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EXPERIMENTAL AND ANALYTICAL STUDY ON A STRUCTURAL DESIGN METHOD TO REDUCE SEISMIC EFFECTS ON A DUAL SYSTEM

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SUMMARY

The purpose of this paper is to present a method to reduce undesirable seismic effects on a dual system building consisting of a flexible column-beam structure and a rigid wall structure. The basic idea is to provide, between these structures, some elastic-plastic dampers which limit the two-way transmission of lateral force within their yielding strength and dissipate input earthquake energy due to their hysteresis damping. By this, not only the shear ratio of the wall structure is reduced but also the displacement and acceleration of the flexible structure can be kept controled within the safe limit.

INTRODUCTION

Dual system is a building which comprises two different types of structures. One is a three dimensional flexible space frame made up of columns, beams and slabs, providing a primary support for the gravity loads. The other is a rigid nonbearing wall or a braced frame which mainly provides resistance for the lateral loads. Ordinarily, these two main structures are combined firmly with slabs and beams so that the earthquake induced lateral force in the flexible structure should be fully transmitted to the rigid structure(Ref.1). We call this conventional dual system, hereafter, a combined dual system (CDS). Primary benefit of this system is to be able to reduce the shear ratio of the flexible space frame and, therefore, to obtain an open wide usable floor space with a minimum of columns in it. However, it accompanies a disadvantage that lateral load carried by the rigid structure under an intense seismic attack, becomes very high and the prevention of its brittle type failure or uplifting type failure becomes very difficult.

The motive of this study is to overcome this disadvantage. The object is to design a structural system which makes it possible to decrease the shear ratio of the rigid structure(RS), without the displacement and acceleration of the flexible structure(FS) becoming much greater than those of CDS. This can be achieved by jointing the FS and RS with some steel ring elements between them. We call this system a separated dual system(SDS), contrary to the CDS. Since the two-way transmission of a force through the damper is limited within their yielding strength, earthquake induced lateral load to be carried by RS is reduced. Furthermore, some input earthquake energy can be dissipated in them due to their hysteresis damping. Therefore, we call this element a steel ring damper or simply a damper(Ref.2). Similar investigation have already been reported by K. David, who call this type of building a distributed dampimg system and compared its seismic behaviors with those of other damping systems(Ref.3).

The purpose of this study is to present a seismic resistant design method for SDS through a shaking table test and an earthquake response analysis.

SHAKING TABLE TEST

Test model Test model is a small size steel model. Configuration is illustrated in Fig.1. Rigid steel plates are supported on columns cut out from the rolled H-steel. A short-column structure is to represent the RS and a long-column structure the FS. To make SDS model, a steel ring, cut out from a SS41 steel pipe, is provided between the two structures. Arrangement is shown in Fig.2. CDS model is obtained by combining two structures directly.

Static load-deflection curve of a single damper is shown in Fig.3. Although it becomes unsymmetric with the increase of deflection, actual deflection of the damper used in the test is small enough to be considered symmetric. Mechanical properties of FS, RS, and the damper are summarized in the Tab.1.

Preliminary analysis Before testing, distinction in dynamic behaviors between CDS and SDS is examined by steady state response to sinusoidal excitation. Each main structure is transformed into a single-degree-of-freedom shear model with a lamped mass as shown in Fig.4. Load-deflection curves of main structures and a damper are considered to be bi-linear. Their stiffness and strength are those listed in Tab.1. Calculations are carried out by applying equivalent linearlization method(Ref.4). Maximum acceleration is 100 gal.

In Fig.5-a, elastic CDS response, elastic SDS response and SDS response when damper alone is elastic-plastic are shown compared. It is observed that installation of an elastic steel ring element causes FS a larger displacement and RS a less displacement than CDS displacement. However, if the damper is elastic-plastic, displacement of the FS can be kept controled under that of elastic CDS model, and the reduction of RS displacement is promoted. It must be noted that there is only a little shift of the fundamental frequency of SDS from that of CDS. In Fig.5-b, main structures are elastic-plastic. In this case, as the amount of energy dissipation in main structures themselves is high, damper does not seem to play much role in decreasing the displacement. However, there is an important difference between the two systems. Yielding do occur in the RS of CDS, whereas, in the SDS , it remains within the elastic range.

