ROCKING-DELAYED SPINE SYSTEM FOR IMPROVING SEISMIC PERFORMANCE OF BUILDING STRUCTURES

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Abstract

Spine frame systems have been investigated which have the ability to prevent damage or deformation concentration as well as to reduce maximum seismic responses. There are generally two types of spine frames, one is non-uplifting spine frame, the other is uplift-allowed spine frame, i.e., rocking frame. Rocking frames are usually equipped with post-tensioning (PT) strands to ensure self-centering ability. However, the required post-tensioning force of PT strands and shear strength demand of spine frames might be uneconomically large. On the contrary, non-uplifting spine frame is not equipped with post-tensioned elements and the spine frame itself does not possess restoring ability for the first mode vibration. Therefore, the non-uplifting spine frames are usually used with moment frames which are designed to remain essentially elastic and provide sufficient restoring force against strong earthquakes. The non-uplifting spine frame system takes the risk of unexpected large deformation if plasticity develops over a certain level in the moment frames, particularly in the case of earthquakes that exceed the maximum considered intensity level in design codes.

In order to solve the problem, this study proposes a rocking-delayed spine system. This system is composed of moment frames, rocking-delayed spine frames, and energy dissipating devices. The rocking-delayed spine is connected to the foundation through a mechanically integrated pin and vertical-roller connection at its center base. At the initial state, a gap exists between the side column bases and the foundation. Energy dissipating devices are equipped at both side column bases. Within a small vibration, the spine frame sways about its center base, and exhibits similar energy dissipating effect as the controlled spine frame system proposed in previous studies. As the vibration amplitude increases, one of the side column bases contact the foundation and the center base uplifts, which provides additional restoring force for the whole system and enables to restrain the maximum deformation response.

Static hysteresis characteristic of the rocking-delayed spine and the necessary condition of eliminating residual deformation in the vertical direction are presented first. Furthermore, dynamic characteristics of full models including rocking-delayed spines and moment frames are investigated by time history analysis. Models with different initial gaps at side column bases of the spine frame are compared (including non-uplifting spine frames, rocking-delayed spine frames and rocking frame). Generally, the non-uplifting spine frame system tends to exhibit the smallest story shear in the braced frame, while the rocking frame system exhibits the smallest maximum story drift ratio. The proposed rocking-delayed spine system behaves as a trade-off between those two systems.

Besides, this study also investigated the effect of initial stress and axial stiffness of post-tensioning (PT) strands on seismic performance of the rocking-delayed spine system. Increasing axial stiffness of PT strands is not as effective as increasing initial stress on reducing residual deformation, whereas, increasing initial stress holds the story shear of spine frame at a high level as long as the column base uplifts during vibration.

Keywords: spine system, delayed rocking, deformation restraining, nonlinear dynamic analysis

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1. Introduction

Spine frame systems have been investigated which have the ability to prevent damage or deformation concentration as well as to reduce maximum seismic responses [1-8]. There are generally two types of spine frames, one is non-uplifting spine frame [1-4], the other is uplift-allowed spine frame, i.e., rocking frame [5-8]. Rocking frames are usually equipped with post-tensioning (PT) strands to ensure self-centering ability. However, the required post-tensioning force of PT strands and shear strength demand of spine frames might be uneconomically large. On the contrary, non-uplifting spine frame is not equipped with post-tensioned elements and the spine frame itself does not possess restoring ability for the first mode vibration. Therefore, the non-uplifting spine frames are usually used with moment frames which are designed to remain essentially elastic and provide sufficient restoring force against strong earthquakes. The non-uplifting spine frame system takes the risk of unexpected large deformation if plasticity develops over a certain level in the moment frames, particularly in the case of earthquakes that exceed the maximum considered intensity level in design codes.

This study proposes a rocking-delayed (uplift-delayed) spine system, which is expected to exhibit behaviors as a trade-off between the non-uplifting spine system and the rocking frame system. Nonlinear computational analyses are applied to investigate the behavior of the proposed system, and validate the expected performance objectives. Models with different initial gaps at side column bases of the spine frame are compared (including non-uplifting spine frames, rocking-delayed spine frames and rocking frame). Effects of different vertically restraining methods on seismic performance through using PT strands on seismic performance are investigated.

