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授与学位	博士（工学）
学位授与年月日	平成8年3月26日
学位授与の根拠法規	学位規則第4条第1項
研究科，専攻の名称	東北大学大学院工学研究科 （博士課程）建築学専攻
学位論文題目	Dynamic Nonlinear Analysis of Three-Dimensional Shear Walls of Reinforced Concrete Structures by Finite Element Method （立体鉄筋コンクリート耐震壁の動的非線形有限要素解析）
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論文内容要旨

1. Introduction

The natural disasters such as flood, volcanic activity and earthquake always result in the destruction of buildings and human being. Compared with the other natural disasters, the earthquake releases tremendous energy under the crust of the earth by a violent seismic event and transmits the ground motion to a wide area, which can severely destroy the human-made constructions in a short time.

Because of the advanced researches on RC structures and dictations of current construction technology and economic feasibility, a great number of large-scale, complex civil engineering structures, such as containment structures for nuclear power plants, shear core structures of high-rise buildings, have been built. Even in earthquake prone areas, construction of various complex RC structures is flourishing. The safty of these structures depends on the designer's ability to predict how such structures will respond under extreme environmental and man-made hazard.

Usually, RC structures consist of different types of components such as beams, columns and shear walls. It may be said that the shear walls are the most important earthquake resistant structural members in RC buildings which have been widely used in areas of strong earthquakes.

Although the design of RC structures is improved considerably recently, there are still many problems remained in design and analysis. For example, the inelastic behavior of 3-D shear walls, such as box walls and L-shaped section or H-shaped section shear walls and shear core structures of buildings etc., are not fully understood due to the many phenomena involved. Therefore, it is necessary to develop a simple method to analyse these kinds of RC structures in detail for actual structural engineering design.

Nowadays the nonlinear dynamic behaviour of RC structures are mainly investigated by various experiments, which used shaking tables to simulate the situation of a structure subjected to an earthquate load. However, such experiments are very expensive and, in some cases, difficult to be performed. These insurmountable difficulties make it necessary to develop proper numerical approaches for the seismic analysis of 3-D shear walls to substitute some expensive experiments. A numerical analysis can also serve as a tool to interpret experimental results, to explicate the mechanism involved and to provide useful information and foresight before an experiment.

Generally, the most important problem in the nonlinear analysis of RC structures by finite element method is to establish a suitable constitutive model of reinforced concrete. During the last decade, in order to get a proper model for finite element analysis available for the structural engineer, many research works have been done which are surely very important. Based on these studies, it becomes possible to establish a practical and reliable nonlinear dynamic analysis algorithm of RC structures by means of finite element method.

2. Objective and Sope

The main objective of this study is to understand the behavior of 3-D RC shear walls which are subjected to the earthquake motions. In order to achieve this goal, the following research components were carried out:

1) To review past researches concerned with nonlinear finite element analysis of RC structures.
2) To establish a numerical method for nonlinear dynamic analysis of RC shear walls subjected to earthquake motions by means of finite element method. Under this objective are the following sub-objectives:
   (a) To propose a simple constitutive model for RC walls under cyclic loading toward formulating a more rational model which can be used in dynamical nonlinear FEM analysis of RC shear walls.
   (b) To develop a simple finite element model which can give the numerical approaches of both 2-D and 3-D RC shear wall by means of the simple constitutive principle proposed in (a).
   (c) To complete the nonlinear static analyses of RC shear walls subjected to monotonic loading based on the above model.
   (d) To complete the nonlinear static analyses of RC shear walls subjected to cyclic loading based on the above model.
   (e) To deduce the general equations and to establish the general method for nonlinear dynamic analysis of RC structure.
   (f) To develop, check and implement computer programs for the proposed numerical model.
3) To conduct a series of numerical investigation on the response of various specimens of RC shear walls and to compare numerical results with experimental results as follows.
   (a) The static numerical investigations on a specimen P2015-A of 2-D shear wall subjected to horizontal monotonic and cyclic loading.
   (b) The static numerical investigations on specimens B-00 and B-45 of box wall subjected to horizontal monotonic and cyclic loading in the wall direction and in the diagonal direction, which is an experiment to simulate a reactor building under seismic loads.
   (c) The static numerical investigations on a specimen RB-15P of H-section shear wall subjected to horizontal monotonic and cyclic loading, which is a confirming experiment of the dynamic test of specimens U-1 and U-2.
   (d) The static and dynamic numerical investigations on specimens U-1 and U-2 of H-section shear walls, which is an experiment to simulate a reactor building. These specimens were subjected to artificial earthquake motions in web direction up to failure through several steps with increasing intensities by a large shaking table.
4) To clarify the behavior of 3-D RC shear walls which are subjected to the earthquake motions by means of the dynamic nonlinear finite element analyses.

This study deals with the elastic and inelastic behavior of both 2-D and 3-D RC shear walls subjected to monotonic, cyclic or dynamic loading in arbitrary direction.

