EARTHQUAKE DAMAGE REDUCTION OF BUILDINGS BY SELF-CENTERING SYSTEMS USING ROCKING MECHANISM

T. Azuhata[1], M. Midorikawa[2] and T. Ishihara[3]

[1] *Head, National Institute for Land and Infrastructure Management, Tsukuba, Japan*
[2] *Professor, Graduate School of Engineering, Hokkaido University, Sapporo, Japan*
[3] *Senior Researcher, National Institute for Land and Infrastructure Management, Tsukuba, Japan*
Email: azuhata-t92ta@nilim.go.jp

ABSTRACT :

Currently lots of buildings are required to be functional or recovered promptly even after sever earthquakes. To make them meet this requirement, we propose a self-centering system composed of rocking structural members, of which part is allowed uplifting during an earthquake. This system can prevent steel building structures from yielding residual deformation after sever earthquakes by using effect of building's self-weight. To examine seismic performance of this system, seismic response analyses are executed on a real-scale steel frame model. Numerical models to express the force-deformation relationship of the rocking structural members are presented. The self-centering ability of the system is examined and its energy dissipation mechanism is investigated. As input ground motions, the 1995 Kobe earthquake record and an artificial ground motion are used. The results of analyses cleared that the proposed system can realize the self-centering system and successfully mitigate seismic damage of buildings against severe earthquakes.

KEYWORDS: Self-centering system, Rocking, Uplift, Steel structure.

1. INTRODUCTION

It has been pointed out that the effects of rocking vibration (uplift response) may reduce seismic damage of buildings subjected to strong earthquake ground motions (Meek 1975, Rutenberg et al. 1982, Hayashi 1996). Based on this knowledge, some rocking structural systems have been proposed and developed as one kind of passive vibration control system (e.g. Clough et al. 1977, Huckelbridge 1977, Kasai et al. 2001, Iwashita et al. 2002, Midorikawa et al. 2003, 2006, Azuhata et al. 2004). Using effect of building's self weight, the rocking system can prevent the building structure from yielding residual deformation even after a sever earthquake and can realize a 'smart' self-centering system. However, most of them have been generally applied only to slender frame structures with single bay.

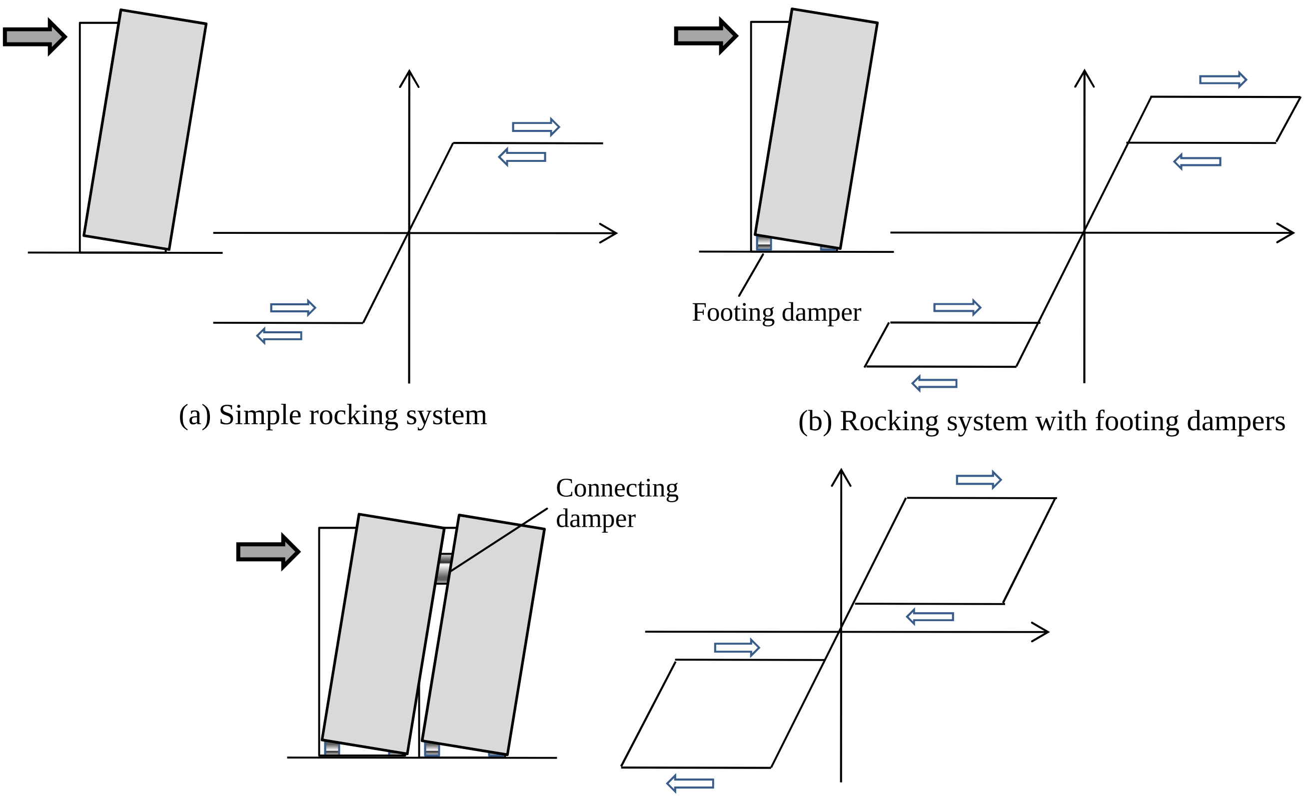
This study aims to apply the concept of the rocking structural system to wider steel frames with multi-bays more efficiently. For this purpose, some rocking structural members, the coupled brace units with yielding base plates and the one-side rocking beams, are introduced. The seismic performance of the proposed self-centering system with these members is examined by seismic response analyses on a steel frame model. And the energy dissipation mechanism is investigated.