2. Description of the rocking-delayed spine system

The rocking-delayed spine system is a seismic lateral force resisting system that is able to dissipate energy during small vibration, and to restrain maximum deformation response of buildings during large vibration. Fig. 1 shows the proposed system, which is composed of moment frames, rocking-delayed spine frames, vertical post-tensioning (PT) strands and energy dissipating devices.

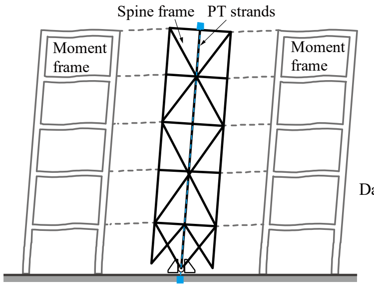
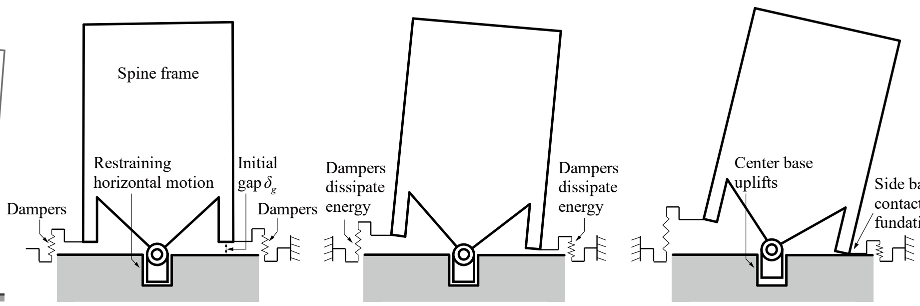


Fig. 1– Description of rocking -delayed spine system

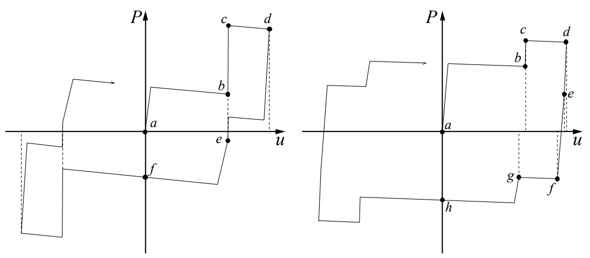


(a) Initial state (b) Small vibration (c) Large vibration

Fig. 2 – Typical vibration behaviors

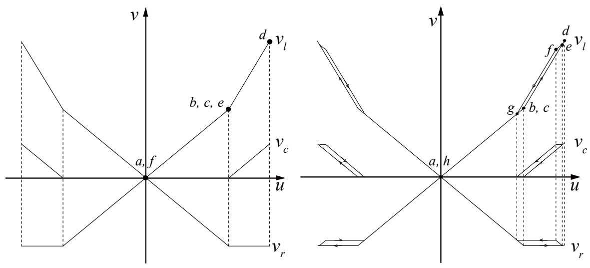
Fig. 2 shows the fundamental concept of the proposed system that behaves in a different manner for each vibration level. PT strands are omitted in Fig. 2. As shown in Fig. 2(a), one spine frame has three column bases. Two column bases are on the two sides and one column base at the center. At the initial state, a gap exists between the side column base and the foundation, while the center column base contacts the foundation. All of the three column bases permit uplift, and horizontal motion is restrained only at the center base. As shown in Fig. 2(b), during small vibration, the spine frame swing about the center base, meanwhile, dampers connected at the side bases dissipate energy. As shown in Fig. 2(c), during large vibration, one of the side column base contacts the foundation and the center base uplifts, which is expected to restrain the maximum horizontal vibration.

The idealized lateral force P – lateral displacement u relation at the top of the rocking-delayed spine frame is shown in Fig. 3. The vertical displacements at the left column base v_l, center column base v_c and right column base v_r versus lateral top displacement u are shown in Fig. 4. In Fig. 3 and Fig. 4, F_v is the total vertical load added on the spine frame. F_{dy} is the vertical yield strength of dampers at each side column base.



(a) $F_v > 2F_{dy}$ (b) $F_v \le 2F_{dy}$

Fig. 3 – Lateral force-displacement behavior



(a) $F_v > 2F_{dy}$ (b) $F_v \le 2F_{dy}$

Fig. 4 – Lateral displacement versus vertical displacement

Global uplift, which means the spine frame lifts vertically off the foundation, should be avoided by satisfying conditions described by Eq. (1) or Eq. (2).

$$F_v > 2F_{dy} \tag{1}$$

$$F_v \le 2F_{dy} \text{ and } \delta_g > \delta_{dy} - \frac{F_v}{2k_d} \tag{2}$$

where, δ_g is the initial gap at column bases. k_d is the vertical stiffness of dampers at each side column base.

