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A STUDY OF POSSIBILITY OF PIN JOINED RC STRUCTURE WITH SHEAR DEVICES WHICH SHARE ALMOST WHOLE HORIZONTAL FORCE

-The conditions of continuous column and shear devices to avoid story collapse.

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SUMMARY

A multi-story structural system composed of pin-jointed RC frame and passive response control devices is proposed in this paper. Story collapse caused by bending failure of continuous columns is serious problem in this structure. The purpose of this study is to clarify the conditions of the structural elements required to avoid story collapse. Dynamic response analyses are performed, and optimum strength distribution is found by trial-and-error method that determines strength distribution so that each story drift is as much as the others when earthquake motion is inputted to series-connected devices. And it is confirmed that optimum strength distribution is effective in avoiding story collapse.

INTRODUCTION

In ordinary RC rigid frames, its beam-ends and column-bases are allowed to yield and dissipate seismic energy under a big earthquake. Therefore when they are repaired, we have to add a hand to structural elements. Additionally in this type of structure, its structural elements have to resist not only static load but also seismic load simultaneously, and aseismic design is inclined to be complicated.

To improve these matters, a new approach separating energy-dissipating function from load-carrying function becomes popular. In this type of structure, the energy-dissipating function is replaceable unit, and repairing nature is improved.

Conformity to this, a multi-story structural system shown in Fig.1 is proposed in this paper. Continuous columns support whole vertical load, and passive response control devices installed in each story share almost whole horizontal force. Column-bases are pin-supported and beam-ends are also joined to continuous columns by pin connections, therefore joint parts of main frame are prevented from bending failure. And the devices can operate efficiently, because an allowable story drift of this structure is larger than that of ordinary RC frame. Additionally, there is another advantage that it is easy to use precast concrete members, because it is not necessary to make the joint parts rigid.

However, it is unknown that whether this structure has enough resistance to earthquakes under actual dimensions of the continuous columns, because there is a risk of story collapse caused by bending failure of the continuous columns.

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The purpose of this study is to clarify the conditions of structural elements required to avoid story collapse. In ANALYSIS-1, dynamic analyses of 6-layer 1-span model are performed, and the influence of parameters on vibration is grasped. The parameters of ANALYSES-1 are dimensions of continuous columns, restoring force characteristics of devices, and distribution of device characteristics: e.g. stiffness distribution and strength distribution. Based on ANALYSYS-1, optimum strength distribution is proposed in ANALYSIS-2, and it is confirmed that the optimum strength distribution is effective to avoid story collapse.

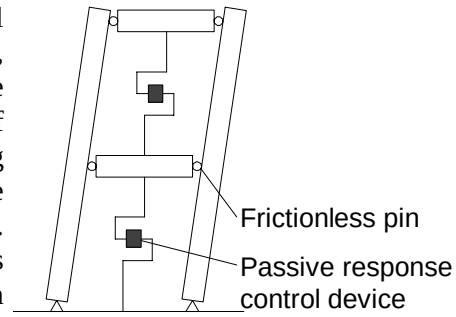

Fig.1: Proposed structural system

ANALYSIS-1

Analytical model

The analytical model is shown in Fig.2. It consists of pin jointed 6-story 1-span plane RC frame and passive response control devices installed in each story. The mass of each story is 42.0(ton). The height of each story is 300(cm), and beam span is 800(cm).

The continuous column is designed as a bending member, and its base end is joined to foundations by a pin. In order to simulate plastic behaviors, revolving springs are set at the critical section of continuous columns. The moment curvature curve for revolving spring is tri-linear model shown in Fig.3. Mc is a moment under which concrete on the tension side of the cross-section breaks along tension cracks, and My is yield strength. Mc and My are determined by dimensions and axial force of the continuous columns. The beam is a perfect elastic body, and its both ends are joined to the continuous columns by pins. The cross-section of the beam is shown in fig.4.

Mechanical characteristics of materials are shown in Table.1.

