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EFFECT OF SEISMIC ENERGY DISSIPATION METAL BEAMS INSTALLED IN STEEL FRAME

ISAO NISHIYAMA 1), MITSUMASA MIDORIKAWA 2), NORIKAZU NAGATSUKA 3) and MITSURU SUGISAWA 4)

1) Coordinator for International Research Cooperation, Building Research Institute, Ministry of Construction, 1 Tachihara, Tsukuba, Ibaraki, 305 Japan.
2) Head of Structure Division, Building Research Institute, Ministry of Construction, 1 Tachihara, Tsukuba, Ibaraki, 305 Japan.
3) Research Engineer, Department of Building Research and Development, Tobishima Corporation, 5472, Kimagase, Sekiyado-machi, Higashi-Katsushika-gun, Chiba, 270-02 Japan.
4) Senior Manager, Building Research Development, Nippon Steel Corporation, 20-1 Shintomi, Futtsu, Chiba, 299-12 Japan.

ABSTRACT

A series of inelastic time-history analyses was carried out to make clear the effect of the seismic energy dissipation devices on the improvement of the seismic performance of steel frames. The devices are H-shaped short steel beams with super-low-yield point steel in web and mild steel in flange. The super-low-yield point steel has the yield strength of about 100MPa and the uniform strain of about 30%. The prototype structure is 60m high office steel building designed as moment resisting frames conforming to the current seismic requirements in Japan. The devices are added to the prototype building structure varying the ratio of the shear strength of devices to that of the prototype frames such as zero (without device), 10%, 20%, 30%, 40% and 50%. So as to compare the seismic performance of these systems which have different natural periods, the time-history analyses were conducted to give "constant plastic strain energy input" into each system using the 1952 Taft EW ground motion. The analytical results showed clearly the effectiveness of devices to improve seismic performance of the prototype frame. However, there is the critical amount of devices effective to seismic improvement. It was 20-30% of device shear strength ratio in this study.

KEYWORDS

inelastic dynamic analyses; high-rise steel building structures; with and without seismic energy dissipation devices; short-beam-shaped devices; hybrid section; super-low-yield point steel.

INTRODUCTION

Short mild steel beams show quite stable hysteretic behavior under reversed shear force loading. It is successfully applied to the eccentrically braced frames (Fujimoto *et al.*, 1972, Roeder and Popov, 1978). Recently, several steel manufacturers started to produce new types of metal materials for building use. Super-low-yield point steel (LYP100) is such an example, which has the yield strength of about 100MPa and the tensile strength of about 250MPa with about 30% uniform strain. Hysteretic behavior of short steel beams can be further improved by using LYP100 in place of mild steel. The improvement of hysteretic behavior of short steel beams has been demonstrated by several research groups (Izumi *et al.*, 1992; Nishiyama and Midorikawa, 1992; Nishiyama *et al.*, 1993; Midorikawa *et al.*, 1994a, 1994b; Nakashima, 1995). The structural interaction between frame and short steel beams has also been investigated by static frame tests (Nishiyama *et al.*, 1995; Midorikawa *et al.*, 1996).

In this paper, the effect of the short steel beams installed in steel frames as seismic energy dissipation devices was investigated by a series of inelastic dynamic analyses (time-history analyses). A high-rise steel office building structure designed as moment resisting frames (60m in height) was selected as a prototype and the seismic energy dissipation devices were added to the prototype as an inverted Y-braces. The shear strength of the added devices was varied to evaluate the effect of the amount of the devices installed on the improvement of seismic performance. The comparison of seismic performance of these building structures with and without seismic energy dissipation devices was carried out on the basis of the "constant plastic strain energy input".

INSTALLATION OF DEVICES INTO FRAMES

The shape of the seismic energy dissipation device (Fig.1) is simply H-shaped section with the shape of H-250*125*6*9 and 500mm in length, which results in the shear span ratio of one. The web stiffeners are placed on the web of the device so as to prevent web shear buckling under largely reversed shear deformation. The arrangement of the web stiffeners are determined as to satisfy the UBC-EBF requirements (UBC, 1991). Although flange local buckling never occur on the calculated yield strength basis, the material strength of the flange plates are selected strong enough not to be subjected to flange buckling even considering large strain hardening in the web. Finally, a hybrid section is selected, that is, the flange is of mild steel and the web is of LYP100.