2. CASE STUDY

2.1 System Concept

Three types of conceptual rocking systems are shown in Fig.1. Each system has self-centering ability as shown in its force-displacement relationship. The simple rocking system in this figure simply allows structures to uplift. This system is easily applied to slender building structures. Probably uplift and roof lateral displacements will become too large during an earthquake. And impact response effects may bring serious damage in the structure. Thus footing dampers to control uplift response are installed in the 'rocking system with footing dampers' in

Fig.1. The authors proposed yielding base plates as one of these footing dampers (Midorikawa et al. 2003, 2006, Ishihara et al. 2003 Azuhata et al. 2004). The yielding base plates are used in this study again. The coupled rocking system in Fig.1 has vertical dampers, which connect two rocking systems. These connecting dampers can improve energy dissipation performance. This paper uses this system to apply the rocking structural system to a wider frame with multi-spans.



(a) Simple rocking system

(b) Rocking system with footing dampers

(c) Coupled rocking system

Fig.1 Three types of rocking systems

2.2 Application Example

A conventional braced steel frame model is shown in Fig.2. It has 10 stories and 3 bays. The height is 37.8m, the width is 18m and the total weight is 540 t. The cross sections of columns, beams and braces are listed in Table 1. The yield stress of steel used for all members is 294 N/mm^2.

To apply the concept of rocking structural system, coupled brace units and one-side rocking beams are introduced to this frame model as shown in Fig.3. In the coupled brace units, the two narrow braced frames are connected to each other by dampers which can deform only vertically. Visco-elastic or friction dampers are used as these connection devices. Probably they need not be repaired after earthquakes. The bases of each brace unit are connected its basement by thin base plates which yield in uplift direction. Fig.4 shows a plan of them. They have four wings with 25mm thickness. During a strong earthquake, the both edges of each wing yield in bending due to tensile force of a column. The base plate is also attached at the bottom of the outside columns. The physical properties of base plates are listed in Table 2. The uplift yield strength Qy is calculated by regarding each wing as a beam with fixed ends. The other physical values are evaluated based on the static test results (Ishihara et al. 2003). Fig.5 shows a schematic view of one-side beam. Ordinary the lower edges of beam ends are attached to column surface. When rotational direction at the beam ends is reversed due to earthquake lateral force effect, these edges can uplift freely.