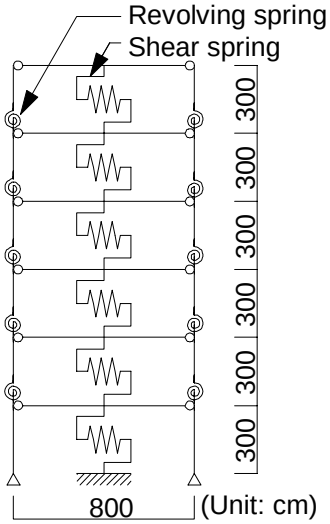

Fig.2: Analytical model

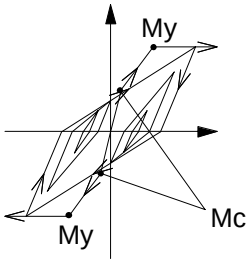

Fig.3: Tri-linear model

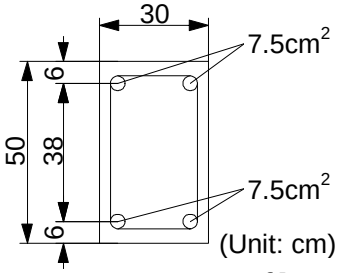

Fig.4: Cross-section of beam

Table 1:Mechanical characteristics of materials

Material	*Strength(MPa)*	*Young's modulus(Gpa)*
Concrete	29.4	20.6
Steel	294	206

In analyses-1, dimensions of continuous columns, restoring force characteristics of devices, and distribution of device characteristics are used as parameters. Their details are as follows.

Dimensions of continuous columns

The cross section of continuous column is shown in Fig.5. This research assumes four types of column dimensions as shown in Table.2. 'C00' on this table represents the analytical model composed of only masses and series-connected passive response control devices.

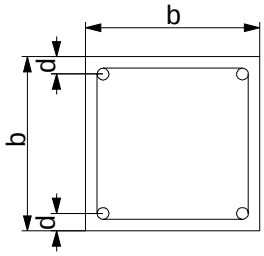

Table 2: dimensions of continuous columns

Column type	*b (cm)*	*d (cm)*	*Steel ratio (%)*
C00	No columns		
C40	40.0	4.00	1.00
C60	60.0	6.00	1.00
C80	80.0	8.00	1.00

Fig.5: Cross-section of column

Restoring force characteristics of devices

Elastic-perfectly plastic model (Fig.6) and origin-oriented model (Fig.7) are assumed as restoring force characteristics of the passive response control devices.

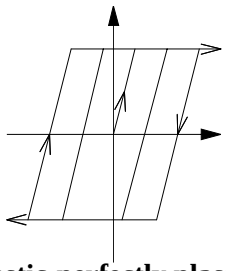

Fig.6: Elastic-perfectly plastic model

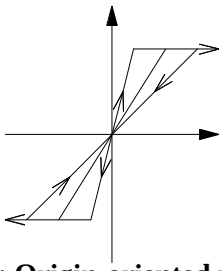

Fig.7: Origin-oriented model

Distributions of device characteristics

To avoid bending failure of continuous columns, it is important for the analytical model to keep itself straight under a big earthquake. Stiffness distribution of each device is determined so that the analytical model transforms keeping straight form when the following lateral seismic coefficient is applied to each story. One is the seismic coefficient expected by SRSS method (AIJ [1]), and the other is uniform seismic coefficient. According to derived seismic coefficient, each stiffness distribution is referred to as 'SRSS stiffness distribution' and 'UNIFORM stiffness distribution'. The initial stiffness of each device is determined so that the primary period of the analytical model will be 0.30(sec).

Strength distribution is determined so that all devices will be yield at same deformation when the analytical model has above stiffness distribution. They are referred to as 'SRSS strength distribution' and 'UNIFORM strength distribution' according to derived stiffness distribution. The strength of each device is determined by the assumption that the base shear coefficient at yield point is 40% of the gravity load of the structure.

Then above-described assumptions are combined and following three types are assumed.

- SRSS type (SRSS stiffness distribution + SRSS strength distribution)
- UNIFORM type (UNIFORM stiffness distribution + UNIFORM strength distribution)
- HYBRID type (SRSS stiffness distribution + UNIFORM strength distribution)

Load-deformation relationships of each device are shown in Fig.8.

