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授与学位	博士（工学）
学位授与年月日	平成１８年９月１３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）都市・建築学専攻
学位論文題目	Energy Based Design Of A System Combined Of Damper And Displacement Controller For Seismically Excited Structures. (エネルギー応答に基づいた地震を受ける建物におけるダンパーと変位制御機構の設計)
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論文内容要旨

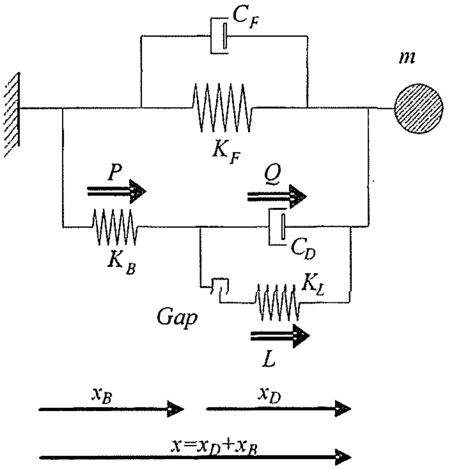
CHAPTER 1　INTRODUCTION

Dampers are effectively used to reduce seismic response of structures. The function of damping mechanisms in a structure is to dissipate the input energy from ground motions and thereby, keeping the structural members undamaged or with minor damage. However, a weak-story in a multi-story structure which means irregular stiffness distribution through the stories may cause exceeding displacement in the structure, when the structure is subjected to a severe ground motion. The use of viscous-dampers on each story is well known to reduce the displacements but the weak-story will still have a large inter-story displacement, which causes a non-uniform inter-story displacement distribution among the stories.

Starting from this point, on the weak-story, a displacement controller device was used in this study. Namely dampers and displacement controlling limiters are used together which can also be called as a "combined energy *dissipation system" and investigated through several different structural parameters and conditions.*

CHAPTER 2　ANALYTICAL MODEL

A special analytical model is developed for the dynamic analyses and the equation of motion is modified, in order that it may include the restoring force of the frame, viscous-dampers and the displacement controlling limiter, as well.



m :　Mass
K_F:　Frame stiffness
C_F:　Frame damping coefficient
C_D : Damper's damping coefficient
K_B:　Steel brace stiffness
K_L:　Limiter stiffness
P: Brace force
Q: Damper force
L: Limiter force
Gap: Deformation value that limiter operates

Figure 2.3 SDOF analytical model

CHAPTER 3 ELASTIC CASE - COMPENSATING THE IRREGULARITY IN STIFFNESS

In this chapter, "compensating the irregularity in the stiffness of an elastic multi-story structure" was discussed. Target inter-story displacement is δdesign=3.0cm. There is a weak-story in the 6th story of the 11-story model building. This irregular stiffness distribution through the stories causes exceeding displacement in the structure, when subjected to a severe earthquake. Target of using the proposed energy dissipation system which is combined of viscous-dampers and displacement limiters is to compensate the stiffness irregularity of the structure. Therefore displacement controlling limiter was used only on weak-story.

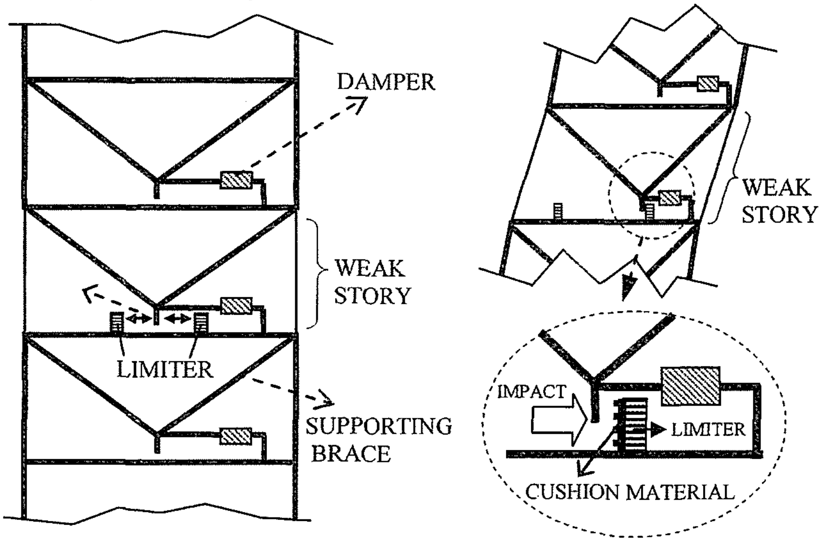


Figure3.3 Limiter and cushion material

Input ground motions were introduced and normalization process was done with elastic displacement spectrum(S_D) of Kobe earthquake which was scaled to peak ground velocity PGV=50cm/sec .