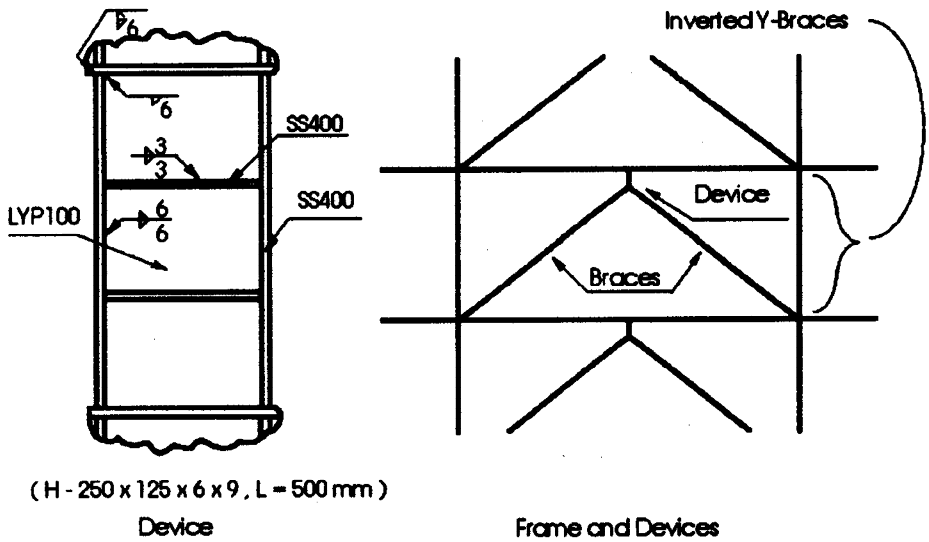

Fig.1 Shape of device and installation of devices into frame

The devices are installed into the moment resisting frame in a vertical position to form inverted Y-braces as shown in Fig.1. This arrangement is determined considering easy replacement of damaged devices after a major earthquake. The braces connected to the bottom of each device are proportioned to safely transmit the shear force in the device to the surrounding frame. In this study, the strength of the braces are assumed to be 1.5 times of the expected ultimate shear strength of the devices. They remains elastic in the analyses. The axial stiffness of the braces are determined correspondingly.

DESIGN OF PROTOTYPE BUILDING STRUCTURE

Fig.2 shows a plan and an elevation of a prototype office-use building structure, which has three spans in X-direction (33m) and five spans in Y-direction (30m) and fifteen stories in height (60m). All the frames in both directions are moment resisting frames. The columns are all box sections which are quite frequently used in Japan.

A building structure taller than 60m such as the prototype structure is designed based on time-history analyses in Japan. The design criteria in the time-history analyses are: 1) the maximum response of story drift is less than 1/200 radian and the members remain elastic under 25cm/s peak ground motion, and 2) the maximum response of story drift is less than 1/100 radian and the member ductility ratio is less than two under 50cm/s peak input. From many design practices for high-rise building structures, the above design criteria are almost equivalent to the Allowable Stress Design (ASD) under the standard design base shear coefficient of 0.3. Therefore, the prototype building structure in this study was first designed by ASD. Then, the designed structure was verified to satisfy the design criteria for high-rise building structures by time-history analyses. Table 1 shows the outline of the prototype building structure. The member list for the typical frame in X-direction is shown in Table 2.