3. Prototype building model and computational modelling

3.1 Prototype building model and analysis parameters

A five-story prototype steel frame model was designed to represent the rocking-delayed spine system, as shown in Fig. 5. Beams and columns of the moment frames consist of typical steel wide flange sections and hollow sections. Members of the spine frame have a cross sectional area of 70680 mm^2, which remains elastic and works as a relatively rigid vertical spine. Elastic-plastic dampers are equipped between the side column bases and the foundation. The vertical yield strength of dampers at each side column base is 600 kN, and the vertical yield deformation is 0.73 mm. Initial axial force and axial stiffness of PT strands as well as the gap at side column bases are the main parameters discussed in this study, as summarized in Table 1. Total weight of the building model is 9555 kN, and the self-weight of spine frame is 2205 kN. The fundamental natural period of the prototype model excluding damper stiffness is 0.709 sec.

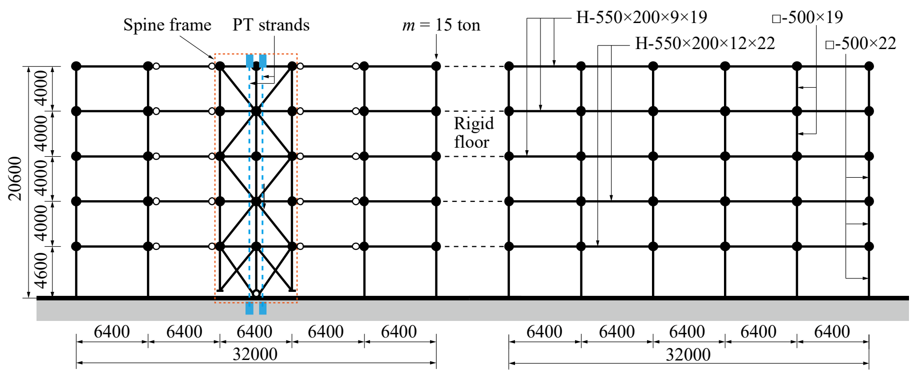


Fig. 5 – Geometry and design information of the prototype building model

Table 1 – Analysis model parameter matrix

Model ID	PT strands					Initial gap δ_g at side column bases (mm)
	Length (mm)	Cross sectional area (mm^2)	Initial axial stress (N/mm^2)	Initial axial force (kN)	Axial stiffness (kN/mm)	
R0g1 ~ R0g64	0	0	0	0	0	1 ~ 64
A1g1 ~ A1g64	8600	6680	0	0	159	1 ~ 64
A2g1 ~ A2g64	8600	13360	0	0	318	1 ~ 64
A3g1 ~ A3g64	8600	20040	0	0	477	1 ~ 64
S1g1 ~ S1g64	20600	16000	317	5072	159	1 ~ 64
S2g1 ~ S2g64	20600	16000	634	10144	159	1 ~ 64
S3g1 ~ S3g64	20600	16000	951	15216	159	1 ~ 64

3.2 Computational modelling

Two-dimensional nonlinear analysis models were created using the OpenSees software ver. 2.5.0 [9]. The beams and columns in the moment frames, and members in the spine frames were modeled using nonlinear beam-column elements. The PT strands were modeled using truss element. Fig 6 shows details in column base modelling. At the column bases, gap elements oriented in the vertical direction were adopted. The gap elements are near rigid in compression while have zero stiffness in tension. The initial gap was 0 mm for center column base. As for side column bases, 1, 2, 4, 6, 8, 16, 32, and 64 mm was set to the initial gap. Fig. 7 and Fig. 8 shows the base shear – first-story story drift ratio (SDR) relations of models with an initial gap of 32 mm, which were obtained from pushover static analysis.

