Strengthening of weak story moment frames using a rocking system with tendons

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ABSTRACT :

This paper proposes a rocking system to limit the residual deformation of moment-resisting frames in order to improve the immediate occupancy performance and reduce the rehabilitation cost. The system consists of a rocking column and a set of tendons to provide the existing frame with extra stiffness in the entire range of deformation, which provides the existing frame a re-centering capability and a limited level of residual deformation. In this study, a parametric study is conducted with a series of time-history analyses. The stiffness of the rocking column and the stiffness and position of the tendons are taken as the major parameters. It is observed that the rocking column, with a stiffness of about 1.0 times that of the weak story, and the tendons attached at the roof, with a stiffness of 0.05 times that of the weak story, are able to provide the optimal performance with a maximum residual story drift angle of 0.5%, the practical tolerance for occupancy. In the implemented substructure online hybrid test, the existing frame is to be simulated numerically and the rocking system tested physically. The experimental results show that the maximum residual story drift angle never exceeds 0.5%, demonstrating the feasibility of the proposed rocking system.

KEYWORDS: Rocking system, Re-centering, Residual deformation, Weak story

1. INTRODUCTION

With the development of performance-based earthquake engineering, the residual deformation after earthquakes has gradually become a focus for researchers, because it is directly related to the immediate occupancy function of buildings and the repair cost associated with the structural and nonstructural components. Around 2003, a performance-based design procedure was proposed, which takes a joint maximum deformation and residual deformation matrix to define the performance objectives (Christopoulos 2004). Tentative values for the limit states based on residual deformation are taken as 0.2%, 0.4%, 0.6%, and 1.0%, for “Serviceability”, “Repairable damage”, “Irreparable damage”, and “Collapse prevention” performance levels, respectively. More recently, a study was conducted in Japan to evaluate the permissible residual deformation in light of the occupancy, constructivity, and safety of buildings (Aburano 2008). The permissible residual tolerance is given as 0.5%, based on the review of construction tolerance for various building types, psychological investigations with respect to uneasiness when standing on an inclined floor, and a physical inspection of an occupied building.

In order to reduce the residual deformation, and thus to improve the performance of buildings, many structural systems are developed. Some researchers focus on the improvement of the beam-to-column connections and the column bases of moment-resisting frames (Ricles 2001; Ikenaga 2007). These developed systems adopted post-tensioned strands to provide the re-centering force, and were often supplemented with hysteretic dampers for the energy dissipation. As an effective means to mitigate seismic hazards, several dampers with self-centering capability were developed in the past twenty years, such as the friction spring seismic damper (Filiatrault 2000) and the damper that employs a shape memory alloy (DesRoches 2002). Recently, systems based on rocking mechanisms were proposed and tested. During an earthquake, the structure is allowed some rocking on the supporting surface. The re-centering behavior is realized by the gravity of the structure (Pollino 2004). The re-centering capability of all of the above systems is based on a flag-shaped hysteresis, which is commonly realized by combining a linear elastic element with hysteretic energy-dissipating components.

Past studies indicate that the second (yielding) stiffness is a major factor influencing the residual deformation of a building (MacRae 1997). MacRae et al. studied the relationship between the residual deformation and the second stiffness ratio as well as the maximum deformation by a series of time history analyses. They found that the residual deformation was significantly reduced if a positive second stiffness greater than 10% of the initial stiffness was adopted. Accordingly, an alternative to the mechanism with flag-shaped hysteresis is to provide the structure with a certain second stiffness in the overall range of deformation under earthquakes.