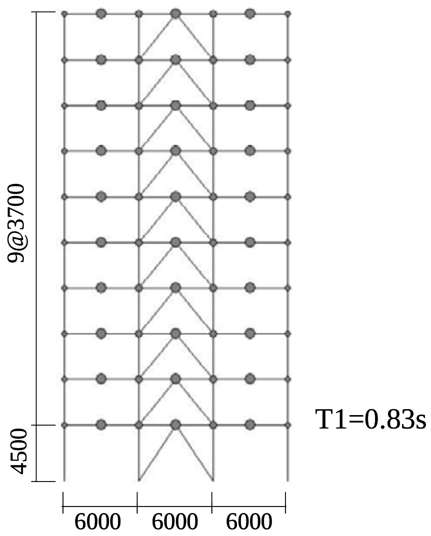


Fig.2 Braced frame model with fixed bases

Table 1 Cross section of structural members

	Floor	Section
Column	8-10	□ 500 x 500 x 19
	1-7	□ 500 x 500 x 25
Beam	7-RF	H 440 x 300 x 11 x 18
	5-6	H 488 x 300 x 11 x 18
	2-4	H 588 x 300 x 12 x 20
Brace	6-10	○ 216.3 x 7
	3-5	○ 267.4 x 9
	1-2	○ 318.5 x 9

Yield stress of steel used for all members: 294N/mm^2

Table 2 Physical properties of yielding base plate

Qy (kN)	δy (mm)	$K1$ (kN/mm)	$K2/K1$
551.25	1.90	289.41	0.15

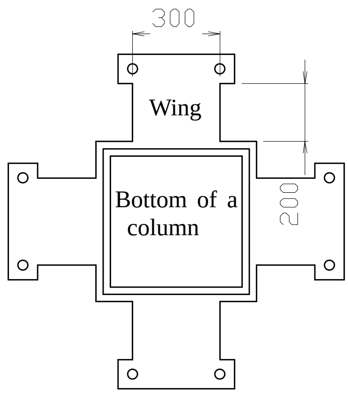


Fig.4 Plan of yielding base plate

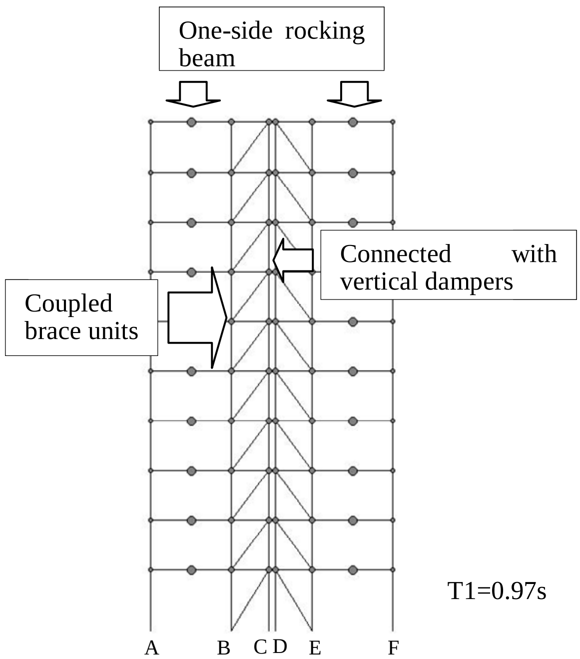
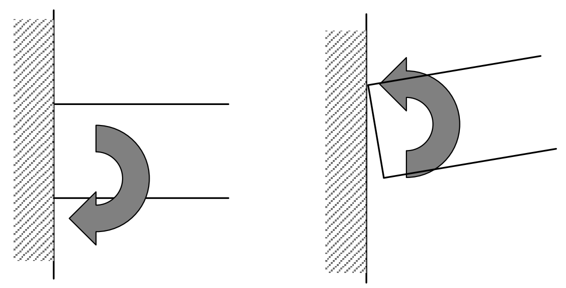


Fig.3 Frame model introduced rocking members



(a) Ordinal condition

(b) Uplift of lower part due to effect of seismic lateral force

Fig.5 Schematic view of one-side rocking beam

2.3 Analytical procedure

For seismic response analyses, a step-by-step time history integration method (linear acceleration method) is used. Damping is assumed to be proportional to the initial stiffness with 2 % damping ratio. To represent uplift response of the frame, two types of springs are attached at each column base as shown in Fig.6. The force-deformation relationships of them are shown in Fig.7. As for base plates, the relationship shown in Fig. 7(b) is modeled based on the test results. The bending force-deformation relationship of edge parts of columns and beams of the original braced frame model is a normal-bilinear type. That of the one-side rocking beam is shown in Fig.8. The axial force-deformation relationship of braces is a bilinear type which shows slip behavior in the compression. And the shear force-deformation relationship of the vertical dampers arranged in the model shown in Fig.3 is shown in Fig.9.