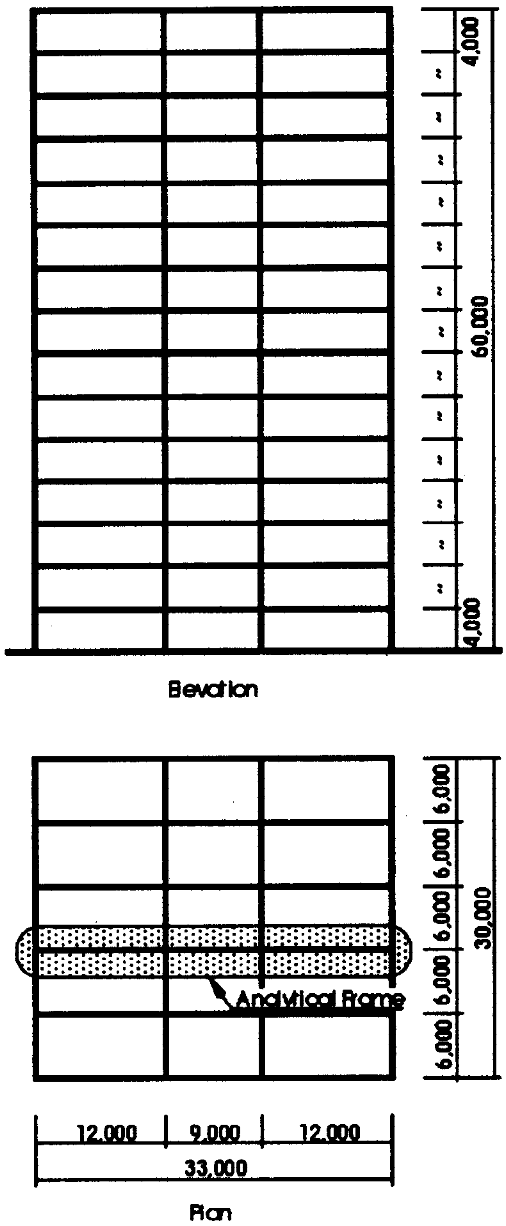

Fig.2 Plan and elevation of prototype building

Table 1 Outline of the prototype building

Use	Office
Number of stories	15
Building height (m)	@4 x 15 = 60
Total floor area (m2)	@990 x 15 = 14,850
Ground (Medium soil)	Tc = 0.6 sec.
Structure Column	Steel moment frame Box section
Natural period (sec.) X-direction Y-direction	 T(1)=1.65, T(2)=0.58 T(1)=1.53, T(2)=0.53
Geometry Vertical Horizontal	 Symmetric Symmetric
Yield base shear coefficient	0.35

Table 2 Member list of analytical frame

Story	Interior column	Story	Exterior column
9-15F	Box-650*650*25	8-15F	Box-600*650*25
5-8F	Box-650*650*28	5-7F	Box-600*650*28
3-4F	Box-650*650*32	3-4F	Box-600*650*32
1-2F	Box-650*650*36	1-2F	Box-600*650*39

Story	Interior beam
14-RF	BH-800*300*17*22
10-13F	BH-850*325*17*22
8-9F	BH-900*350*17*28
6-7F	BH-950*350*18*32
4-5F	BH-950*350*18*34
2-3F	BH-950*350*18*36
Story	**Exterior beam**
14-RF	BH-800*300*17*22
11-13F	BH-850*325*17*22
10F	BH-900*325*17*25
8-9F	BH-900*350*17*32
6-7F	BH-950*350*18*34
4-5F	BH-950*350*18*36
2-3F	BH-950*350*18*38

The shadowed frame in X-direction shown in Fig.2 is selected to be investigated in comparison to frames with devices, which is installed only in the mid span of the frame. It is natural that the devices will be installed into not all the frames (six frames in X-direction) but into only the selected frames concentrically. However in this study, for simplicity, the devices are assumed to be installed into every frames uniformly. The ratio of the shear strength of the installed device to that of the frame, which is called "device strength ratio" varies 0, 10, 20, 30, 40 and 50%. The monotonic shear force versus story drift relationships for frames with and without devices are shown in Fig.3, where elastic perfectly plastic model is used for columns, beams and devices in the static analyses. The yield displacement of the prototype frame is about 54cm at the top of the frame which corresponds to the overall drift angle of 1/113 radian. The frames with devices show tri-linear curves. The initial yield occurs at the displacement of the top of the frame of 9 to 18cm (1/667 to 1/333 radians), which is due to device yield. The secondary (final) yielding occurs at the top displacement of about 52cm. The initial yield tends to occur earlier in the frames with less device strength ratio except for frame without devices. The device itself in each model is designed to have identical yield displacement, but the initial yield displacement does not coincide due to the difference in brace stiffness. As the braces are designed to have 1.5 times the strength of devices, the effective stiffness of braces in each model is different. In Table 3, the characteristic values of frames with and without devices are summarized.