In Japan, there are many low-rise steel buildings that were designed before 1981 when the Building Standard Law (BCJ 1981) was significantly revised. The strength of these buildings may not be enough to resist a contemporary large earthquake demand. Moreover, they commonly have weak column bases which would results in a weak first story during earthquakes. In this study, a rocking system is proposed to retrofit such buildings. A rocking column pinned to the ground is used to strengthen the first story, and a set of tendons are employed to provide the entire system with an additional stiffness and a re-centering capability. The rocking system is kept elastic during earthquakes to give the existing structure with a certain second stiffness. A parametric study is conducted with the stiffness of the rocking column, using the stiffness and position of the tendons as the parameters. A series of time history analyses are carried out to determine the optimal seismic performance of the entire system. The substructure online hybrid test is also implemented to verify the feasibility and validity of the proposed rocking system.

2. CONCEPT OF THE ROCKING SYSTEM

The proposed rocking system consists of two parts, i.e., the rocking column and a set of tendons, as shown in Fig.1 (a). The rocking column is pinned to the ground and linked to the existing frame at each story level. The tendon is connected to the rocking column at one end, and to the ground at the other end. They are designed with enough flexibility to remain elastic even when sustaining very rare earthquakes. The rocking system provides an extra stiffness. The mechanism can be explained by the simplified model shown in Fig.1 (b), where a two-story shear type building is taken as the existing structure with the story stiffness of k_1 and k_2; the rocking column has a uniform section along the height, the flexible stiffness denoted as EI; the tendon is simplified as a spring attached at the roof with a stiffness of k_t. Supposing the story height to be $h_1 = h_2 = h$, the force-displacement relationships for the existing frame, rocking column, and the tendon can be formulated as Eqn.2.1:

$$\begin{Bmatrix} F_1^e \\ F_2^e \end{Bmatrix} = \begin{bmatrix} k_1 + k_2 & -k_2 \\ -k_2 & k_2 \end{bmatrix} \begin{Bmatrix} \delta_1 \\ \delta_2 \end{Bmatrix}, \quad \begin{Bmatrix} F_1^r \\ F_2^r \end{Bmatrix} = \begin{bmatrix} \dfrac{6EI}{h^3} & -\dfrac{3EI}{h^3} \\ -\dfrac{3EI}{h^3} & \dfrac{3EI}{2h^3} \end{bmatrix} \begin{Bmatrix} \delta_1 \\ \delta_2 \end{Bmatrix}, \quad \begin{Bmatrix} F_1^r \\ F_2^r \end{Bmatrix} = \begin{bmatrix} \dfrac{6EI}{h^3} & -\dfrac{3EI}{h^3} \\ -\dfrac{3EI}{h^3} & \dfrac{3EI}{2h^3} \end{bmatrix} \begin{Bmatrix} \delta_1 \\ \delta_2 \end{Bmatrix} \tag{2.1}$$

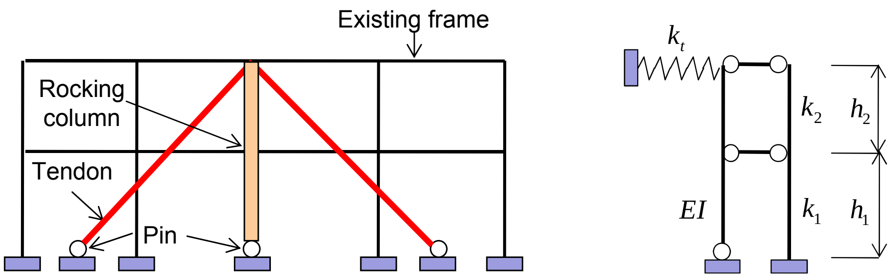
where F^e, F^r, and F^t represent the restoring force provided by the existing frame, the rocking column, and the tendon, respectively; δ is the story displacement. Then the total restoring force, F, can be formulated as the sum of the restoring forces of the three parts, as Eqn.2.2:

$$\begin{Bmatrix} F_1 \\ F_2 \end{Bmatrix} = \begin{bmatrix} k_1 + k_2 + \dfrac{6EI}{h^3} & -k_2 - \dfrac{3EI}{h^3} \\ -k_2 - \dfrac{3EI}{h^3} & k_2 + \dfrac{3EI}{2h^3} + k_t \end{bmatrix} \begin{Bmatrix} \delta_1 \\ \delta_2 \end{Bmatrix} \tag{2.2}$$

