This paper investigates experimentally the seismic performance of a self-centering frame system with rocking behavior. The frame system consists of a three-story one-bay self-centering rocking frame and a three-story one-bay steel moment resisting frame (MRF). The beam-ends of the MRF are directly connected to the column of self-centering rocking frame at each floor level through energy dissipating structural fuses. The columns of the self-centering rocking frame are concrete-filled double-skin steel tubular (CFDST) members equipped with pre-stressed concrete (PC) steel bars inside the inner steel tube. The CFDSTs can detach from the footing (steel basement beam) experiencing a rocking behavior. Under lateral forces, one column uplifts, while the other column rotates and transmits the lateral force to the footing. A frame specimen was tested under quasi-static cyclic loading with increasing amplitudes up to a 4.0% frame rotation angle. The observed hysteretic loop of the test specimen was characterized by a flag-shaped behavior. The residual deformation of the specimen was effectively limited even after the specimen experiences significant inelastic deformation. Finally, simple expressions to estimate the main response quantities of the proposed self-centering rocking frame system are provided.

Keywords: Self-centering; Rocking; Uplift; Residual deformation; Hysteretic behavior

1. INTRODUCTION

Mega-earthquakes that drive the structures to exceed the design performance levels specified in current design standards, such as the 1995 Hyogo-ken Nanbu Earthquake in Japan, have occurred throughout the world. To achieve quick recovery and continuous operation in building structures after such mega-earthquakes, important research is carried out nowadays for controlling the damage of the main structural members and reducing residual deformations of entire structure. Damages should be easily and economically repaired after earthquakes. Currently, many structural systems have been proposed wherein the majority of damage can be concentrated in replaceable or repairable structural elements (Ji et al. 2017) while the main structure remains elastic, thus force the structure to re-center, or it is allowed for minor inelastic deformation (for example, Mansour et al. 2011; MacRae and Heristchian 2017).

Among proposed structural systems, of great interest are self-centering systems. Their re-centering behavior mitigates residual drifts and damage can be concentrated in replaceable and ductile fuse elements. Self-centering structural systems could be divided into two categories: (1) those systems where a pretension force applies to individual components, keeping thus their damage in low levels (Ikenaga et al 2006; Erochko et al. 2015); and (2) those systems where a highly elastic mechanism with re-centering behavior runs along the height of building to reduce overall residual deformation (Wiebe and Christopoulos 2009; Eatherton and Hajjar 2014; Dowden et al. 2016). Systems that fall into the latter category can allow for an uplifting behavior of the column bases under the seismic force. Thus, the self-centering frame experiences a controlled-rocking behavior. The previous studies showed that the main features in the design of self-centering rocking frame systems are: (a) the design of a strong and stiff vertical spine with rocking behavior which remains elastic to sustain the large restoring forces derived from the self-centering mechanism and self-weight loads, and (b) the use of ductile energy...
dissipating devices in order to absorb large amount of seismic energy in strong seismic events. Energy dissipation in multiple locations is advantageous.

This paper proposes a braced frame with concrete-filled steel tubular columns and steel beams to serve as the vertical spine connected to a steel moment resisting frame. The uniform distribution of the hysteretic energy over the structure height is achieved by placing energy dissipating devices at multiple locations. To enhance the energy dissipation capacity, energy dissipating structural fuses made of low-yield point steel are utilized.

2. EXPERIMENTAL SETUP

This paper investigates experimentally the seismic behavior of a self-centering rocking frame, which acts together with a steel moment resisting frame (MRF). Figure 1 shows the specimen configuration. The self-centering frame consists of a braced frame, which is designed to rock off its foundation, placed next to a steel MRF. Both frames are linked together at each floor level using steel fuses. The column base can detach from the footing experiencing uplifting, while the horizontal load is transmitted to other column base which remains in contact with the footing, as shown in Figure 2.