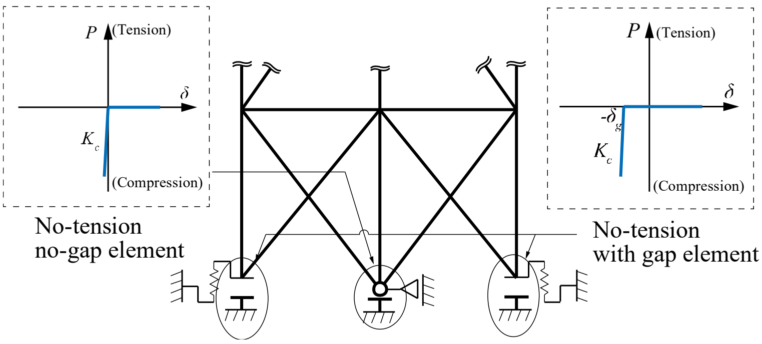


Fig. 6 – Boundary element details in computational modelling

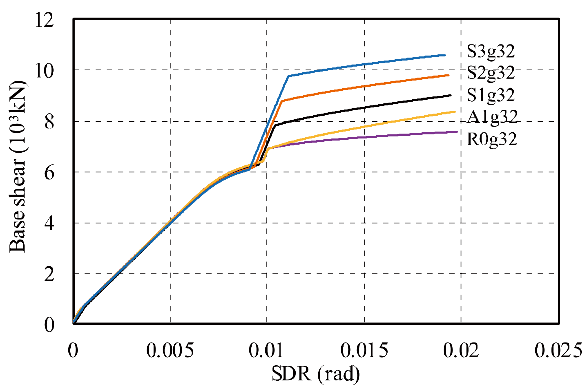


Fig. 7 – Base shear-first story drift ratio behavior of models with different PT strands initial stress

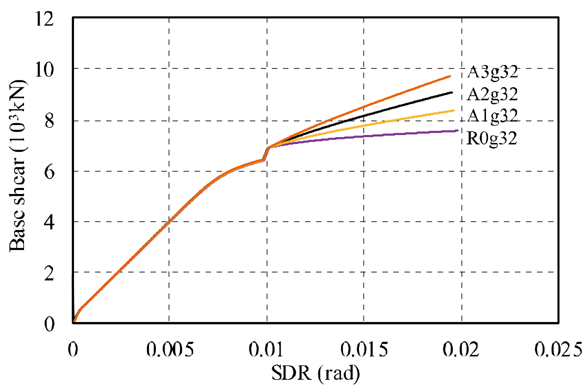
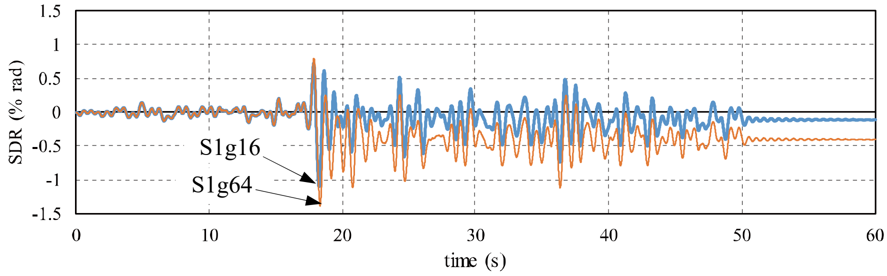


Fig. 8 – Base shear-first story drift ratio behavior of models with different PT strands stiffness

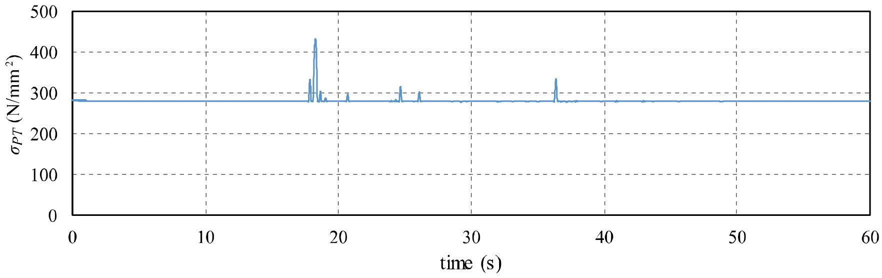
4. Dynamic analysis results

4.1 Story drift ratio and axial stress of PT strands

Hachinohe NS (1968) is used as the input ground motion, in which the response acceleration spectrum was scaled to follow the life-safety limit state design spectrum in Japan. Maximum and residual SDRs of S1g16, as shown in Fig 9(a), is smaller than those of S1g64. Fig 9(b) shows that the PT strands axial stress increases rapidly from around 300 N/mm^2 to more than 400 N/mm^2 when SDR exceeds approximately 0.5% rad, which efficiently reduces the maximum SDR. Similar behaviors are observed in A2-series models [Fig. 10(a)]. In model A2g16, the PT strands axial stress increases from around 0 to more than 400 N/mm^2 [Fig. 10(b)] when SDR exceeds approximately 0.5% rad.