Next, the relationship between the base shear force and the roof displacement is examined, giving an indication of the overall stiffness of the entire system. Supposing $F_1 = 0$, the base shear force equals F_2, given as Eqn.2.3:

$$\frac{F_2}{\delta_2} = \frac{(k_1 + k_2)(\frac{3EI}{2h^3} + k_t) + \frac{6EI}{h^3}k_t + k_1 k_2}{k_1 + k_2 + \frac{6EI}{h^3}} \tag{2.3}$$

Now, the overall stiffness is examined using a specific case with $k_1 = k_2 = k$ and $12EI/h^3 = k_r$. The overall stiffness is $k_t + k/2$, meaning that the rocking column does not contribute to the system. Once the first story yields, having $k_1 = 0$, the rocking column works and the overall stiffness is $kk_r/(8k + 4k_r) + k_t$. The loading continues until the second story yields, giving the overall stiffness as k_t, which represents the yield stiffness of the overall system. The above derivation indicates that the tendon works as the major member to provide the second stiffness, and thus the re-centering capability, while the rocking column cannot contribute to the re-centering capability particularly in a larger deformation.



(a) Configuration (b) Simplified model

Figure 1 Proposed rocking system

3. PARAMETRIC STUDY

To explore the effect of the rocking column on the residual deformation of the existing building, a parametric study was conducted through a series of time history analyses. The stiffness of the rocking column, and the stiffness and position of the tendons are taken as the major parameters.

3.1. Design of existing building

Table 3.1 Story parameters of designed structures

Story	Beam		Column	
	Strength (kNm)	Stiffness (kNm/rad)	Strength (kNm)	Stiffness (kNm/rad)
4	685	156,637	2,147	327,135
3	1,738	397,269	2,147	327,135
2	2,383	544,901	2,147	327,135
1	2,862	654,269	438	327,135

A four-story four-bay steel moment-resisting frame is designed following a typical Japanese seismic design procedure (BCJ 1997). Each story height is 3.5 m, and each bay has a span of 5.0 m. The gravities are 600 kN and 700kN for the first three stories and the roof, respectively. The seismic force reduction factor is selected as 0.35, a typical value for Japanese design practice. When sustaining Level 1 design earthquakes, the drift of each story is less than 0.5%. The strength of columns is 1.5 times that of the beams connected at the same joint, while the stiffness ratio between columns and beams at the same joint is 1.0. Then a uniform column using the first-story column section is set for all stories. Finally, a weak story is intentionally defined at the first story by reducing the first story strength to 0.1 of the total weight. This structure represents the most critical buildings without any seismic design consideration. The story parameters are listed in Table 3.1.

3.2. Definition of parameters

The stiffness of the rocking column and the stiffness and position of the tendons are taken as the parameters. The lateral stiffness of the first story of the existing structure is used as the reference, expressed as $k_1^e = 12EI_c / h^3$, where I_c is the sum of the moment of inertia of all columns at the first story. The lateral stiffness of the rocking column is defined as $k_1^r = 12EI_r / h^3 = \alpha_r k_1^e$, and the stiffness of tendon is given as $k_t = \alpha_t k_1^e$. In this study, the considered α_r ranges from 0.1 to 2, while α_t ranges from 0.1 to 0.2. The selection of these parameters depends on the manufacturability of steel members. Four positions of the tendon, located at each story level, are considered.