Based on the previous researches, a simple numerical method for dynamic nonlinear analysis of RC shear wall is proposed.

The constitutive model of RC material is developed from the smeared models of reinforcements and cracks for concrete. It considers the tension stiffening in tension and the degradation of stiffness and strength in compression of concrete. Reinforcement is modeled by a bi-linear relationship.

It makes use of 2-D iso-parametric finite element for walls and 3-D iso-parametic finite element for the slab on the walls. The joint nodes, which tie a wall to its orthogonal wall and the slab, are defined to be 3-D nodes in the plane element in order to model the 3-D shear wall structures. The wall is considered as inelastic material, while slab is considered as relatively rigid elastic material.

In order to correct the error caused by the overshoot at modulus-changing points of the stress-strain curve and to deal with the downward sloping portion in tension stiffening and compression softening of concrete, the modified Newton-Raphson Method is applied in static analysis. The iteration is performed until the error vector meets accuracy requirements in each incremental step.

To solve the nonlinear dynamic equations and obtain the responses of structures the Impulse Acceleration Method (*i. e.* Newmark-β Method in case of $\beta=0$) is employed. The damping effect is considered by assuming equivalent viscous damping. The analyses were performed continuously from the elastic range to the failure.

According to the model proposed herein, the software DYSCO (DY namic analysis of Shear COre structure) was developed, which is efficient for nonlinear dynamic analyses of RC 3-D shear walls by finite element method. It can be applied to both static and dynamic nonlinear FEM analyses of both 2-D and 3-D shear walls under both monotonic and cyclic loading in arbitrary direction.

Lastly, numerical approaches were conducted to verify this model and to clarify the behavior of RC shear walls under earthquake motions. The time history of displacement and acceleration and their response spectra, the load-displacement relations, furthermore, the crack pattern of concrete and the yielding zone of reinforcement at the maximum load, are investigated.

3. Brief Description of Chapters

This paper is arranged in six chapters. The explanation for each chapter is given as follows.

Chapter one is the introduction consisting of the simple introductory remarks, the objectives and the scope of this study, as well as the organization and the layout of this paper.

Chapter two gives a brief review about previous related researches in this field. A large number of available works of nonlinear analyses of RC structures by finite element method in past several decades are discussed in this chapter. From the basic studies on RC nonlinear finite element analysis to the detail investigations on RC shear walls, the rough summary includes the researches about the constitutive law of concrete and reinforcement, the analyses of 2-D and 3-D shear walls, and the static and dynamic approaches et al.. Furthermore, two representative constitutive models of RC shear walls are introduced concretely.

Chapter three describes the FEM model and material model in this study. The explanation about the FEM model contains the basic assumptions proposed here for 3-D shear wall structures and the introduction for the conventional elements used in this study which include 4-node isoparametric quadrilateral elements, rectangular elements, 8-node isoparametric hexahedron elements, rectangular hexahedron elements and the 3-D truss elements. The explanation about the material model contains the proposed nonlinear constitutive law of concrete and a conventional stress-strain relationship of reinforcement.

Chapter four shows a static analysis procedure for RC structures using finite element method based on the proposed model. Also, four specimens of three RC shear wall experiments are analyzed by the above mentioned static procedure. Four specimens include : one plane shear wall (2-D), two box shear walls (3-D) and one shear wall with H-shaped section (3-D). The comparison with the experimental results demonstrated that the proposed model and algorithm had good accuracy.

In *Chapter five*, a free vibration scheme for the dynamic system is deduced, and a dynamic analysis procedure for RC structure using finite element method based on the proposed model and Impulse Acceleration Method is given by a series of mathematical derivations. The Impulse Acceleration Method is proved to be an efficient method in nonlinear dynamic analysis for RC structures by finite element method here. By means of this method, the numerical investigations of a 3-D shear wall specimen with H-shaped section, which is a well-known seismic ultimate dynamic response test of nuclear reactor building, are conducted to verify the model and to clarify the behavior of 3-D RC shear walls under earthquake motions.

In *Chapter six*, the significant conclusions derived from the analytical results in this study are summarized. Also, the expected study in the future is pointed out.

Lastly, in *Appendix*, the difficult points in this study summarized by experience and the direction of the software DYSCO which is developed in this study to perform the above static or dynamic calculations are introduced.

4. Conclusions

A nonlinear model suitable for analysis of both static monotonic or cyclic loading and dynamic loading by finite element method is proposed to analyse 3-D RC shear wall structures subjected to earthquake motions in this study.

The finite element model is developed by assembling the plane elements for walls and 3-D solid elements for the slab on the walls. The joint nodes, which tie a wall to its orthogonal wall and the slab, are defined to be 3-D nodes in the plane element in order to model the 3-D shear wall structures. The wall is considered as inelastic material, while the slab is considered as relatively rigid elastic material.