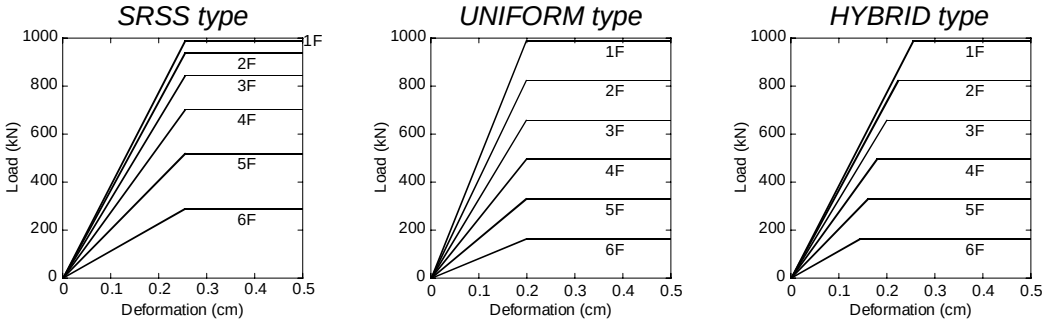

Fig.8: Load-deformation relation ships of each devices

Analytical method

Dynamic analyses are performed based on the assumption that the floor slab is rigid body. Damping ratio of 5.00% is assumed for all eigen modes, and damping is determined from the initial stiffness of the structure. Linear acceleration method is applied to the dynamic analyses, and numerical integration is performed by NEWMARKβ method (β=1/6). Unbalanced forces and unbalanced moments are eliminated in current time step by iterative calculations. The time interval is 0.002 (sec), and the duration of the analyses is 40.0(sec). The influence of P-δ effect is taken into consideration.

Actual earthquake motions used in the analyses are KOBE and ELCENTRO. KOBE is north-south component of 1995 Hyogoken-Nanbu Earthquake observed at Kobe Marine Observatory. ELCENTRO is north-south component of 1940 Imperial Valley Earthquake observed at El Centro.

Simulated earthquake motions are also used as input waves. The simulated earthquake motions are made by means of superposition of sine waves, and their velocity response spectra are adjusted to 'design velocity response spectrum' (AIJ [2]). Figure 9 shows the simulated earthquake motions used in this research. They are different from one another in the respect of principal shock period, and that of SEM4 is equal to whole earthquake duration. The principal shock period is fixed using the similarity between the envelope curve of acceleration history and the shape of phase difference spectrum (Ohsaki [3]). The acceleration response spectra of the simulated earthquake motions are shown in Fig.10, and the velocity response spectra of them are shown in Fig.11.