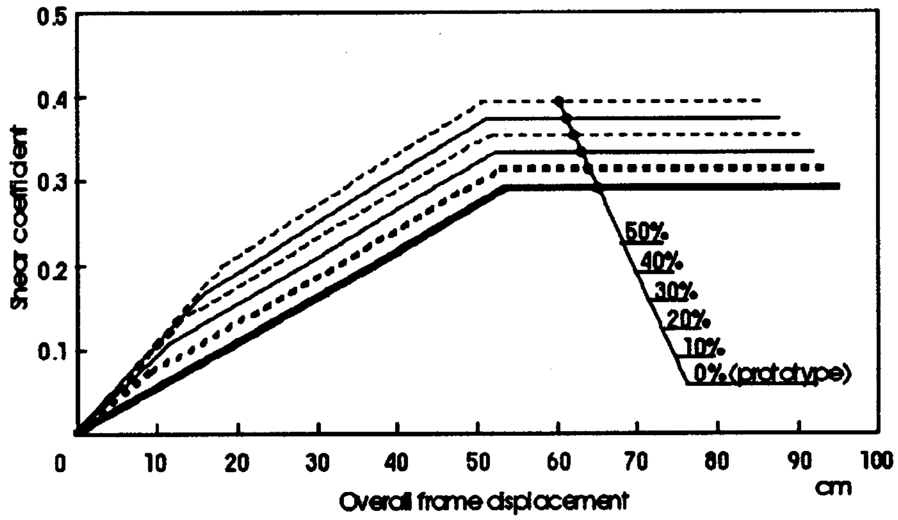

Fig.3 Shear coefficient versus overall frame displacement relationships of frames with/without devices

Table 3 Structural characteristics of frames with/without devices

	Device strength ratio					
	0%	10%	20%	30%	40%	50%
Device yield						
Shear coef.	-	0.073	0.110	0.142	0.174	0.200
Disp. (cm)	-	9.0	11.5	13.7	15.8	18.0
Frame yield						
Shear coef.	0.290	0.312	0.333	0.354	0.374	0.394
Disp. (cm)	53.6	52.9	52.3	51.8	51.1	50.5
Period (sec.)	1.85	1.47	1.34	1.27	1.23	1.20
Input motion (cm/s)	130	116	121	128	133	137

Note: Displacement is estimated at the top of the frame.

SEISMIC PERFORMANCE OF FRAMES WITH/WITHOUT DEVICES

Ductility and ductility ratio are both frequently used to compare the seismic performance of frames. However, they are not enough to compare the seismic performance of the frames which have different fundamental natural periods and damping characteristics. It is also used for practical structural design that the required member ductility ratio estimated from time-history analyses is compared with critical one. However, in this method, several time-history analyses using several motions are needed to lead general conclusions on the seismic performance of the frame. Recently, synthesized ground motions are available which have flat spectrum over wide range of frequencies (Huang *et al.*, 1993). These synthesized ground motions might be useful to compare the seismic performance of different frames.

In this paper, the following method is adopted to compare seismic performance of different frames. First, the prototype frame is analyzed and the maximum cumulative plastic deformation ratio of the members is estimated. By changing the peak acceleration or velocity level of the ground motion, the maximum cumulative plastic deformation ratio of members can be set to be six, which is thought to be the critical cumulative plastic deformation ratio for members of compact section. To realize member's cumulative plastic deformation ratio of six for the prototype frame, the peak velocity of the ground motion (1952 Taft EW) is scaled to 130cm/s, which is far beyond 50cm/s used in the practical design for high-rise building structures in Japan. This fact indicates that ordinary high-rise building structures such as the prototype frame have a potential to resist much larger motions used in practical design. Here, the critical damping ratio of 2% is used in the analyses. For frames with devices, the motion is scaled to give the identical seismic energy, which contributes to plastic deformation, to the frame with devices as that given to prototype frame. Therefore, the peak velocity of the ground motion is different in each case as shown in Table 3.

Static Elastic Analyses

Static elastic analyses were conducted on the prototype frame and frames with devices. The shear force distribution along the height is coincided with Ai-distribution specified in the Building Standard Law of Japan (Building Center of Japan, 1994). Fig.4 shows the analytical results, in which the ratios of the shear deformation to the overall displacement along the height of the frames are shown for frames with and without devices. It can be seen from this figure that the shear deformation is predominant in the prototype frame (moment resisting frame) and is becoming less for frames with devices especially in higher stories.