Energy based viscous-damper design is performed. Target of the damper design is to obtain the necessary viscous-damping coefficient (C_{Di}) that makes δmax (maximum displacement of the model building) smaller than or equal to target inter-story displacement δ_{design}. Briefly, (1) Total input energy was predicted by using an elastic MDOF system with no additional dampers but increased frame damping to represent a similarity to the model with dampers. (2) The relation between E_I (total input energy) and E_D (total energy absorbed by viscous-dampers) was investigated and it was found out that the relation between E_I and E_D is depending on frame damping factor h_F and viscous-damper damping factor h_D. It was independent of initial period T_1, input motion and input motion intensity. Regression analysis was performed to evaluate the ratio of dissipated energy by dampers. (3) It was assumed that dampers on each story absorb energy equally. (4) As ΔE_{Di} is assumed to define the maximum energy that can be absorbed by the viscous-damper with one cycle, the number of equivalent cycles (n_c) that is necessary to dissipate the viscous-damping energy was evaluated. (5) Depending on the assumed damper response, necessary viscous-damping coefficient (C_{Di}) to obtain target displacement was calculated.

Next, gap distance of the displacement limiter was calculated for the weak-story. The method to obtain the gap distance was presented.

Dynamic response analysis was performed for "frame+designed damper+limiter" type of structure. Dynamic response results of building with proposed energy dissipation system was shown.

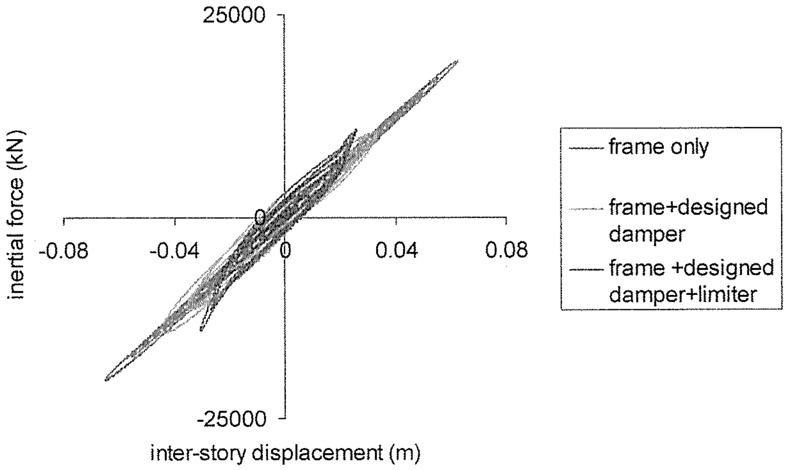


Figure 3.22(b) Inertial force - inter-story displacement relation on weak-story. (Kobe case)

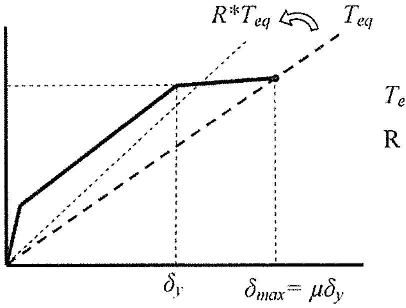
As a result for this chapter; exceeding displacement can be successfully controlled by using the displacement limiter. It makes almost no change in the acceleration and inertial force values. Gap distance was designed for the displacement controlling limiter, based on the lack of stiffness on the weak-story. After using the limiter with designed gap distance, exceeding inter-story displacement on the weak-story was reduced to the target displacement value effectively.

By the use of energy based damper design method, necessary viscous-damping coefficient was determined and target maximum displacement values were obtained among the stories successfully. It was shown that proposed energy dissipation system, can effectually compensate the stiffness irregularity in an elastic structure.

CHAPTER 4 INELASTIC CASE – COMPENSATING THE IRREGULARITY IN STRENGTH

In this chapter, "compensating the irregularity in the strength of an inelastic multi-story structure" is discussed. Inelastic properties are defined in order to represent a reinforced concrete building model. Target ductility is $\mu=1.0$ which aims the steel bars of reinforced concrete members not to yield. There is a weak-story in the 6th story of the 11-story model building. This irregular strength distribution through the stories causes exceeding displacement in the structure, when subjected to a severe earthquake. Target of using the proposed energy dissipation system which is combined of viscous-dampers and displacement limiters is to compensate the strength irregularity of the structure. Therefore displacement controlling limiter was used only on the weak-story.

In this study inelastic case parameters are intended to be evaluated from elastic properties. For such purpose relation between elastic and inelastic cases were investigated and a period reduction factor (R) was defined.