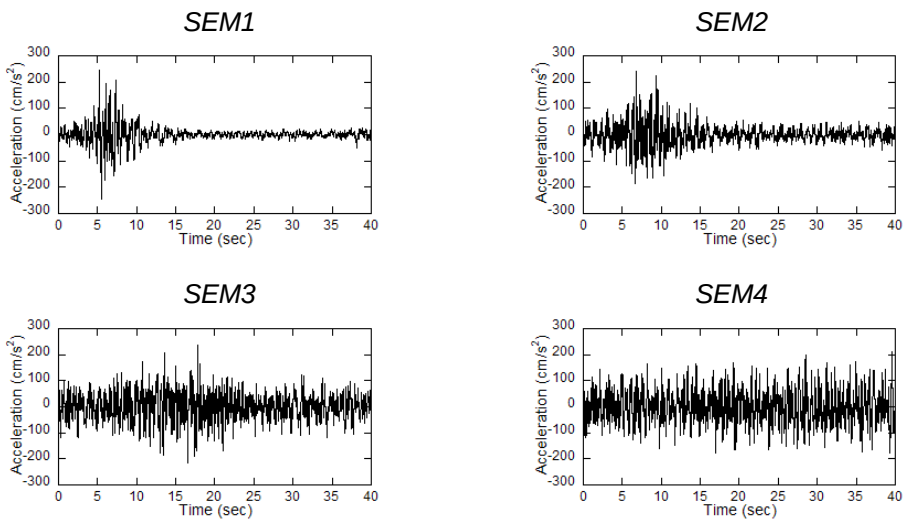

Fig.9: Simulated earthquake motion

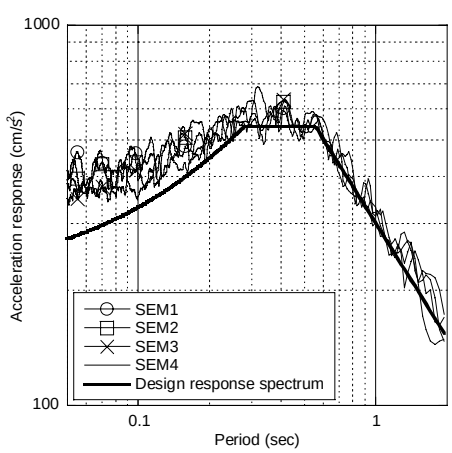

Fig.10: Acceleration response spectrum

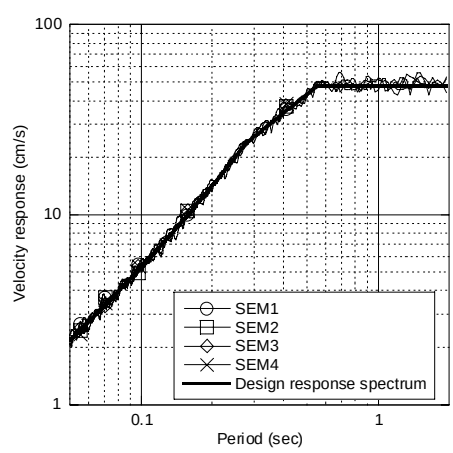

Fig.11: Velocity response spectrum

Analytical results

Influence of Dimensions of continuous columns

The results of response analyses performed with C00-C80 are shown in Fig.12. The restoring force characteristic of the devices is elastic-perfectly plastic model, and the distribution of the device characteristics is SRSS type. Earthquake motion used in these analyses is KOBE.

In the case of C00, the story drift between ground floor and second floor is distinctly large, and story collapse may arise at bottom layer. However, as the dimensions of the continuous columns increase, the residual story drift of each story approaches one another, and in the case of C80, the continuous columns are kept approximately straight.

Figure 13 shows the distribution of maximum bending moment produced in the continuous columns while the ground motion is applied to the analytical model. Mc indicates the crack point of the continuous columns, and My is the yield strength. The continuous columns of both C40 and C60 are cracked at lower story, but do not yield at all. However, the large bending moment of C40 is concentrated to lower stories, and it is likely to cause story collapse.

These results reveal the fact that the analytical model brings out enough strength with the continuous columns of actual dimensions that are as large as the columns' dimensions used in current general RC multi-story structure.