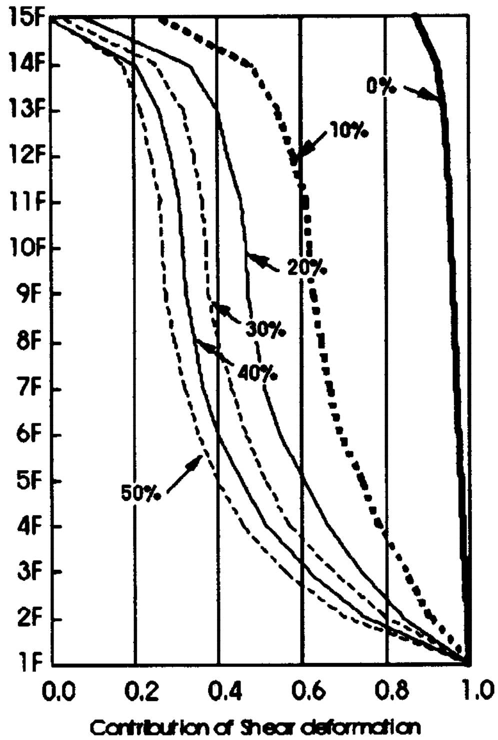

Fig.4 Contribution of shear deformation on the overall frame displacement

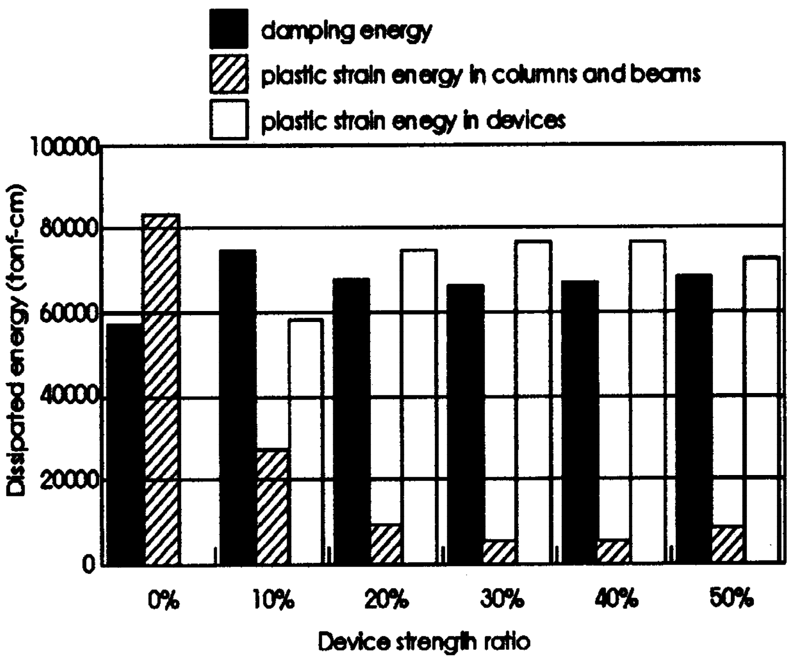

Fig.5 Total input energy into frames with/without devices

Time-History Analyses

The 1952 Taft EW ground motion is used in the analyses. The maximum acceleration is determined by the method explained previously. The critical damping ratio is 2% and is proportional to the initial stiffness. The hysteretic behavior of the members such as columns, beams and devices are assumed to be elastic perfectly plastic (bi-linear) model neglecting strain hardening.

Fig.5 shows the results of the time-history analyses. The seismic input energy is decomposed into energy of damping, plastic strain in columns and beams, and plastic strain in devices. The prototype frame dissipates the energy about 83,000 tonf-cm by the plastic strain of the columns and beams. The damping dissipation energy reaches about 57,000 tonf-cm. Therefore, the total energy dissipation reaches about 140,000 tonf-cm. The frames with devices dissipated more damping energy than the prototype frame and it varies from 66,000 to 74,000 tonf-cm. The total of the plastic strain energy dissipated by columns, beams and devices coincides with that of the prototype. The plastic dissipation energy by the devices is saturated at the device strength ratio of 20%. This results show that even a small amount of devices effectively dissipate seismic energy and can improve seismic performance of the frames.

Figs.6 and 7 show the dissipated energy distribution along the height of the frames. The device strength ratios are shown in the figures. The prototype frame shows larger energy dissipation in 9th and 10th stories, which coincides with the 2nd mode shape. It is also shown that the energy dissipation by columns and beams is reduces remarkably in the frames with devices. Meanwhile, the energy dissipation is improved in the lower stories by the effect of the devices as shown in Fig.7. However, the effect of the devices looks deteriorated in case that the device strength ratio is over 30%.