An artificial ground motion (BCJ L2) and the 1995 JMA Kobe NS are input. The BCJ L2 is used for structural design of high-rise buildings in Japan. The time duration is 120s and the peak velocity is 0.5m/s. The linear response spectra for 1-DoF systems with damping ratio h=0.05 are shown in fig. 10.

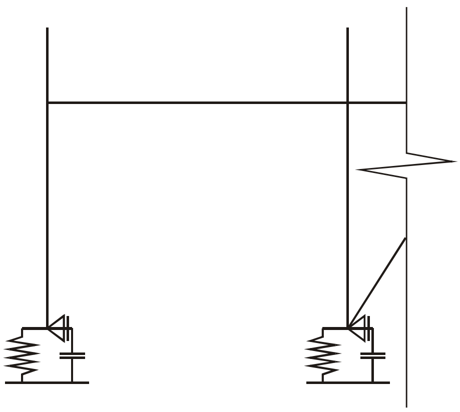


Fig.6 Column bases with two types of springs

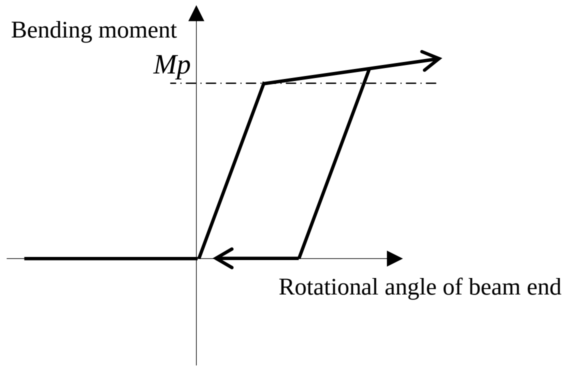


Fig.8 Force-deformation relation of one-side rocking beam

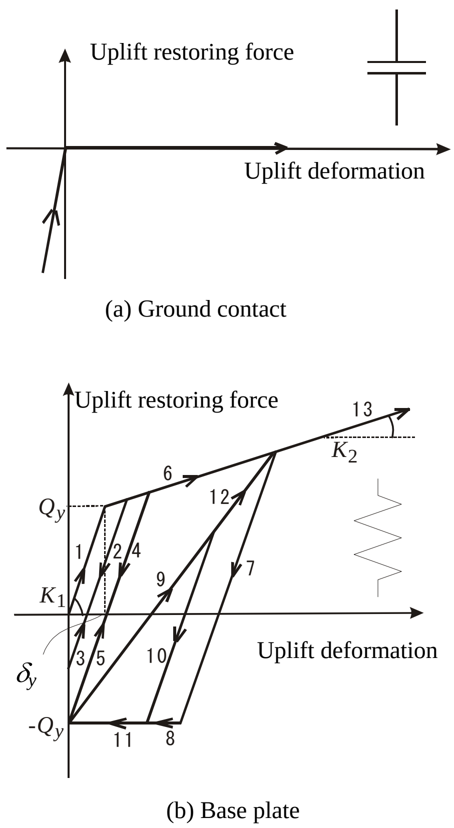


Fig.7 Force-deformation relation of two types of springs

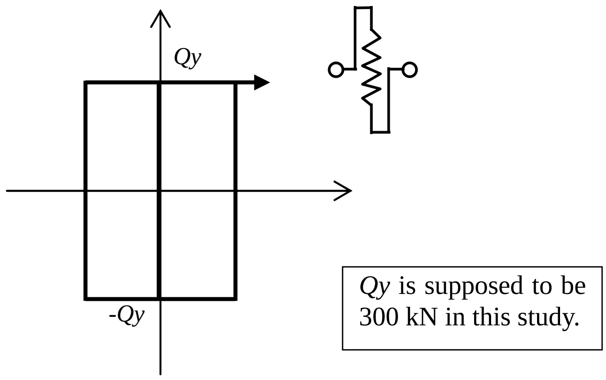


Fig.9 Force-deformation relation of vertical dampers used in coupled brace unit

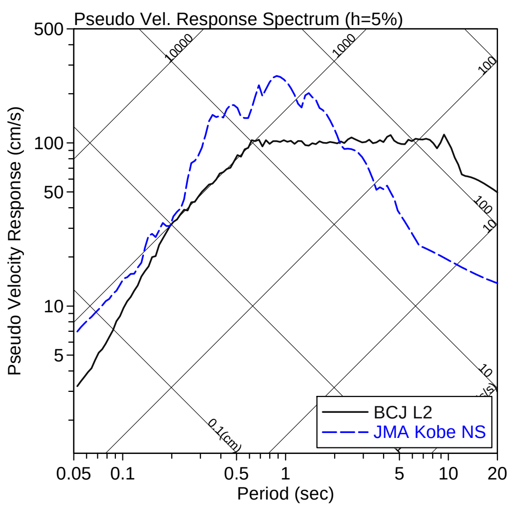


Fig.10 Tripartite response spectra of input ground motions

2.4 Analytical results

Fig.11 shows the relationships between the roof displacement and the base shear of the original braced frame model with fixed bases (F model) and the proposed self-centering model with rocking structural members (SCR model) obtained by static pushover analyses. The Ai-distribution, which is regulated by Japanese building seismic code, is