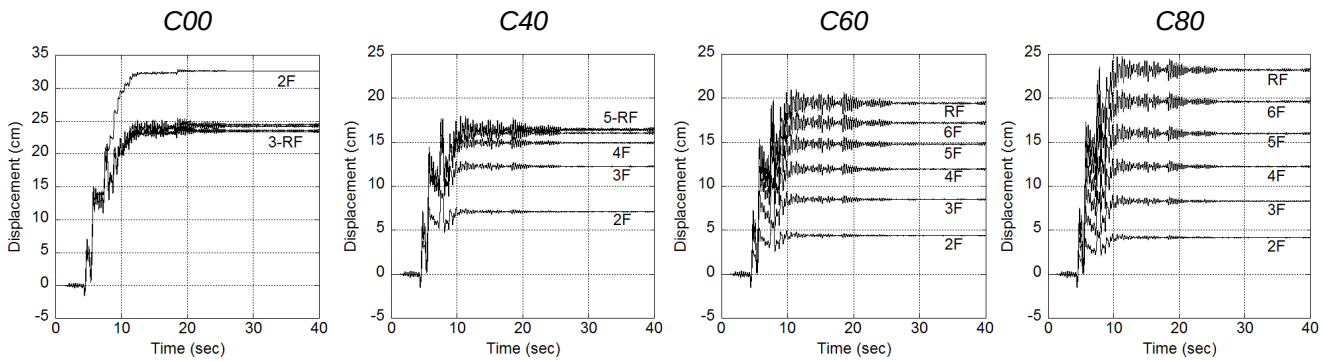

Fig.12: Horizontal displacement history

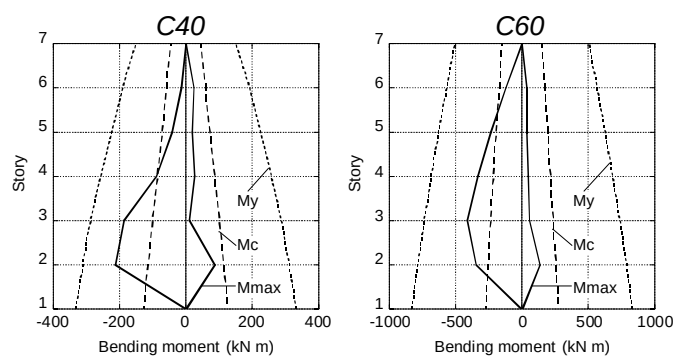

Fig.13: Maximum bending moments of continuous columns

Influence of restoring force characteristics of devices

Next, the analyses are performed with the devices of origin-oriented model. The type of the continuous columns is C60, and the distribution of the device characteristics is SRSS type. Inputted ground motion is KOBE.

Figure 14 shows the history of horizontal displacement. The maximum horizontal displacement is larger than that of the result performed with elastic-perfectly plastic model. In the case of origin-oriented model, the residual story drifts do not appear, and the vibration period stretches when the inelastic deformations of the devices develop.

Figure 15 shows the distribution of the maximum bending moment produced on the continuous columns. Compared with the result of C60 shown in Fig.13, larger bending moments are recognized in the continuous columns, and the risk of the story collapse is higher.

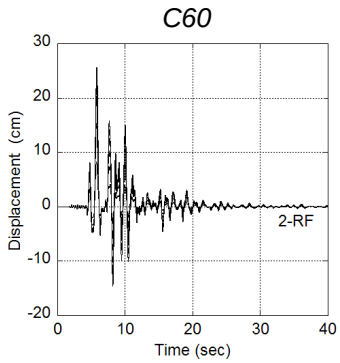

Fig.14: Horizontal displacement history

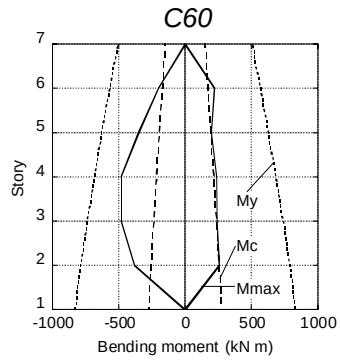

Fig.15: Maximum bending moment

Influence of device characteristics distributions

Figure 16 shows the results of the analyses performed with some intensity of input ground motion. The vertical axis of them indicates the maximum bending moment produced in the continuous columns, and the horizontal axis indicates the maximum velocity of input ground motion. The intensity of the input ground motion is adjusted by the magnifications that are applied to original waveform. The original waveform used in these analyses is SEM4. The column type is C60, and the type of the restoring force characteristic is elastic-perfectly plastic model.

When the maximum velocity of the ground motion is under 40(cm/s), large bending moments are produced in UNIFORM type. It is considered that the influence of initial stiffness distributions appears clearly, because the vibration characteristics under a small earthquake are similar to that of elastic vibration. However in the case that the maximum velocity of ground motion is over 40(cm/s), large bending moment is produced in SRSS type, and the result of UNIFORM type and that of HYBRID type are alike. It turns out that the maximum bending moment produced in the continuous columns under a big earthquake is mainly determined by the strength distribution.

In the result of HYBRID type, large bending moments are produced in higher stories under small earthquakes. However, as the intensity of input ground motion increases, the maximum bending moments of higher story becomes relatively small, and the maximum bending moment of each story is as much as the others in the range of 60-100(cm/s). That represents that the adequate strength distribution changes according to the intensity of input ground motion.