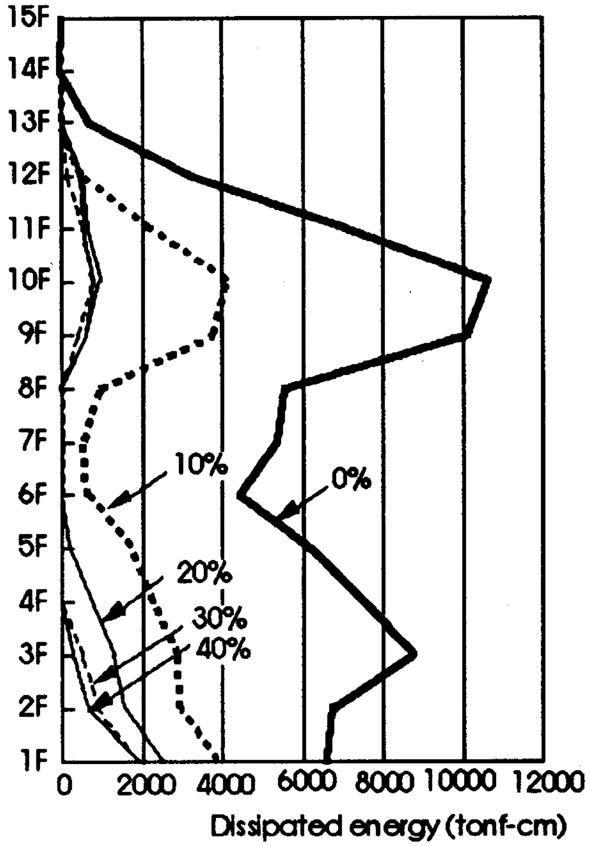

Fig.6 Dissipated energy by columns and beams along the height of the frame

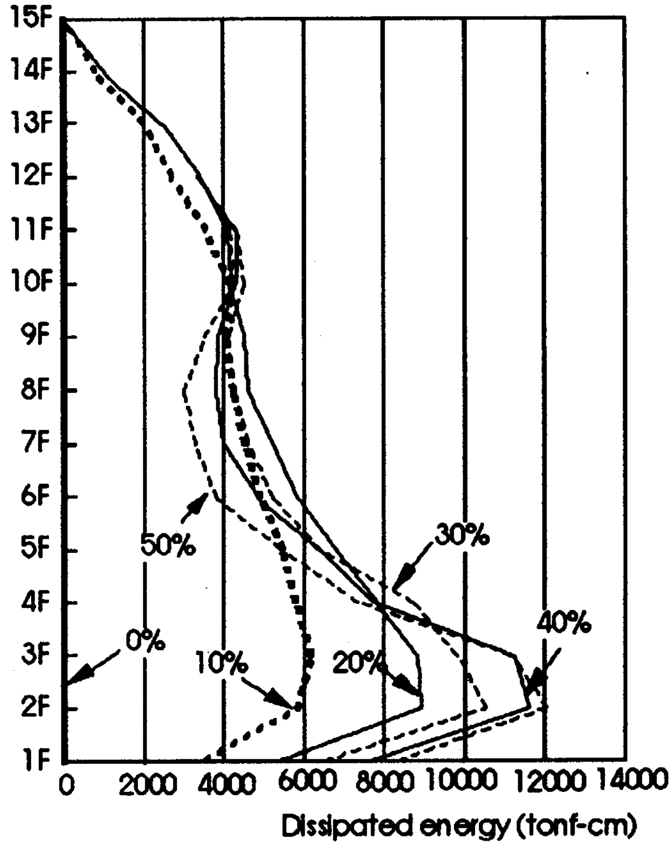

Fig.7 Dissipated energy by devices along the height of the frame

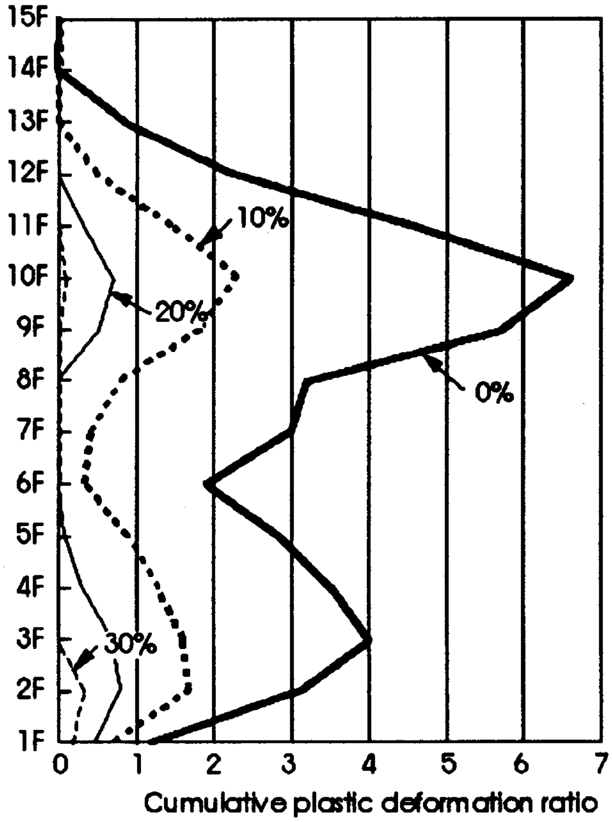

Fig.8 Cumulative plastic deformation ratios of interior beams along the height of the frames

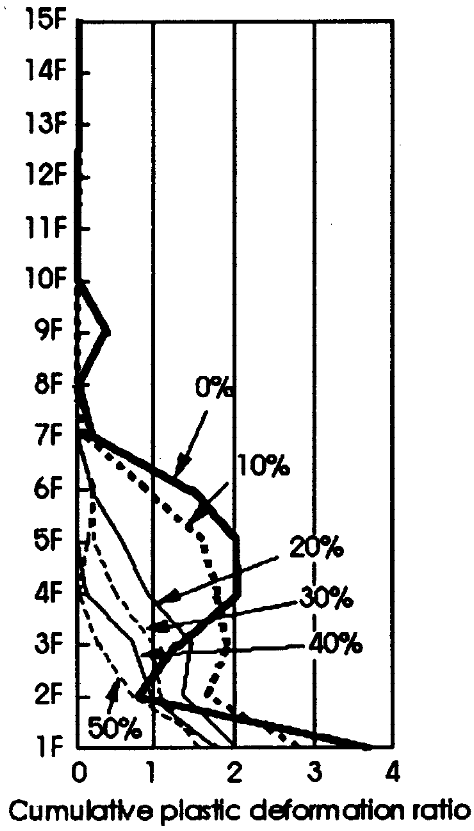

Fig.9 Cumulative plastic deformation ratios of interior columns along the height of the frames

Figs.8 and 9 show the cumulative plastic deformation ratios of the interior beams and columns, respectively. The required cumulative plastic deformation ratio of interior beams is rapidly decreased in the frames with devices. On the other hand, the required cumulative plastic deformation ratio of columns is not always improved by adding the devices. It is because that the column axial force is increased by the effect of devices, which is much severe to column members.

SUMMARY AND CONCLUSIONS

The seismic performance of frames with and without seismic energy dissipation devices are evaluated in this study. The required cumulative plastic deformation ratio of members in frames is compared each other under the same "plastic strain energy input" by the 1952 Taft EW ground motion. The following analytical results and future research issues are obtained from these inelastic time-history analyses.

(1) The prototype high-rise building structure which was designed to conform to current seismic requirements in Japan showed seismic performance potential to resist ground motion of about 130 cm/s peak velocity.

(2) The seismic performance was clearly improved in frames with seismic energy dissipation devices. The required member's cumulative plastic deformation ratio reduced in great deal in frames with devices compared to that without devices.

(3) There seems to be a critical ratio of device shear strength to frame one to give effectively seismic improvement to the frame without devices. It is because the excessive increase in device shear strength results in the increase in column axial force, which reduces the column ductility. In this study, the critical device shear strength ratio was around 20-30%.

(4) The input ground motion was scaled to give constant plastic strain energy input into the frames considered. Therefore, neither peak acceleration nor peak velocity of the input ground motions were common in the analyses. Use of the concept of constant plastic strain energy input for the purpose of comparing seismic performance of different building structures should be justified in future.

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