The self-centering frame is a ¼-scaled three-story structure with 800 mm story height. Columns are concrete-filled double-skin steel tubular (CFDST) members with outer diameters equal to 150 mm. The CFDSTs are equipped inside the inner steel tubes with pre-stressed concrete (PC) bars of 26 mm diameter (yield stress: 1022 MPa), as shown in Figure 3. This column member is made of ultra-high strength Japanese steel (nominal yield stress: 780-1000 MPa). Concrete-filled steel tubular columns made of high strength steel exhibit adequate seismic performance for use as a building structural member (Skalomenos et al. 2014; Hsiao et al. 2015; Skalomenos et al. 2016). A pre-tension force is applied between the bottom of the steel basement beam and column top. This column-system is intended to: 1) directly transmit the large tensile forces resulting from the PC bars and self-weight of structure to the CFDST columns, which have large axial stiffness and high strength capacity; and 2) directly transmit the pretension forces to a pile foundation member placed under the column base.

Beams and braces of the self-centering frame are made of conventional Japanese steel SS400. Their cross-sections are WF-200×100×5.5×8 and WF-100×100×6×8, respectively, with all joints welded. In MRF, the bottom end of the column is supported by a mechanical pin. Therefore, when a horizontal force acts in the specimen, only the beam ends of MRF yield. Replaceable steel fuses connect both frames at the floor levels made of low-yield point steel (nominal yield stress: 80-100 MPa). As the height of a structure increases, it might be difficult to control the total dissipation energy only by few and specific locations. Past study suggests that a uniform distribution of hysteretic energy along the entire height of the structure is more efficient and advantageous. (Nakashima et al. 1996). Figure 4 illustrates a design concept for the beam-ends of the MRF. The top flange of the beam is connected to a steel bracket welded to the column via a steel T-shaped segment. Fuses are placed on the bottom flange. This connection referred to the design suggested in Kishiki et al. (2004). At each beam-end, the steel T-shaped segment accommodates beam rotation, as shown in Figure 4, and shear force at this connection configuration is sustained by the web of segment. This rotation enables the fuse element placed on the bottom flange to yield, thereby effectively dissipates energy.

A horizontal jack is attached to the column head of the self-centering frame to perform quasi-static cyclic loading (Figure 1). The load steps are gradually increased from a frame rotation angle of 0.0025, 0.005, 0.0075, 0.01, 0.015, 0.02, 0.03 to 0.04 rad. The specimen is loaded using two cycles for each amplitude. Note that frame rotation angle is equal to the relative drift between the frame’s column head and column base divided by the 2,400 mm specimen height.

Lateral drifts at the column head and column base are measured by displacement transducers DT1 and DT2 shown in Figure 1, to determine the relative drift of the self-centering frame in the horizontal direction. Column base uplift is measured from displacement transducers in the vertical direction, DT3 and DT4, placed at both column bases of the self-centering frame. In PC bars, pretension forces are measured using load cells placed on the frame top, while steel bar yielding is determined by strain gauges attached at the bottom of the PC bar.
Figure 1. Specimen configuration (Unit: mm)

Figure 2. Uplifting behavior of the column base

Figure 3. Cross-section of CFDST Column (Unit: mm)

Figure 4. Details of the MRF beam-end (Unit: mm)
3. EXPERIMENTAL RESULTS

Figure 5 shows the experimental moment-frame rotation relationship. The vertical axis corresponds to the moment due to horizontal load at the column base, while the horizontal axis is the rotation angle of the self-centering frame. The moment is obtained by multiplying the horizontal load by the height of the loading point (2,400 mm) and the rotation angle is obtained by dividing the relative drift of the frame's column head by the frame height (2,400 mm). Figure 5(a) shows the moment-frame rotation relationship up to 0.01 rad, while Figure 5(b) up to 0.04 rad.

The moment-frame rotation relationship shown in Figure 5 is characterized by the beneficial flag-shaped behavior, which is ideally defined in Figure 6. Steel fuses at the beam ends of MRF were yielded at a frame rotation angle nearly at 0.00125 rad. The measured moment at the time of column uplifting was 285 kNm. The PC bar yielded at a frame rotation angle 0.009 rad. The proposed self-centering rocking frame system showed satisfactory seismic performance. The residual deformations were very small after the loading cycle of 0.01 rad.