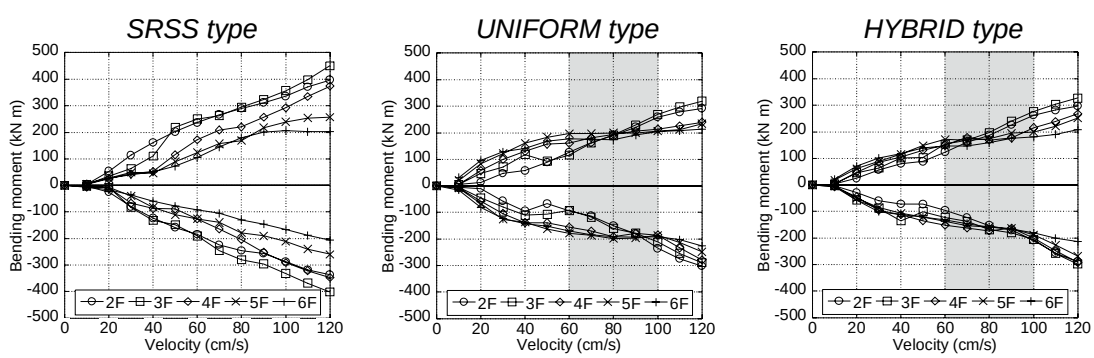

Fig.16: relationships between maximum bending moment and intensity of ground motion (The result of SEM4)

Figures 17 and 18 show the results of the other original waveforms, KOBE and ELCENTRO. The column type is C60, and the type of the restoring force characteristic used in these analyses is elastic-perfectly plastic model. As shown in Fig.17, when maximum ground motion is less than 30(cm/s), the bending moments produced in the continuous columns of SRSS type are smaller than that of HYBRID type. But in the range of more than 30(cm/s), the maximum bending moments of HYBRID type are smaller than that of SRSS type. Figure 18 shows the same inclination, but the bound is about 50(cm/s).

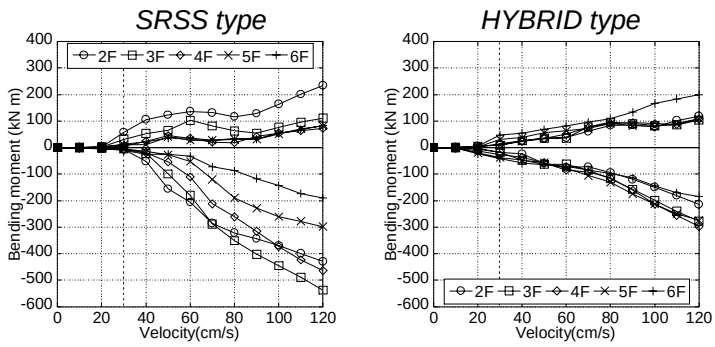

Fig.17: The result of KOBE

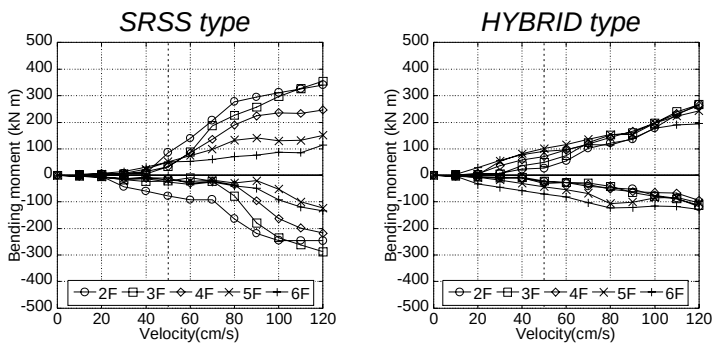

Fig.18: The result of ELCENTRO

Figure 19 shows the results of origin-oriented model. In this case, the results of UNIFORM type and that of HYBRID type are almost equal, and large bending moments are produced in middle story and the continuous columns yield at some critical section. On the other hand, the maximum bending moments of SRSS type are always smaller than that of the others, regardless of the intensity of the ground motion.

It is considered that these results are derived from the following two characteristics superior to origin-oriented model.

One is the similarity to the elastic vibration. The vibration characteristics of origin-oriented model are similar to that of elastic vibration, because origin-oriented device hardly absorbs seismic energy and hysteretic damping is very little.

The other is conservation of stiffness distribution. In the case of origin-oriented model, stiffness distribution is saved as long as the analytical model vibrates with straight form as shown in Fig.20. Additionally the SRSS stiffness distribution under inelastic region is not much different from that of elastic region as shown in Fig.21, even as the primary period of the analytical model is enlarged to about 1.5(sec) from 0.3(sec) under a big earthquake like KOBE.

It is considered that the above-mentioned matters lead the results, that is, in the case of origin-oriented model, the adequate stiffness distribution is close to SRSS stiffness distribution regardless of the intensity of the input ground motion.