used as the lateral force distribution for the static analyses. Also the corresponding results of dynamic response analyses are plotted in this figure. The seismic response results of base shear of the SCR model are smaller than those of the F model in the both cases of BCJ and JMA Kobe. However the corresponding roof displacement of the SCR model is almost equal to or smaller than that of the F model. This figure shows the base shear of the frame can be reduced by introducing rocking structural members.

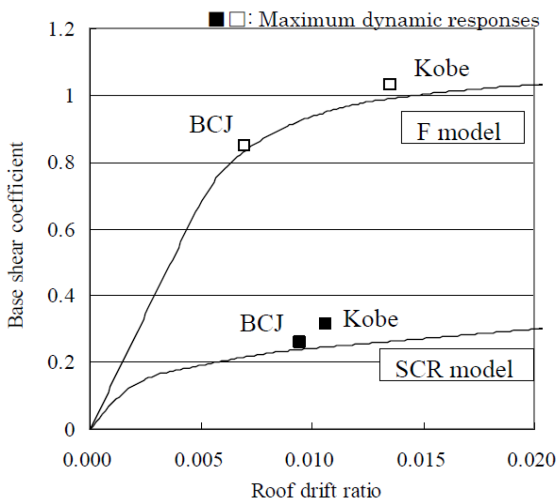


Fig.11 Relationship between roof displacement and base shear obtained by static pushover analysis and corresponding maximum dynamic responses.

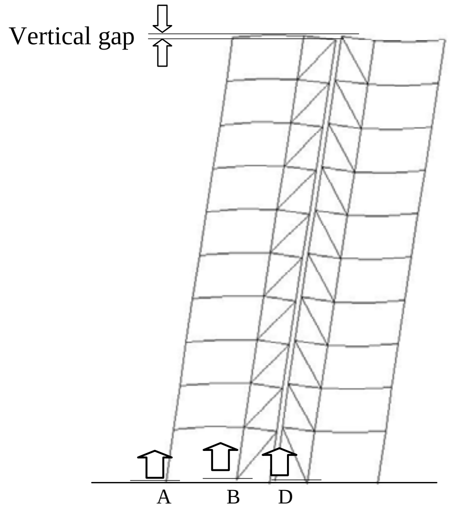


Fig.12 Uplift aspect of SCR model

Fig.12 shows the uplift aspect of the SCR model which is derived from the pushover analyses. Fig.13 and 14 show time history of the uplift response of the SCR model by dynamic response analyses. Figs.12-14 clear the all columns with the yielding base plate can cause uplift response. But they do not simultaneously uplift. The maximum uplift is observed at the column bases of the coupled brace units.