3.3. Numerical modeling

A generic model (Nakashima 2002) is used to model the existing frame, in which the beams at one story are simplified as one elastic-plastic spring, and the columns in one story are condensed into one beam element with distributed perfect plasticity. The strength and stiffness parameters listed in Table 3.1 are employed for the model. The story mass and gravity are imposed at the nodes located at each story level. The rocking column is simulated by beam elements elastically, while the tendons are simulated as one elastic spring having both tension and compression behavior. For dynamic analysis, a damping of 2% of the critical damping is used for all models. Each model is constructed by the software application called Open System for Earthquake Engineering Simulation (OpenSEES) developed by Pacific Earthquake Engineering Research Center (Mazzoni 2006). A situation under collapse level of earthquakes is considered. Twenty ground motions are adopted, which are developed by the FEMA/SAC project with an exceedance probability of 2% in 50 years (Someville 1997), denoted as BSE2. Another ground motion recorded at JR Takatori station during the 1995 Hyogoken-Nanbu earthquake is also adopted to represent the largest earthquake considered in Japanese seismic design. Each ground motion is appended by 10 s free vibration to lead the structure to the resting position.

3.4. Results of parametric studies

3.4.1 Position of tendon

The position of the tendon was first examined. The set of ground motions in BSE2 were adopted. The contour line of the maximum residual story drift angle of 0.5% with 84% probability were plotted in Fig.2 with respect to α_t and α_r .

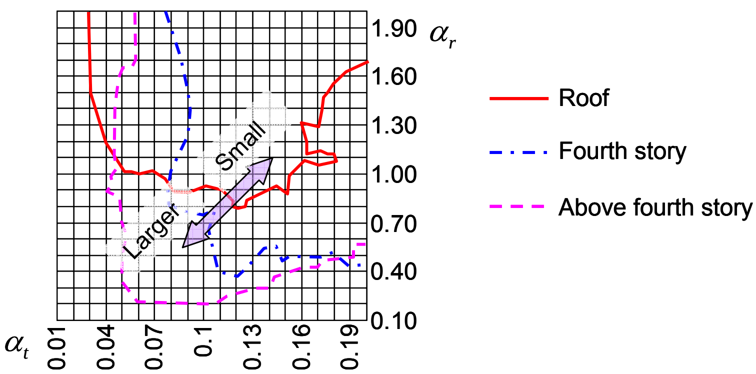
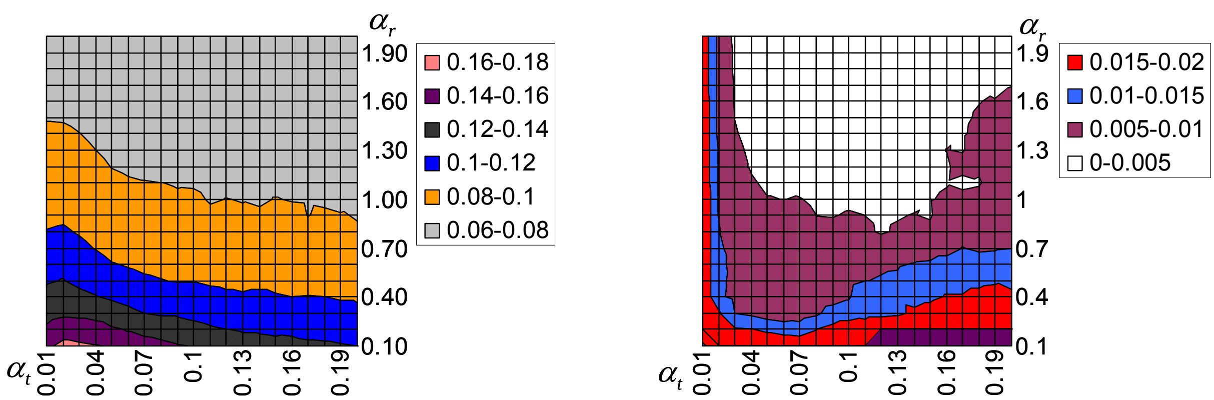