T_{eq} : Equivalent period
R : Period reduction factor

Figure 4.8 Reduced equivalent period

After the period reduction factor was defined input ground motions were introduced and normalization process was done in a similar way with the previous chapter. Energy based viscous-damper design was performed. Target of the damper design is to evaluate the necessary viscous-damping coefficient (C_{Di}) in order to obtain target ductility μ=1.0. Briefly, (1) Total input energy was predicted by using an "equivalent linear MDOF system". (2) The relation between E_I (total input energy) and E_D (total energy absorbed by viscous-dampers) was investigated and it was found out that the relation between E_I and E_D is depending on frame damping factor h_F , viscous-damper damping factor h_D and ductility factor μ. It was independent of initial period T_1, input motion and input motion intensity. Regression analysis was performed to evaluate the ratio of dissipated energy by dampers. (3) As ΔE_{Di} is assumed to define the maximum energy that can be absorbed by the viscous-damper with one cycle, the number of equivalent cycles (n_c) that is necessary to dissipate the viscous-damping energy was evaluated. (4) Depending on the assumed damper response, necessary viscous-damping coefficient (C_{Di}) to obtain target ductility was calculated. In the next stage gap distance of the displacement limiter was calculated for the weak-story.

Finally, dynamic response analysis was performed for "frame+designed damper+limiter" type of structure. Dynamic response results of building with proposed energy dissipation system were shown. Design of gap distance for the displacement controlling limiter was based on the lack of strength on the weak-story. After using the limiter with designed gap distance, exceeding inter-story displacement on the weak-story was reduced to the target ductility value effectively.

By the use of energy based damper design method, necessary viscous-damping coefficient was determined and target ductility values were obtained successfully. It was shown that proposed energy dissipation system, can effectually compensate the irregularity of strength in an inelastic structure.

CHAPTER 5 INELASTIC CASE – COMPENSATING THE LOW CAPACITY of STRUCTURE

In this chapter, "compensating the low story shear strength of an inelastic multi-story structure" is discussed. Target ductility is μ=1.5 and there is no weak-story. After yielding, low capacity of the structure causes exceeding displacement and irregular shape in the displacement distribution. Target of using the proposed energy dissipation system which is combined of viscous-dampers and displacement limiters is to compensate the low capacity of the structure. Therefore displacement controlling limiter was used on every story.

First, the model building was introduced. It was the same building model with the Chapter0 except for there was no weak-story in the building. Next, input ground motions were introduced and normalization process was done with elastic displacement spectrum(S_D) of Kobe earthquake which was scaled to peak ground velocity PGV=75cm/sec.

Energy based viscous-damper design is performed in a similar way to the previous chapter. Target of the damper design is to evaluate the necessary viscous-damping coefficient (C_{Di}) in order to obtain target ductility μ=1.5. In the next section, gap distance of the displacement limiter was calculated. As the limiter was used on every story. The method to obtain the distribution of the gap distance among the stories was presented

At last, dynamic response analysis was performed for "frame+designed damper+limiter" type of structure. Results for the dynamic response results of proposed system were shown. Following conclusions can be done for this chapter of the study.

Design of gap distance for the displacement controlling limiter on every story was based on the assumption of inertial force increase. After using the limiter with designed gap distance distribution, exceeding displacement among the stories was prevented and maximum inter-story displacement was reduced to the target ductility value effectively.

By the use of energy based damper design method, necessary viscous-damping coefficient was determined and target ductility values were obtained successfully. These results show that proposed energy dissipation system combined of damper and displacement controller limiter, can effectually compensate the low capacity of an inelastic structure.

Moreover, additional viscous-damping of the structure was increased to high values, to see the high damping effects and be able to compare high damping effect with the proposed system. It was shown that even after high additional damping values were used lower stories had exceeded the target ductility value.

Finally, to see the effect of displacement controlling limiter more clearly base shear coefficient of the model building was increased in order to increase the strength of the structure. It was shown that increase of strength in the structure almost makes the same effect with using the displacement controlling limiters. On the other hand, increasing the capacity of the structure also causes higher acceleration values comparing with the proposed displacement controlling limiter. Which shows that, using displacement controlling limiters to compensate the low capacity of a structure is a cost-effective method, as well.

CHAPTER 6 CONCLUSIONS

In this study, viscous-damper and displacement controlling limiter were used together which can also be called as a "combined energy dissipation system" to reduce seismic response of structures. The amount of the viscous-damper was obtained by using an "energy-based" method. And the gap distance of the displacement controlling limiter was also designed, depending on different conditions.

First of all, the combined energy dissipation system was applied to an elastic multi-story structure with a weak-story caused by stiffness irregularity. Exceeding displacement on the weak-story can be successfully reduced to the target displacement value by using the displacement limiter with designed gap distance. And by the use of energy-based damper design method, necessary viscous-damping coefficient was determined and target maximum displacement values were obtained among the stories successfully. It was shown that, proposed combined energy dissipation system can effectually compensate the stiffness irregularity in an elastic structure.