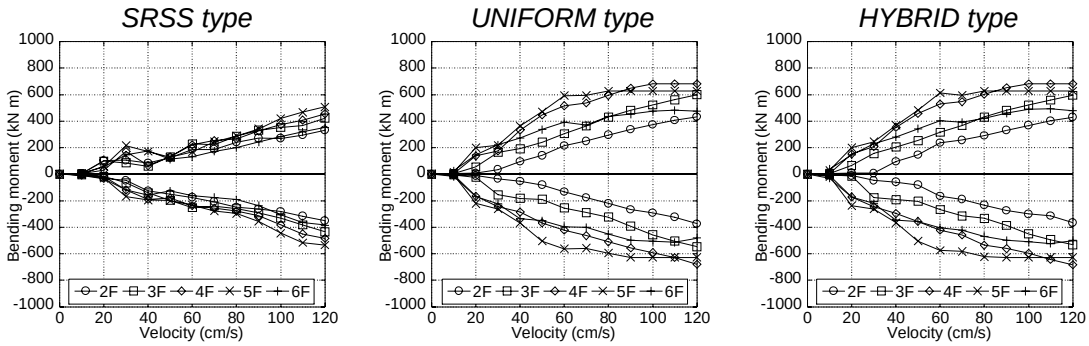

Fig.19: relationships between maximum bending moment and intensity of ground motion (The result of origin-oriented model)

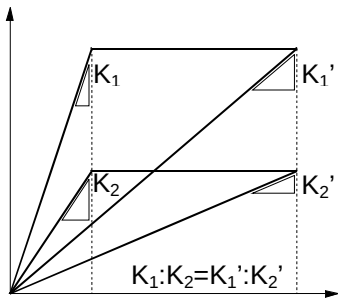

Fig.20: Conservation of stiffness distribution

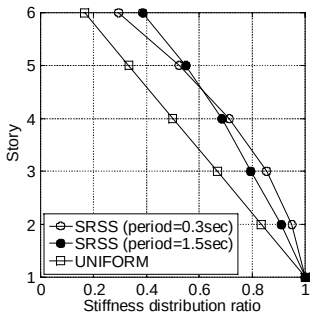

Fig.21: Stiffness distribution

ANALYSIS-2

ANALYSIS-1 reveals the fact that the bending moments produced in continuous columns are mainly dependent on strength distribution of the passive response control devices under a big earthquake. Consequently, it is important to find the adequate strength distribution to avoid story collapse of the analytical model. However it is difficult to find the optimum strength distribution from the view point of minimizing the maximum bending moment produced in the continuous columns, because this method needs the convergence operation to the whole analytical model and it takes good amount of a time. In ANALYSIS-2, a simpler method is proposed, and it is confirmed that this strength distribution is effective in avoiding story collapse.

Obtaining method of the optimum strength distribution

The 6-layer model composed of mass and series-connected devices as shown in Fig.22 is considered. The stiffness distribution of this model is SRSS stiffness distribution, and the mass of each story is 42.0(ton). If the strength distribution is adequate, and this model vibrates linearly under the earthquake, there are no bending moments produced in the continuous columns that are attached to this series-connected devices model.

According to this account, optimum strength distribution is determined by trial-and-error method that determines the strength distribution so that the width of each story drift (shown in Fig.23) is as much as the others when the earthquake motion is inputted to the series-connected devices model. In the case of the condition that the primary mode is dominant, it is considered that this model with the optimum strength distribution vibrates linearly. And in the case of conditions that the higher modes take effect, it is considered that this model does not extremely swerve from straight shape, because the width of story drift is restricted.

Fig.22: 6-layer series-connected devices model

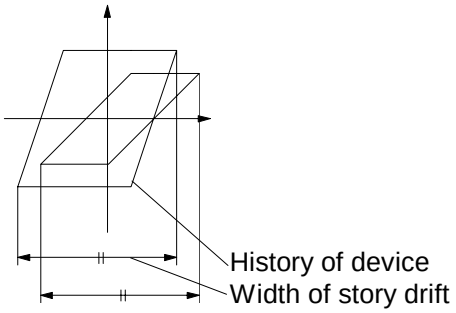

Fig.23: Optimization technique

Analytical results

Figure 24 shows the relationships between the optimum strength distributions and the intensity of input ground motion. SRSS strength distribution is shown in left periphery of each chart, and UNIFORM strength distribution is shown in right periphery. These are the results of the case of elastic-perfectly plastic model. The intensity of input ground motion is adjusted by the magnifications that are applied to original waveform. The original waveforms used in these analyses are SEM4, KOBE, and ELCENTRO.