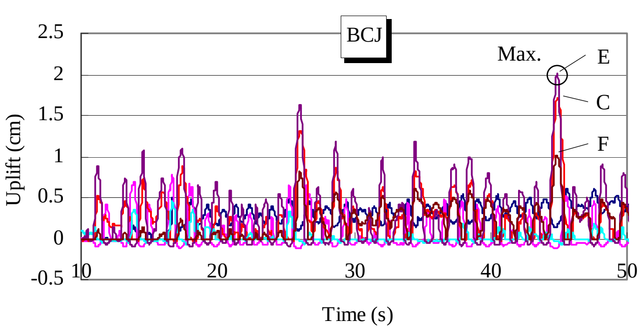


Fig.13 Time history of uplift of SCR model against BCJ

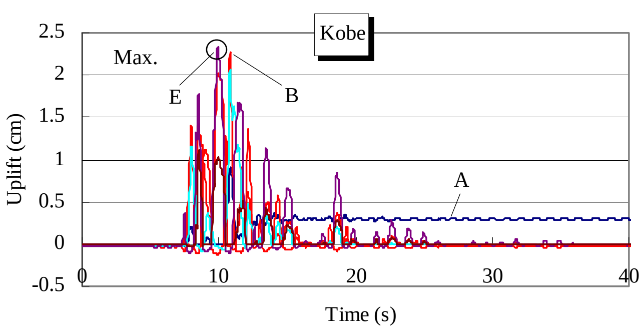
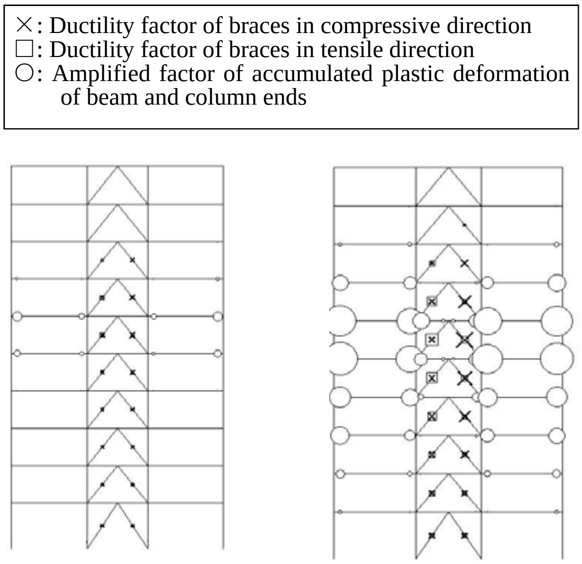


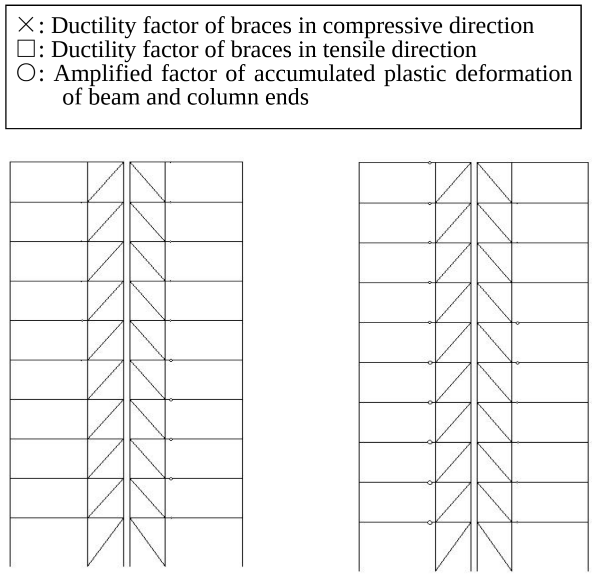
Fig.14 Time history of uplift of SCR model against Kobe

Fig.15 and 16 show damage aspects of the F model and the SCR model respectively. And Table 3 and 4 list maximum damage of members in the frame. As shown in Fig.15, the F model suffers considerable damages especially in the middle stories against the JMA Kobe. In contrast, the SCR frame model almost keeps elastic except base plates as shown in Fig.16. By applying the proposed self-centering system, structural damages can be largely reduced even against the JMA Kobe.