From this analysis, fundamental function of the elasti-plastic damper installed has been identified. Since it confines the two-way transmission of lateral force between the main structures to its yielding strength and it possesses an excellent energy dissipating capacity, it can not only lower the shear ratio of RS but also can prevent FS from excessive deflection.

Shaking table test These CDS and SDS models are placed on the shaking table which is subjected to NS component of EL. Centro 1940 earthquake motion. Target peak acceleration were 80, 160 and 350 gal. Actually, measured acceleration have been 84, 177 and 368 gal for CDS test and 87, 162 and 352 gal for SDS test. In Fig.6, load-deflection envelope curves of main structures are illustrated, on which maximum displacements are plotted. It is seen that, as a whole, a damper plays the same role as has been identified in the steady state response analysis. In CDS, yielding of RS precedes that of FS, while in SDS, the order could be reversed. By preceding the yielding of FS, reduction of RS displacement is promoted which could make it possible to prevent RS from yielding. In the case of 350 gal excitation, time history of the SDS displacement as well as measured input acceleration are shown in Fig.7. Corresponding hysteresis loop of the steel ring damper is shown in Fig.8. The curve is almost symmetric and fully stable. Maximum ductility factor is about five and there was no break down of the damper. Fourier spectra of the absolute acceleration response in the same test is shown in Fig.9. Around the fundamental frequency, peak acceleration of SDS is considerably less than that of CDS. However, there are another peaks around the second mode frequency, which might account for the SDS peak acceleration on the time history not remarkably decreased.

Correlation between analysis and test Earthquake response analysis is carried out for the same model. Input excitations are those measured on the shaking table during the test. Viscous damping factor is assumed to be the same for all natural modes as listed in Tab.1. Comparing Figs.10-12 with Figs.6-8, it is confirmed that the calculated response correlate quite well with those measured in the test. Therefore, it could be justified that the further study to make more practical comparison between the dynamic behaviors of SDS and those of CDS is carried out by computer analysis.

EARTHQUAKE RESPONSE ANALYSIS

Analytical model One story lamped mass models, shown in Fig.4, are chosen for the analysis. Mechanical properties of CDS and SDS are summarized in Tab.2. Fundamental period is 0.2 sec. for CDS and 0.252 sec. for SDS. The ratio of the fundamental period of FS to that of RS is about three and sufficiently greater than 2.0, which is known to be the minimum value required for SDS to make the best use of the enrgy absorbing capacity of a damper(Ref.5). Hysteresis loop for RS and FS is assumed to be origin-oriented type and bi-linear type respectively. Envelope curve is represented by bi-linear for FS and tri-linear for RS as shown in Fig 13. Post-yielding stiffness of the RS is -20% of its initial stiffness. With the increase of deflection, strength decreases until it comes to 25% of its maximum. This is to cosider the essential feature of RS being very rigid but brittle. Maximum strength of FS is assumed to be one third of that of RS and not to change after yielding. Elastic stiffness of damper is determined to be 40% of the total shear stiffness of the main structures(Ref.5). Load-deflection relation of the damper is assumed to be bi-linear, with its post yielding stiffness equal to 30% of the initial stiffness. Input motion is NS component of El. Centro 1940 earthquake record. Peak velocity is scaled to 25 kine and 50 kine. Duration of the excitation is 10 seconds.

Earthquake response analysis Calculations carried out are divided into four cases. They are elastic response of CDS model(25 kine), response of SDS model when damper alone is elastic-plastic(25 kine), elastic-plastic response of SDS model(50 kine) and elastic-plastic response of CDS model(50 kine). Maximum displacement by all calculations are plotted on the corresponding load-deflection curve in Fig.13. Let it be assumed that the seismic design criteria for main structures is to keep them within the elastic range when subjected to 25 kine excitation, and maximum strength of RS is determined to 540 ton. Maximum strength of FS is assumed to be one third of that of RS, i.e., 180 ton.