Figure 2 Contour of maximum residual story drift with respect to tendon position

Four positions were considered, located at each story level. The results indicate that the tendon at the roof or the fourth story level is able to reduce the residue deformation to 0.5%, while the tendons at the other story levels cannot. The optimal position of the tendon is at one third of the story height above the fourth level, shown as the dashed line in Fig.2. However, the connection to such a point is constructively infeasible. The performance of the rocking system can be basically classified into two regions, i.e., the tendon-sensitive region where the tendon stiffness ratio is less than 0.1, and the rocking column-sensitivity region where the tendon stiffness ratio is larger than 0.1. In the tendon-sensitivity region, the cases with the tendon at the roof need a smaller tendon than those with the tendon at the fourth level to achieve the same residual drift. While in the rocking column-sensitivity region, a larger rocking column is needed for the cases with the tendon at the roof than those with the tendon at the fourth floor. And the cases with the tendon at the roof show a dependency on the tendon stiffness even in the rocking column-sensitivity region. The cases with the tendon at the roof are selected for the following study, considering its ease of construction.

3.4.2 Discussion of the effectiveness of rocking system

The cases with the tendon at the roof are further discussed here to examine the effectiveness of the rocking system. The maximum story drift angle and maximum residual story drift angle with 84% probability are plotted in Fig.3. The maximum story drift angle is not as sensitive to the stiffness of the tendon as on the stiffness of the rocking column. With a rocking column stiffness ratio larger than 1.0, the maximum story drift angle is limited under 8%. If a tendon stiffness ratio ranging from 0.03 to 0.16 is adopted, the residual story drift angle will be less than 0.5%. When a tendon stiffness ratio larger than 0.16 or less than 0.03 is adopted, the residual story drift angle of 0.5% cannot be achieved. A smaller tendon stiffness is not able to provide enough second stiffness for the entire system, while a larger tendon stiffness leads to significant plastification in the upper stories, which is not recoverable due to its larger strength than the first weak story. The smaller stiffness ratio of the rocking column results in larger maximum story drift ratio, which is larger than 8% when the rocking column stiffness ratio is less than 1.0. In this range, the residual story drift angle is always larger than 0.5%.



(a) Maximum story drift angle (b) Maximum residual story drift angle

Figure 3 Responses of models with tendon at roof under BSE2 (84% exceedance probability)

3.4.3 Ground motion dependency

Shown in Fig.4 are the contour lines representing 0.5% residual story drift angle for BSE2 and JR Takatori ground motions. Comparing 84% contour lines, it can be observed that the rocking system performance is quite different between BSE2 and JR Takatori ground motions, particularly for models with larger tendon stiffness. The ground motions in BSE2 also result in significant deviation as the deviation curve is almost identical with the mean curve, as shown in Fig.4. Therefore, the residual deformation of the proposed rocking system significantly depends on the ground motions.