However, once the PC bars yields, the ability of the self-centering mechanism to reduce residual deformation is less effective as Figure 5(b) indicates. In the specimens of the present experimental study, a residual deformation was recorded after 0.02 rad (i.e., frame rotation at PC bars yielding). Nonetheless, it is assumed that the residual deformation would be smaller if a real scale frame with actual self-weight, dead and live loads were included in the test. These loads contribute to the re-centering action of structure.

Figure 5. Experimental moment-frame rotation relationship: (a) up to 0.01 rad; and (b) up to 0.04 rad.

Figure 6. Load-deformation relationship of an ideal self-centering system
The dashed double-dotted lines in Figure 5 shows the uplifting moment $M_{up}$ of column base calculated using the following equation,

$$M_{up} = F_i B + nD MD$$  \hspace{1cm} (1)

The first term on the right side of the above equation represents the effect of initial tension given to the PC bars; the second term represents the effect of yielding at the beam ends (steel fuses) of MRF. Here, $F_i$ is the initial tension introduced in the PC bars, $B$ is the self-centering frame width, $nD$ is the number of the beam ends of MRF, and $M_D$ is the full plastic moment of beam members.

Moreover, the dashed-dotted lines in Figure 5 shows the yielding moment $M_y$ of PC bar calculated using the following equation,

$$M_y = p_c \sigma_y A_{pc} B + nD MD$$  \hspace{1cm} (2)

Here, $p_c \sigma_y$ is the yield stress of the PC bars, and $A_{pc}$ is the PC bar cross-sectional area. The calculated $M_{up}$ and $M_y$ correspond with experimental results.

The $h_{eq}$ (equivalent damping ratio) of specimens is shown in Figure 7. $h_{eq}$ is calculated based on Equation 3 (AIJ 2014).

$$h_{eq} = \frac{\Delta W}{(4\pi W)}$$  \hspace{1cm} (3)

where $\Delta W$ is the energy dissipation of the hysteretic loop calculated for each story drift ratio. $W$ is potential energy of each story drift ratio. The vertical axis in Figure 7 shows the value of $h_{eq}$ and the horizontal axis shows the rotation angle of the self-centering frame. The $h_{eq}$ in the first loading cycle at each story drift ratio is around 0.07. The $h_{eq}$ in the second loading cycle differs at each story drift ratio.

In 0.0025 rad where the deformation is small, the $h_{eq}$ of the second cycle is around 40% of the first cycle. On the other hand, at 0.005 rad to 0.01 rad, where an uplifting behavior of the column base is prominent, $h_{eq}$ is 80% to 90% of the first cycle. A relatively stable energy dissipation is achieved.

![Figure 7. The $h_{eq}$ (equivalent damping ratio) of the specimen](image)

Figure 8 shows the overall deformation of the self-centering frame system in 0.04 rad frame rotation. The deformation of the self-centering frame and MRF can easily be observed. In addition, the column base uplift from the footing was about 40mm. Even in this large deformation state, no fracture on the PC bars or beam ends of MRF was observed demonstrating the efficiency and high-performance of the proposed seismic system.
4. CONCLUSIONS

Main conclusions of this study are as follows:

A. The hysteretic behavior of the specimen was characterized as a flag-shaped behavior. The residual deformation of the specimen was almost negligible, when the system reached a rotation angle equal to 0.01 rad (beam ends of MRF have already yielded, and the column of the self-centering frame has been uplifted from the footing).

B. The self-centering mechanism was less effective after PC bar yielding, however, in real-scale building structures, restoring forces resulting from the building weight will contribute to the structure re-centering. Residual deformations can be significantly reduced.

C. Even in large deformation state, such as a rotation angle equal to 0.04 rad, no fracture on the PC bars or beam ends of MRF was observed, demonstrating a high-performance of the proposed seismic system.

D. Based on the frame dimensions and the material strengths of the proposed seismic system, hysteretic characteristics, such as the uplifting and yielding moment of system, can be estimated accurately using the proposed equations.

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6. REFERENCES