By providing a proper strength(=59.4 ton) with the damper installed, displacement of FS under 25 kine excitation could be decreased to nearly its yielding displacement which satisfies the above-mentioned design criteria. Maximum displacement of CDS under 50 kine excitation becomes much greater than its yielding displacement out of the safe limit, whereas, in the SDS response, RS remains within the elastic range and the ductility factor of FS is within the safe limit of about two. Time histories of these displacement response are shown and compared in Fig.14. There is a notable difference in elastic-plastic behaviors between the two models. In the case of SDS, response curves are stable and nearly symmetric with respect to the time axis. On the contrary, in the case of CDS, stiffness and strength degradation of RS causes a large amount of unstable drift of the displacement into one direction.

EARTHQUAKE RESISTANT DESIGN PROCEDURE FOR SEPARATED DUAL SYSTEM

Earthquake resistant design procedure for a SDS building is described below step-by-step. Althogh this SDS structural design can be applied to any type of construction, a reinforced concrete construction is supposed in here. Distinctive feature of this procedure is to design FS against a vertical load only and, to make up for its shortage in lateral resistance, strength of the damper is determined .

Step1 ASUMPTION OF STRUCTURAL MEMBER DIMENSION Dimension of FS members could be determined by the vertical load stress. Dimension of SDS wall could be determined by assuming that the lateral load carried by SDS wall is twice as small as that carried by the CDS wall.

Step2 ESTIMATION OF FUNDAMENTAL PERIOD OF SDS Fundamental period of SDS, which is required to determine the base shear force, could be approximated to that of CDS.

Step3 DECISION OF DESIGN SEISMIC LOAD Distribution of lateral seismic force along the height of each main structure could be determined in accordance with the Ai distribution recomended for general building structures(Ref.6).

Step4 CALCULATION OF RESISTANCE OF FS FOR LATERAL LOAD Lateral load resistance of FS members is considered to be provided by as much steel reinforcement as practically possible in given member sections assumed in Step1.

Step5 DECISION OF DAMPER STRENGTH Let RS be a center-core-wall with FS around it and dampers are installed between them as shown in Fig.15. Then, a load-deflection relation of damper could be assumed to be symmetric bi-linear one. In allowable stress design of FS, extra lateral force to make up for the shortage in lateral resistance of it, is supposed to be the yielding strength of the installed dampers.

Step6 DECISION OF LATERAL FORCE CARRIED BY RS Allowable stress design lateral load to be carried by RS is determined to be the sum of the seismic induced lateral load and the yielding strength of dampers.

Step7 ALLOWABLE STRESS DESIGN OF WALL Correct the assumed wall dimension, if necessary, to be able to sustain the lateral load determined in Step6.

Step8 CHECK OF DAMPER DEFORMATION Providing a SDS with design seismic load again, calculate the deformation of dampers installed between the main structures. These deformation should be nearly their yielding displacement to satisfy the condition assigned in Step5.

Step9 ASSURANCE OF SUFFICIENT ULTIMATE LATERAL STRENGTH In calculation of the ultimate lateral strength, increase of damper strength due to the strain hardening of the steel used must be taken into cosideration. It must be assured that shear failure will not precede the bending failure in any part of the building, except the wall which will not fail.

Step10 ASSESSMENT OF SEISMIC SAFETY BY EARTHQUAKE RESPONSE ANALYSIS Seismic design criteria for FS and RS could be the same as for the normal ductile frame structures and wall structures respectively. Steel ring dampers are satisfactorily safe if their ductility factors are not greater than 10.

CONCLUSION

The study carried out shows:

1) Steel ring have two fundamental functions. One is to limit the transmission of earthquake induced lateral force from a flexible structure into a rigid structure. The other is to offer a sufficient damping due to the hysteretic properties.

2) Installment of steel ring dampers makes it possible not only to prevent the rigid structure from a brittle type failure but also to keep the displacement of flexible structure controled within the safe limit.

3) By the shaking table test, it is assured that a steel ring damper can really offer an excellent energy dissipating capacity and sufficient durability under dynamic loading conditions.

4) CDS and SDS response measured in the shaking table test correlate quite well with those predicted by the computer analysis.

5) A seismic resistant design procedure for SDS building is formulated. It can satisfy the current seismic resistant design criteria for general buildings.