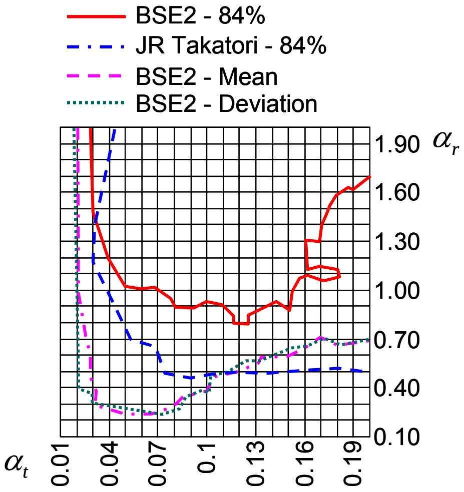


Figure 4 Responses to different ground motions

4. ONLINE HYBRID TEST

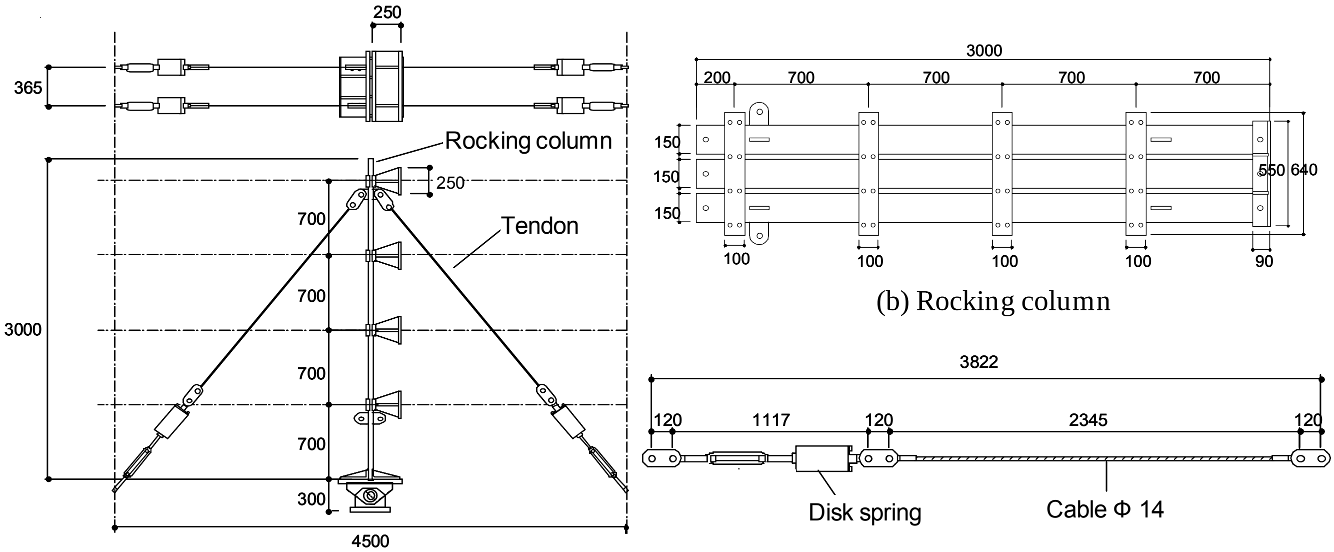
4.1. Design of the specimen

To demonstrate the validity of the proposed rocking system, online hybrid tests were conducted. According to the responses to both the BSE2 and the JR Takatori ground motions, as shown in Fig.4, it is observed that if a tendon stiffness ratio ranges from 0.05 and 0.16, and the rocking column stiffness ratio is larger than 1.0, the residual performance target, 0.5%, will be achieved. The design of the specimen is thus based on the two stiffness ratios of 0.05 and 1.0 for the tendon and the rocking column, respectively. A scaled model of 1:5 to the prototype was designed as shown in Fig.5 (a). The specimen consists of one rocking column and four tendons. The rocking column has a flat section to achieve a large flexibility and to keep elastic. The thickness is 32 mm, and the width is 450 mm. It is divided into three pieces for easy manufacturing, as shown in Fig.5 (b). Four tendons are connected to the top end of the rocking column. Each tendon consists of one set of disk spring and a cable with a diameter of 14 mm, arranged in series, as shown in Fig.5 (c). The disk spring is adopted to achieve a larger flexibility. Two pieces on one side combine to provide a tendon stiffness ratio of 0.05 when under tension. To reduce the releasing induced nonlinearity, the tendons are pre-tensioned when being installed, so that the initial tendon stiffness ratio shall be 0.1 and switch to 0.05 when the pretension in one side disappears.

4.2. Substructure online hybrid test

A substructure online hybrid test was conducted using the JR Takatori ground motion. The first 15 s record having the largest pulse component was adopted and another five-second free vibration was appended. The online hybrid test adopted a separated model framework (Wang 2006), in which the simple dynamics are solved by a homemade application, while the force-displacement relationships are obtained from the tested rocking system and the numerically simulated existing frame, as shown in Fig.6. The existing frame is simulated by a generic model constructed by OpenSEES, and the story parameters are listed in Table 3.1. The tested rocking system is loaded quasi-statically by four identical hydraulic jacks. The controllers for these jacks are well adjusted to move each story synchronously.