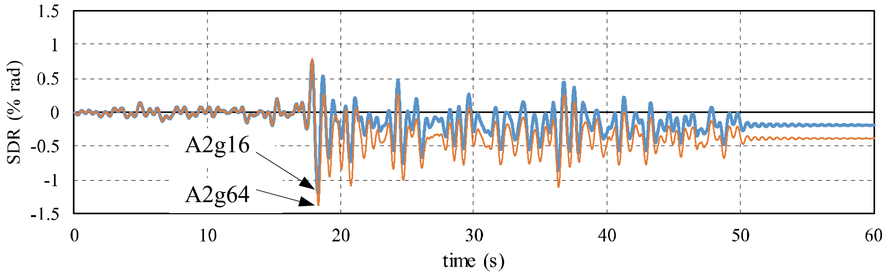


(a) First-story story drift ratio (Model S1g16 & S1g64)

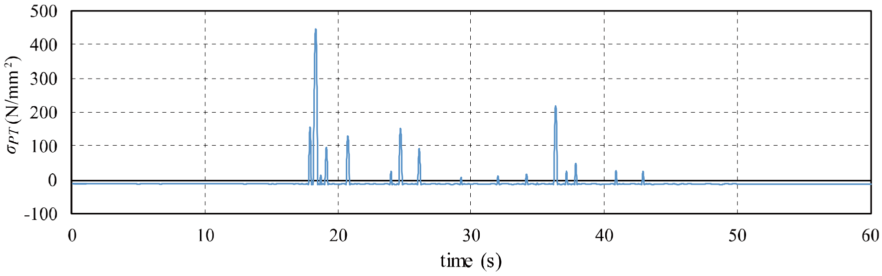


(b) Axial stress of PT strands (Model S1g16)

Fig. 9 – Time-history results samples of S1-series models



(a) First-story story drift ratio (Model A2g16 & A2g64)

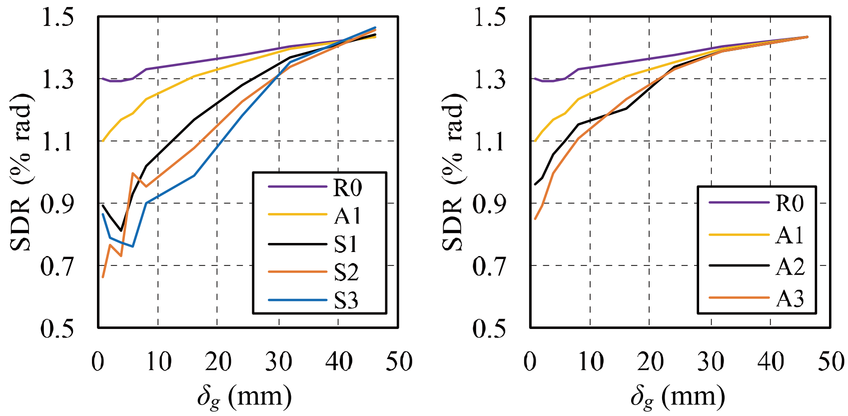


(b) Axial stress of PT strands (Model A2g16)

Fig. 10 – Time-history results samples of A2-series models

4.2 Maximum story drift ratio

Fig. 11(a) and (b) show the maximum story drift ratio of S-series models and A-series models. In both model series, models with larger initial gap δ_g at side column bases generally exhibit larger story drift ratio. Increasing initial stress or axial stiffness of the PT strands improves the deformation restraining ability.