These results suggest that proposed separated dual system could effectively be put into practice in the seismic resistant structural design.

ACKNOWLEDGMENT

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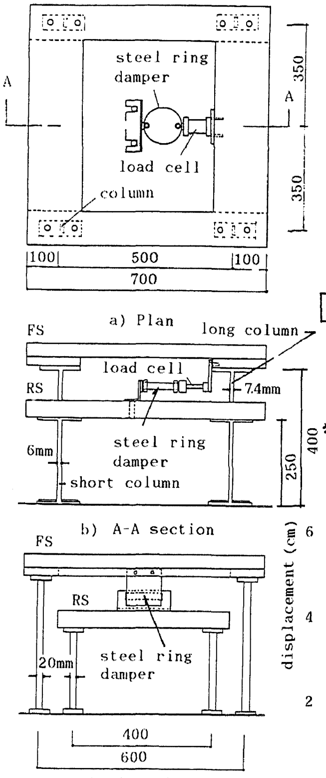


RS: rigid structure

FS: flexible structure

Fig.1 Test model

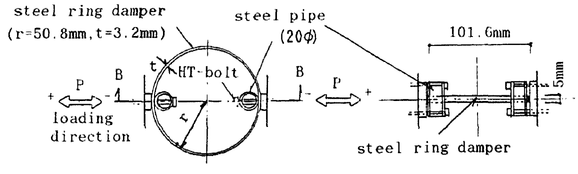
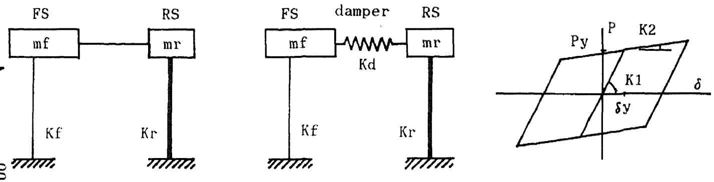


Fig.2 Detail of steel ring damper



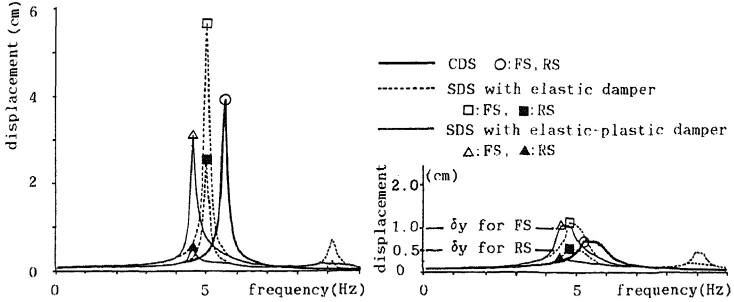
a) CDS Model

b) SDS Model

c) Bi-linear load-deflection curve

RS : rigid structure FS : flexible structure

Fig.4 Analytical models



a) main structures are elastic b) main structures are elastic-plastic

Fig.5 Displacement resonance curve(Max.=100 gal)

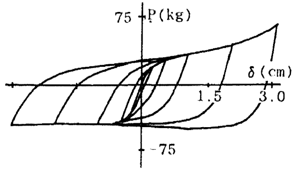


Fig.3 Load-deflection curve of steel ring damper

Tab.1 Mechanical properties of test models

	K1 (kg/cm)	K2 (kg/cm)	δy (cm)	m ($kg\cdot sec^2/cm$)	h (%)	f (Hz)
RS	293.8	29.38	0.50	0.140	0.5	7.29
FS	134.2	13.42	1.00	0.203	0.5	4.09
Damper	128.0	38.4	0.14	-	-	-