The displacement history of the first story obtained from the test is plotted in Fig.7 and compared with that of the existing frame only. It can be observed that (1) the maximum story drift angles of both systems (with or without rocking system) are quite similar, 0.123 rad and 0.116 rad, respectively; (2) the residual story drift angle of the enhanced system is significantly lower than that without enhancement, 0.007 rad compared with 0.06 rad; and (3) the phase moves forward for the case with the rocking system due to the introduced extra stiffness.



(a) Scaled specimen (c) Tendon

Figure 5 Specimen for online hybrid test

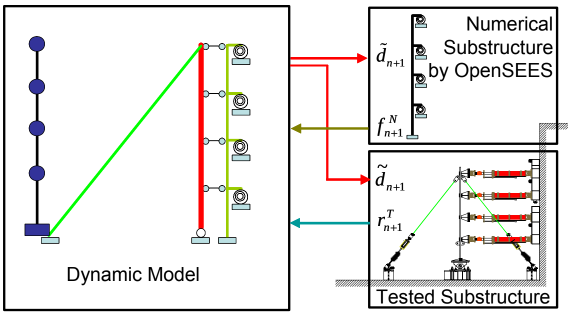


Figure 6 Substructure online hybrid test scheme

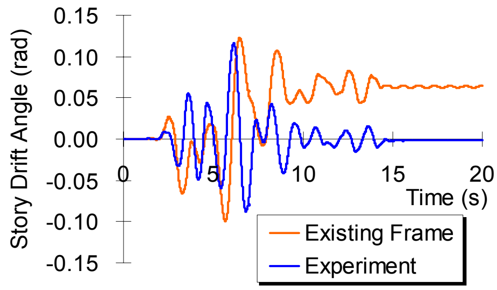


Figure 7 Online hybrid test results

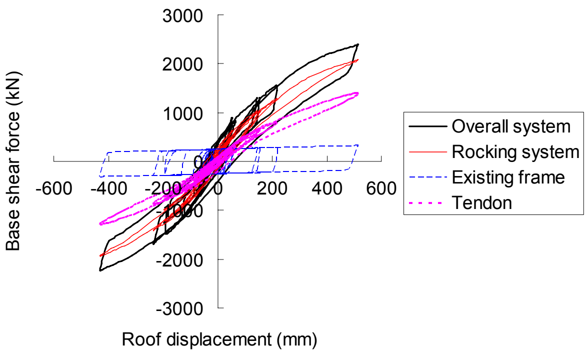


Figure 8 Hysteresis of the overall system

Figure 8 shows the relationship between base shear force and roof displacement. It indicates that the rocking system provides a large portion of stiffness after the existing structure yields at the first story. The first stiffness of the overall system is about 20.2 kN/mm, and the yielding stiffness is about 4.2 kN/mm, which is provided by the rocking system. In the rocking system, the tendon contributes two thirds of the rocking system restoring force, and the rest is contributed by the rocking column. It behaves as a bilinear hysteresis due to the pre-tension in the tendons. It also dissipates some energy because of the friction existing in the disk spring. However, the force in the tendon is so large that a special connection is required.

5. SUMMARY

A novel rocking system is proposed in this study which is capable of mitigating the residual deformation of existing buildings with weak stories. Through parametric study, it is found that the rocking system with the tendon at the roof has good performance and constructability. The system is sensitive to the ground motions. For the specific existing frame, a rocking system with the tendon stiffness ratio ranging from 0.05 to 0.16, and the rocking column stiffness ratio of 1.0 provides an optimal performance, which has been demonstrated by a substructure online hybrid test. This is a preliminary study for concept examination. A further study is underway for the connection design of the rocking system to the existing frame as well as to the ground. It would also be appealing to introduce nonlinearity into the rocking system to reduce the connection forces.

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