In the result of SEM4, the optimum strength distribution is similar to SRSS strength distribution under 30(cm/s). The optimum strength of the stories except for the base story become weak as the velocity of ground motion increases, and the optimum strength distribution is similar to UNIFORM strength distribution in the range of 60-100(cm/s). This result shows good correspondence to the result as shown in Fig.16. The results of KOBE and ELCENTRO also show the same inclination as that of SEM4, and they show good correspondence to the result as shown in Figs.17 and 18.

Figure 25 shows the result of origin-oriented model. The original waveform used in this analysis is SEM4. In the case of origin-oriented model, optimum strength distribution is similar to SRSS strength distribution in the all range of input ground motion. This result also corresponds to the results as shown in Fig.19.

According to these results, it turns out that the optimum strength distribution is effective in controlling the bending moment of continuous columns.

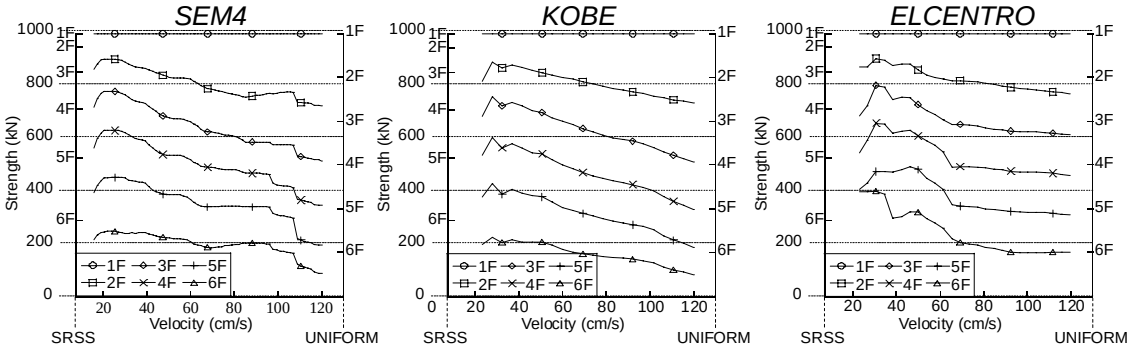

Fig.24: Optimum strength distribution (elastic-perfectly plastic model)

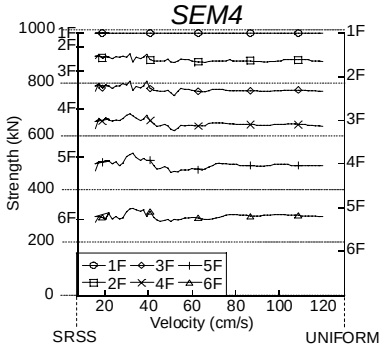

Fig.25: Optimum strength distribution (origin-oriented model)

CONCLUSIONS

As for the proposed pin-connected RC structural system with continuous columns and passive energy-dissipating devices, the following knowledge is obtained by the analyses that investigate the conditions of structural elements required to avoid story collapse.

1) When the distribution of device characteristics is adequate, continuous columns of conventional dimensions are enough strong to avoid story collapse. Though when the dimensions of continuous columns are too small, story drift will concentrate on a few stories and there is a danger of story collapse.
2) In the case of elastic-perfectly plastic model, there is same inclination regardless of the input waveform, that is, under a small earthquake, the influence of stiffness distribution is relatively large, and SRSS strength distribution (determined by SRSS seismic coefficient) is effective in controlling the maximum bending moments of continuous columns, however under a big earthquake, the influence of strength distribution is relatively large, and UNIFORM strength distribution (determined by uniform seismic coefficient) is effective.
3) In the case of origin-oriented model, SRSS strength distribution is effective in controlling the maximum bending moments of continuous columns regardless of the intensity and the waveform of the input ground motion.

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