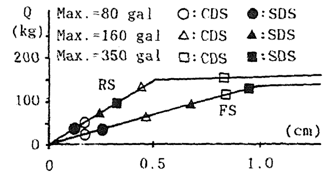


Fig.6 Measured maximum displacement on load-deflection envelope

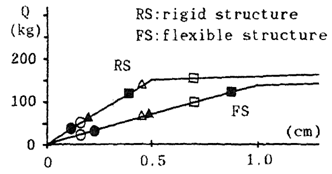


Fig.10 Calculated maximum displacement on load-deflection envelope

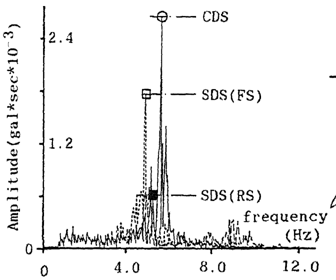


Fig.9 Fourier spectra of measured acceleration

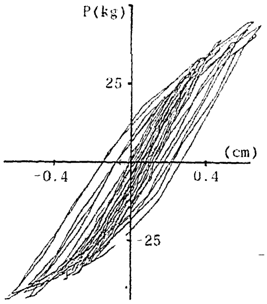


Fig.8 Measured hysteresis curve of damper

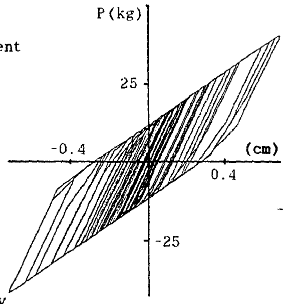
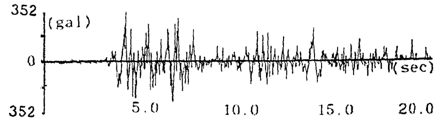
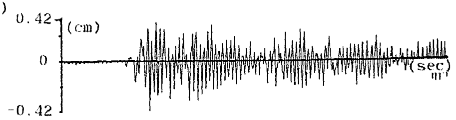


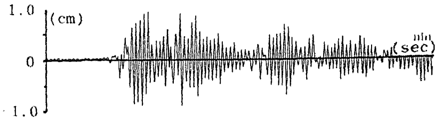
Fig.12 Calculated hysteresis curve of damper



a) input acceleration

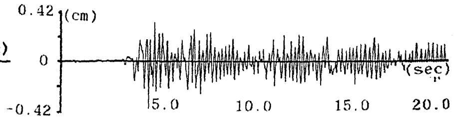


b) RS displacement

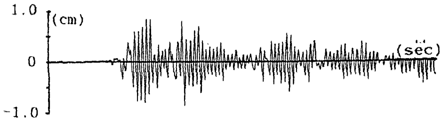


c) FS displacement

Fig.7 Measured time history of SDS displacement(Max.=350 gal)



a) RS displacement



b) FS displacement

Fig.11 Calculated time history of SDS displacement(Max.=350 gal)

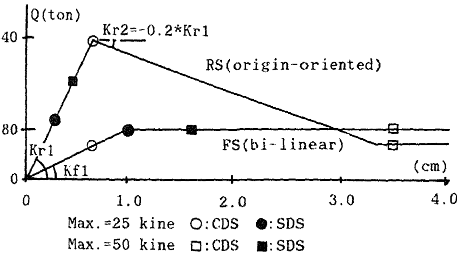
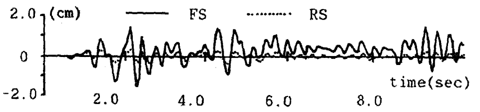


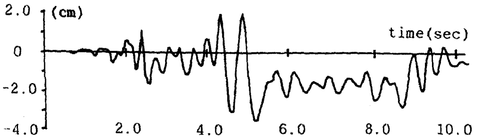
Fig.13 Envelope of load-deflection curve

Tab.2 Mechanical properties of analytical models

	K1 (ton/cm)	K2 (ton/cm)	δy (cm)	m (ton·sec^2/cm)	h (%)	f (Hz)
RS	789.5	-157.9	0.68	0.300	2.0	8.16
FS	194.7	0.0	0.93	0.700	2.0	2.65
Damper	394.8	118.4	0.15	-	-	-



a) SDS model



b) CDS model

Fig.14 Displacement time history(50kine)

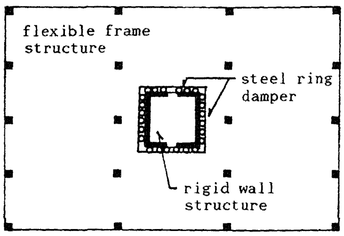


Fig.15 Example of SDS plan and arrangement of steel ring dampers