The proposed constitutive model is based on the nonlinearity of concrete and reinforcement. It considers the tension stiffening in tension and the degradation of stiffness and strength in compression after cracking of concrete. Reinforcement is modeled by a bi-linear relationship.

In static analysis, to correct the error caused by the overshoot at modulus-changing points of the stress-strain curve and to deal with the downward sloping portion in tension stiffening and compression softening of concrete, the modified Newton-Raphson Method is applied. The iteration is performed until the error vector meets accuracy requirements in each incremental step. The analyses and their comparisons with the experimental results of load-displacement relation, stress state, concrete softening zone, concrete crack pattern and yield zone of reinforcement for six 2-D or 3-D specimens were done using proposed method. The calculations were conducted continuously from elastic range to the failure of structure and reliable results with high accuracy were obtained.

In dynamic analysis, to solve the nonlinear dynamic equations and obtain the response of structures the Impulse Acceleration Method is employed. The damping effect is considered by assuming equivalent viscous damping. This analytical method was applied to a test specimen of the wall with H-shaped section which is one of the dynamic model tests for evaluation of the seismic behavior of reactor buildings. This specimen was subjected to artificial earthquake motions in X-direction up to failure through several steps with increasing intensities. The anlayses were conducted to know the nonlinear dynamic behavior of RC shear walls. The calculation were performed continuously from the elastic range to the vicinity near failure of the specimen. The analytical results compared with the observed ones in the time history of displacement and acceleration and inertial force-displacement relationship. Furthermore the response spectra are investigated. The comparisons with experimental results demonstrated that the analytical results by the simple model proposed herein can give a quite good simulation of the test under dynamic loading up to the shear deformation angle of about 2/1000. But further studies are needed to simulate the final behavior well. As a presentation of the merit using dynamic FEM to analyze a structure, many detail investigations, such as the representative results of time history of vertical displacement and acceleration at the edge of top slab, time history of rotational angle of top slab and angular acceleration of top slab, the relationship between rotational angle and lateral displacement of top slab, the relationship between rotational angular acceleration and lateral acceleration of top slab, which present the interaction of lateral movement and rotational movement, and time history of vertical strain et al., were given in this study.

In conclusion the model proposed herein is effective for dynamic nonlinear analysis of 3-D RC shear wall structures subjected to earthquake motions. It is applicable to not only reactor buildings but also the other structures such as 3-D shear walls with L-shaped section or T-shaped section and the shear core walls of buildings.

審 査 結 果 の 要 旨

建築物の耐震コアや原子炉建屋などの立体鉄筋コンクリート耐震壁構造の大地震にたいする動的弾塑性挙動を解明するためには，コンクリートの異方性と非線形性のモデル化及び立体壁の有限要素によるモデル化に関する適切な手法並びに精度と安定性に優れた動的非線形応答解析技術の開発が不可欠である。しかしながら，これに関する研究はまだ十分に進展しているとは言えない。

本論文は，鉄筋コンクリート立体壁の非線形有限要素解析法をコンクリートの構成則に関する適切な諸仮定のもとに開発し，静的繰り返し加力及び動的地震応答の解析が可能な解析プログラムを作成し，これを用いて平面壁と立体壁模型の静的繰り返し加力実験及び振動台による耐震壁模型の地震動入力に対する動的破壊実験の解析シミュレーションを行い，実験結果と解析結果を比較したもので，全6章からなる。

第1章は序論である。

第2章では，鉄筋コンクリート構造物，特に耐震壁構造物の静的及び動的非線形有限要素解析に関する既往の研究結果を整理し，その問題点を指摘している。

第3章では，立体壁解析のための有限要素モデル並びに動的解析にも適用できる鉄筋とコンクリートの実用的な構成則モデルを提示している。

第4章では，静的非線形有限要素解析の手法を示している。釣り合い条件を満たすための反復計算には，修正ニュートンーラプソン法を用いている。作成した静的解析プログラムにより，繰り返し載荷を受ける平面壁，原子炉建屋を模擬したボックス壁，H型壁などの静的実験の解析シミュレーションを行い，解析手法の有効性を示している。

第5章では，動的非線形有限要素解析の手法と解析プログラムを示している。数値積分法には衝撃加速度法を用いている。大型振動台によるH型耐震壁の地震動入力に対する振動破壊実験の動的解析シミュレーションを行い，実験結果と解析結果が極めてよく一致することを示し，衝撃加速度法に基づく本手法が信頼性の高い効率的な方法であることを明らかにしている。

第6章は結論である。

以上要するに，本論文は鉄筋コンクリート耐震壁構造物の静的及び動的有限要素解析の新しい手法を開発し，実験結果との比較によってその有用性を明らかにしたもので，建築学及び耐震工学の発展に寄与するところが少なくない。

よって，本論文は博士（工学）の学位論文として合格と認める。