The next topic was compensating the irregularity in the strength of an inelastic multi-story structure. Inelastic properties of model building were defined in order to represent a reinforced concrete building model. Target ductility was $\mu=1.0$. The irregularity in the strength of the 11-story model building caused a weak-story in the middle, similar to the elastic case. Inelastic case parameters are intended to be evaluated from elastic properties. For such purpose relation between elastic and inelastic cases were investigated and a period reduction factor was defined for linearization process.

Exceeding displacement on the weak-story of the inelastic building was successfully controlled by using the displacement limiter. And necessary viscous-damping coefficient to obtain target ductility overall the building was determined successfully.

Finally the combined energy dissipation system was applied to an inelastic multi-story structure with low story-shear-strength. Target ductility was $\mu=1.5$ and there was no weak-story. After yielding, low capacity of the structure causes exceeding displacement in the entire building. Therefore displacement controlling limiter was used on every story.

After using the limiter with designed gap distance distribution, maximum inter-story displacement was reduced to the target ductility value effectively.Amount of viscous-dampers necessary to obtain target ductility value was determined successfully by proposed energy-based damper design method.It was shown that proposed energy dissipation system combined of damper and displacement controller limiter, can effectually compensate the low capacity of an inelastic structure.

論文審査結果の要旨

兵庫県南部地震の後、大地震時に人命を守るだけではなく、建物としての財産を保持したいという要望が高まり、地震に対する建物の損傷を制御する設計法が多く提唱され実建物に採用されるようになった。本論文では、粘性系のダンパーと変位を制御する機構（リミッター）を併設した新しい制振装置を提案し、その装置を建物内部に設置した場合の有効性を検討するとともに、エネルギー応答の考え方に基づいて本制振装置を設計する方法を示したもので、全6章よりなっている。

第1章は序論である。

第2章では、粘性系ダンパーに関する既往の解析手法を概説するとともに、粘性系ダンパー及び支持部材との間に適切な隙間（ギャップ）を有するリミッターを併設した場合の新たな解析手法を、1自由度系と多自由度系について示している。また、本制振装置を建物内部に設置する場合の基本的方針を示している。

第3章では、鉄骨造建物を想定して、多層建物の中間層の剛性が低く、高さ方向の剛性分布に不整形性がある場合を対象とし、全層に同量の粘性系ダンパーを設置した上で、剛性が低い層にはさらにリミッターを併設したモデルを設定し、複数の地震波に対する応答解析を行っている。その結果、本装置を設置して剛性が低い層に硬化型復元力特性を与えることにより、加速度やせん断力の応答値はほとんど増加させずに剛性が低い層の過大な応答変形を補正できること、及び、エネルギー応答の考え方に基づいて、必要ダンパー量と適切なリミッターのギャップを与えれば全層の層間変形を目標の値以内に概ね収めることができることを示している。

第4章では、鉄筋コンクリート造建物を想定して、多層建物の中間層の耐力が低く、高さ方向の耐力分布に不整形性がある場合を対象として、第3章と同様な検討を行っている。ただし、鉄筋コンクリート造建物の復元力特性は非線形性を示しているので、エネルギー応答の考え方に基づいて、必要ダンパー量と適切なリミッターのギャップを定める場合に、等価線形化手法を用いて建物周期の読み替えを行い、弾性時の応答値を基にして算定を行っている。検討結果としては、本制振装置を設置することにより耐力分布の不整形性を補正することができ、さらに、全層の塑性率を目標の値以内に概ね収めることができることを地震応答解析より示している。

第5章では、鉄筋コンクリート造建物を想定して、剛性・耐力とも高さ方向の不整形性はないものの、耐力が小さくて、大きな地震動を受けた場合には局部的に過大な塑性率が生じて応答変形に過大な不均一性が見られるような基本建物モデルを設定し検討を行っている。この建物に対し、塑性率1.5を目標として必要ダンパー量と適切なリミッターのギャップを定めて本制振装置を全層に設置すれば、加速度や層せん断力の値はやや増加するものの、全層の塑性率を目標の値以内に概ね収めることができることを示している。さらに、この基本建物に対してダンパーのみ設置してその量を多くしても、全層を目標塑性率以下にすることは困難であること、また、建物の耐力を2倍程度に増加すれば制振装置がなくても目標塑性率以下にできるものの過大な加速度応答が生じてしまうことを示し、本制振装置の有効性を示している。

第6章は結論である。

以上を要するに、本論文は、粘性系のダンパーとリミッターを併設した新しい制振装置を建物内に設置した場合の動的応答性状を明らかにし、さらに、多層建物に適用した場合の有効性を示すとともに、本制振装置の設計法を示すものであり、建物の損傷制御設計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。