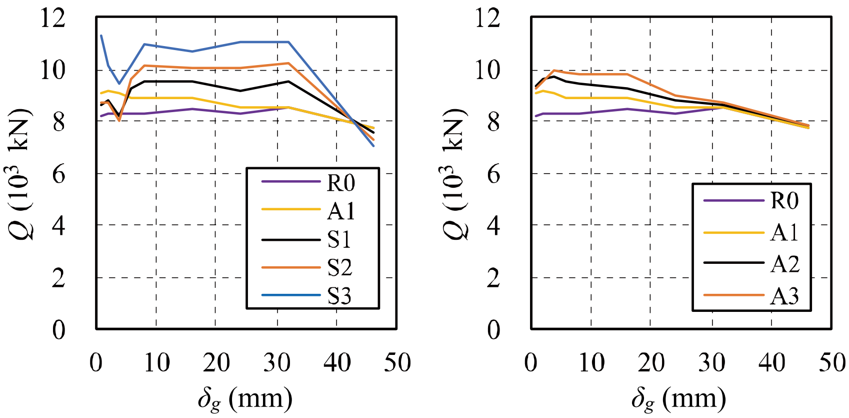


(a) S-series models (b) A-series models

Fig. 11 – Maximum story drift ratio

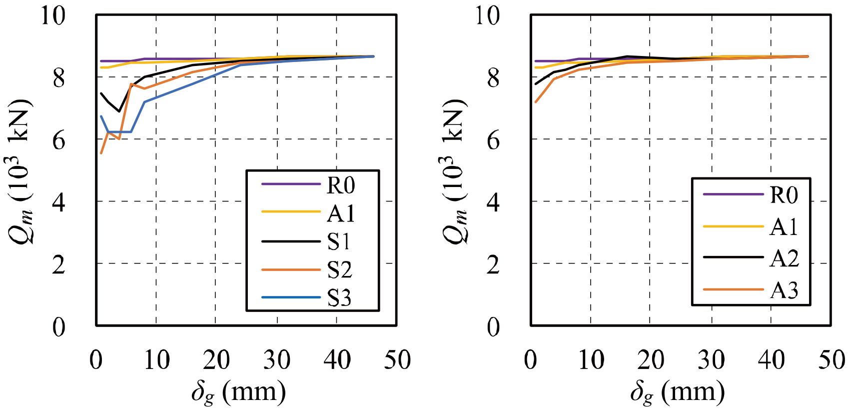
4.3 Maximum shear force

Shown in Fig. 12(a) and (b) are the maximum base shear of S-series models and A-series models. In S-series models, base shear tends to be constant when the initial gap δ_g is smaller than 32 mm. On the contrary, in A-series models, base shear decreases as the initial gap increases. Fig. 13(a) and (b) demonstrates that maximum story shear of moment frames increases as the initial gap varies from 1 mm to 24 mm. Compared to S-series models, story shear of moment frames in A-series models is relatively less sensitive to the initial gap. Shown in Fig. 14(a) and (b) are the maximum story shear of spine frames in S-series models and A-series models. Similar with the base shear results, in S-series models, maximum story shear of spine frames is almost constant when the initial gap δ_g is smaller than 32 mm. On the contrary, in A-series models, increasing initial gap could reduce story shear of spine frames.