(a) BCJ (b) Kobe

Fig.15 Damage aspect of F model



(a) BCJ (b) Kobe

Fig.16 Damage aspect of SCR model

Table 3 Maximum damage of structural members in F model

	BCJ	Kobe
Ductility factor of brace in compressive direction	2.81 (6F)	7.20 (6F)
Ductility factor of brace in tensile direction	2.10 (7F)	5.27 (6F)
Amplified factor of accumulated plastic deformation of beam ends	4.18 (7F)	15.05 (6F)
Amplified factor of accumulated plastic deformation of beam ends	0.51 (7F)	0.83 (1F)

Table 4 Maximum damage of structural members in SCR model

	BCJ	Kobe
Ductility factor of brace in compressive direction	No damage	No damage
Ductility factor of brace in tensile direction	No damage	No damage
Amplified factor of accumulated plastic deformation of beam ends	0.97 (4F)	1.70 (4F)
Amplified factor of accumulated plastic deformation of beam ends	No damage	No damage

Fig.17 shows time history of energy response of the SCR model against the JMA Kobe. The energy dissipation of the base plates and vertical dampers occupies about 70% of the total energy dissipation of the structural system. Fig.18 shows the force-deformation (base shear coefficient–roof drift angle) relationship by a static pushover analysis under cyclic load schedule shown in fig.19. It shows the proposed system realizes a self-centering system and brings hysteresis damping.

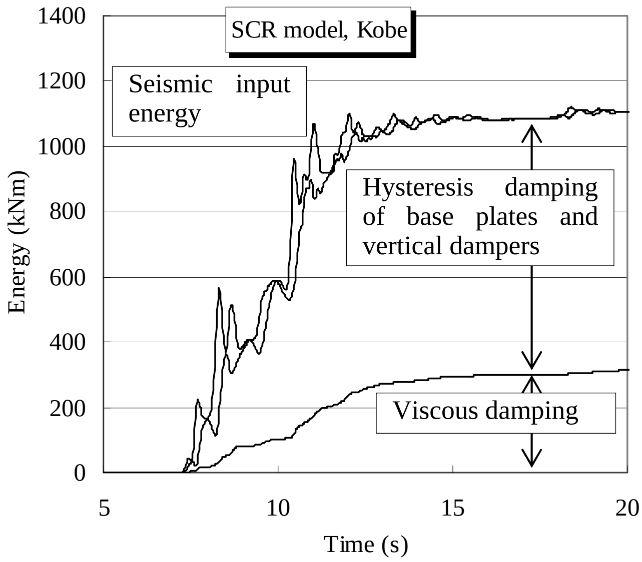


Fig.17 Time history of energy response of SCR model against Kobe

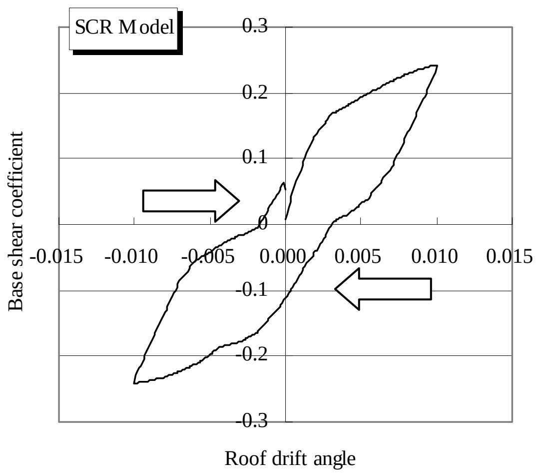


Fig.18 Relationship between roof displacement and base shear for static cyclic load of SCR model

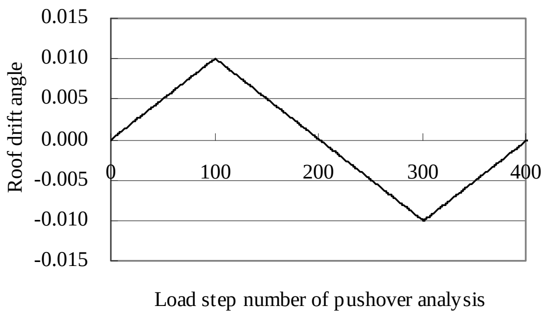


Fig.19 Cyclic load schedule

3. CONCLUSION

The self-centering system with rocking structural members was proposed to reduce seismic damage of steel buildings. This system is allowed to uplift and realize a self-centering system using effect of building's self weight. The seismic performance of the proposed system was successfully demonstrated by earthquake response analyses to a real scale steel frame model. The analytical result showed it can keep the frame almost elastic even against severe earthquake ground motions like the JMA Kobe.

The seismic response of proposed system largely depends on the vertical connection dampers arranged in the frame. Thus to evaluate its performance more appropriately, we need further studies on physical characteristics of these dampers.

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