.1
0.0
0
0.5
1
1.5
2
Ductility Index, F


Bldg# 21 in X direction
Strength Index, C
0.4
0.3
0.2
0.1
0
0
0.5
1
1.5
2
Ductility Index, F

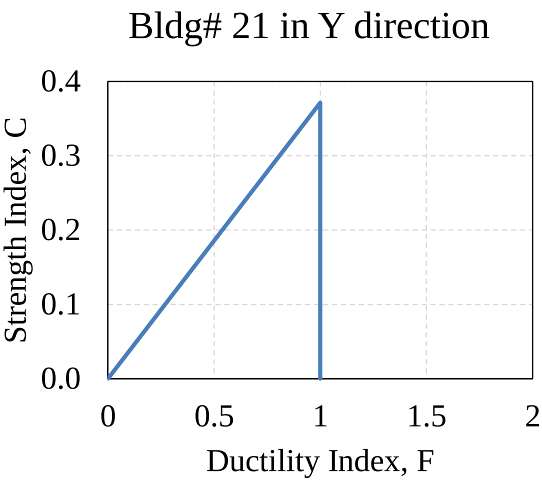

Bldg# 21 in Y direction
Strength Index, C
0.4
0.3
0.2
0.1
0.0
0
0.5
1
1.5
2
Ductility Index, F

Table C1: Seismic index (I_{S2}) of existing RC buildings

Building ID	Strength Index of column, (C_C)	Strength Index of masonry infill, (C_{inf})	Strength Index of RC wall, (C_{CW})	Basic Seismic Index, (E_o)	Irregularity Index, (S_D)	Time index, (T)	Seismic Index, (I_s)
Bldg # 1	0.43	0.04	-	0.47	1.00	1.0	0.47
Bldg # 2	0.08	0.03	-	0.11	1.00	0.9	0.09
Bldg # 3	0.18	0.03	-	0.21	1.00	1.0	0.21
Bldg # 5	0.23	0.00	-	0.23	1.00	1.0	0.23
Bldg # 6	0.28	0.03	-	0.31	1.00	1.0	0.31
Bldg # 7	0.31	0.18	-	0.49	0.90	0.9	0.35
Bldg # 8	0.21	0.04	-	0.25	1.00	1.0	0.25
Bldg # 9	0.31	0.01	-	0.32	1.00	1.0	0.32
Bldg # 10	0.24	0.03	-	0.27	1.00	1.0	0.27
Bldg # 11	0.19	0.02	0.16	0.32	0.95	1.0	0.26
Bldg #12	0.14	0.06	-	0.20	0.95	1.0	0.16
Bldg #13	0.45	0.05	-	0.49	1.00	1.0	0.49
Bldg #14	0.22	0.05	-	0.27	1.00	1.0	0.27
Bldg #15	0.31	0.00	-	0.31	1.00	1.0	0.31
Bldg #16	0.19	0.01	-	0.20	1.00	0.9	0.18
Bldg #17A	0.17	0.05	-	0.22	1.00	1.0	0.22
Bldg #17B	0.25	0.01	-	0.26	0.81	1.0	0.26
Bldg #18A	0.19	0.00	-	0.19	1.00	1.0	0.19
Bldg #18B	0.21	0.03	-	0.24	1.00	1.0	0.24
Bldg #19	0.18	0.03	-	0.20	0.90	0.9	0.16
Bldg #20	0.19	0.01	0.06	0.21	1.00	1.0	0.19
Bldg #21	0.15	0.001	0.02	0.13	0.90	1.0	0.11

Table C2: Seismic index (I_{S2}) of existing RC buildings

Building ID	No of story	Basic Seismic Index, E_0			Irregularity Index, S_d	Time Index, T	Seismic Index (I_{S2})
		x-direction	y-direction	Basic seismic index, (E_o)			
Bldg # 1	2	0.63	0.94	0.63	1.00	1.00	0.63
Bldg # 2	5	0.22	0.20	0.20	1.00	0.90	0.17
Bldg # 3	6	0.31	0.46	0.31	1.00	1.00	0.31
Bldg # 5	6	0.45	0.74	0.45	1.00	1.00	0.44
Bldg # 6	4	0.34	0.37	0.34	1.00	1.00	0.34
Bldg # 7	3	0.65	1.06	0.65	0.95	0.90	0.56
Bldg # 8	5	0.44	0.39	0.39	1.00	1.00	0.40
Bldg # 9	3	0.53	0.61	0.53	1.00	1.00	0.53
Bldg # 10	8	0.41	0.44	0.41	1.00	1.00	0.41
Bldg # 11	10	0.32	0.28	0.28	0.98	1.00	0.27
Bldg #12	6	0.19	0.34	0.19	0.98	1.00	0.19
Bldg #13	2	0.48	1.20	0.48	1.00	1.00	0.48
Bldg #14	6	0.36	0.47	0.36	1.00	1.00	0.36
Bldg #15	5	0.35	0.64	0.35	1.00	1.00	0.35
Bldg #16	3	0.26	0.36	0.26	1.00	0.90	0.23
Bldg #17A	4	0.38	0.36	0.36	1.00	1.00	0.38
Bldg #17B	4	0.37	0.57	0.37	0.86	1.00	0.32
Bldg #18A	10	0.30	0.62	0.30	1.00	1.00	0.60
Bldg #18B	10	0.35	0.43	0.35	1.00	1.00	0.35
Bldg #19	6	0.19	0.24	0.19	0.95	0.90	0.16
Bldg #20	7	0.22	0.31	0.22	1.00	1.00	0.22
Bldg #21	12	0.33	0.37	0.33	0.90	1.00	0.30