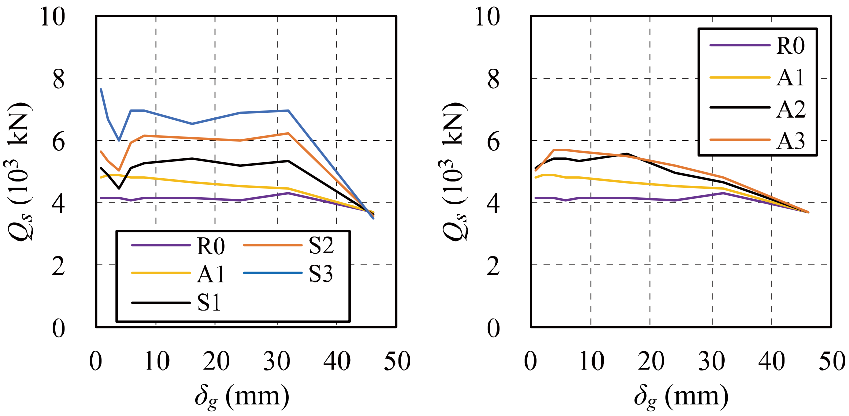
(a) S-series models (b) A-series models

Fig. 12 – Maximum base shear of the whole frame



(a) S-series models (b) A-series models

Fig. 13 – Maximum story shear of moment frames

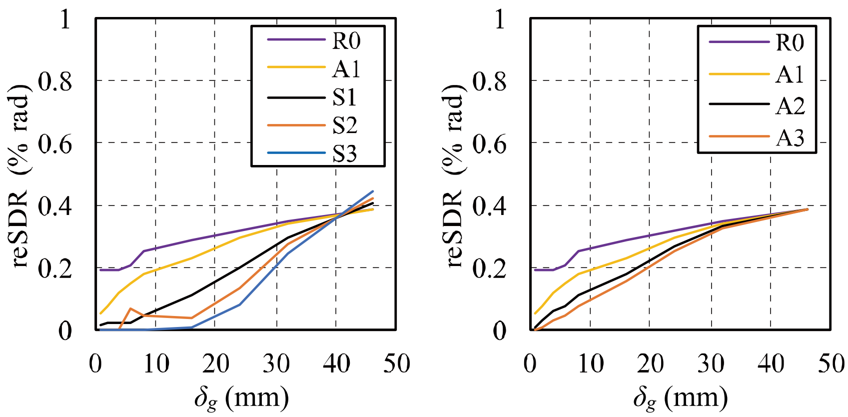


(a) S-series models (b) A-series models

Fig. 14 – Maximum story shear of the spine frame

4.4 Residual story drift ratio

Fig. 15 (a) and (b) shows the maximum residual story drift ratio of S-series and A-series models. Residual deformation of S-2 and S-3 models is close to 0 when the initial gap is less than 16 mm. As for the other models, residual deformation increases with the initial gap increasing.



(a) S-series models (b) A-series models

Fig. 15 – Residual story drift ratio

5. Conclusions

This study proposed a rocking-delayed spine frame system that introduces initial gap at side column bases of spine frames. Seismic performance of the proposed system was investigated through nonlinear time-history analysis. The analysis results revealed the influence of initial gap at column base, initial stress and axial stiffness of PT strands on maximum and residual seismic responses.

Acknowledgements

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References

[1] Qu Z, Wada A, Motoyui S, Sakata H, Kishiki S (2012): Pin-supported walls for enhancing the seismic performance of building structures. *Earthquake Engineering and Structural Dynamics*. 41:2075-2091.

[2] Takeuchi T, Chen X, Matsui R (2015): Seismic performance of controlled spine frames with energy-dissipating members. *Journal of Constructional Steel Research*. 114:51-65. DOI: 10.1016/j,jcsr.2015.07.002.

[3] Chen X, Takeuchi T, Matsui R (2018): Seismic performance and evaluation of controlled spine frames applied in high-rise buildings. *Earthquake Spectra*. 34(3): 1431-1458.

[4] Lai J, Mahin S (2015): Strongback system: A way to reduce damage concentration in steel-braced frames. *Journal of Structural Engineering, ASCE*. 141(9):04014223.

[5] Midorikawa M, Takeuchi T, Hikino T, Kasai K, Deierlein G, Ohbayashi M, Yamazaki R, Kishiki S (2010): Seismic performance of controlled rocking frames with shear fuse and PT wire anchorage - Shaking table tests on controlled rocking steel frames using multipurpose inertial mass system: Part 1 -. *Journal of Structural and Construction Engineering (Transactions of AIJ)*. 75(654): 1547-1556. DOI: 10.3130/aijs.75.1547. (in Japanese)

[6] Takeuchi T, Yamamoto Y, Midorikawa M, Kasai K, Hajjar JF, Hikino T, Matsui R, Kishiki S (2011): Response prediction of controlled rocking frame using buckling restrained brace - Shaking table tests on controlled rocking steel frames using multipurpose inertial mass system: Part 2 -. *Journal of Structural and Construction Engineering (Transactions of AIJ)*. 76(667): 1695-1704. DOI: 10.3130/aijs.76.1695. (in Japanese)

[7] Eatherton MR, Ma X, Krawinkler H, Deierlein GG, Hajjar JF (2014): Quasi-static cyclic behaviour of controlled rocking steel frames. *Journal of Structural Engineering, ASCE*. DOI: 10.1061/(ASCE)ST.1943-541X.0001005.

[8] Eatherton MR, Ma X, Krawinkler H, Mar D, Billington S, Hajjar JF and Deierlein GG (2014): Design concepts for controlled rocking of self-centering steel-braced frames. *Journal of Structural Engineering, ASCE*. DOI: 10.1061/(ASCE)ST.1943-541X.0001047.

[9] Open system for earthquake engineering simulation (OpenSees). Available from: http://opensees.berkeley.edu/ (last accessed Jan 2020)

