Seismic behavior of the multistory steel-braced building with self-centering tension-only braces

Pei Chi\textsuperscript{1,2,*} and Wenlong Tian\textsuperscript{2}
\textsuperscript{1} School of Civil Engineering, Southeast University, Nanjing, Jiangsu Province, 210096, China
\textsuperscript{2} College of Civil Science and Engineering, Yangzhou University, Yangzhou, Jiangsu Province, 225009, China
*chipei@yzu.edu.cn

Abstract. Recent research has developed the self-centering tension-only brace (SC-TOB) that provides both seismic resilience and load mitigation to the structure. This study examined the seismic behavior of the SC-TOB frames (SC-TOBFs) through pushover and nonlinear dynamic analysis. The results indicate that the SC-TOBs can be designed to perform as conventional tension-only braces just offering required lateral stiffness to the structure under minor earthquakes and to function with excellent energy dissipation and recentering capabilities during significant earthquakes. The SC-TOBFs are capable of recentering both within 2% roof drift angle in pushover analysis and under the most severe hazard level in the dynamic analysis. The SC-TOBs are thereby deemed to be promising bracing members that have the potential to minimize the repair costs and operation disruption after earthquakes.

1. Introduction
Conventional seismic-resisting systems designed according to current building codes are prone to residual deformations after significant earthquakes, resulting in substantial losses associated with repair costs and operation downtime\cite{1-2}. To this end, self-centering braces (SCBs) were developed as an effective means for structures to reduce or even eliminate residual deformations. The configurations generally consist of a pre-tensioning (PT) system to provide a recentering capability along with an energy-dissipative mechanism to protect primary structures (e.g., \cite{3-8}). Although analytical and experimental studies have confirmed that the SCBs and the corresponding structures can achieve a stable SC hysteretic response under cyclic loadings, they tend to exhibit increasing seismic demands due to the smaller energy dissipation capacity compared with conventional systems\cite{9}. Meanwhile, tension-only braces (TOBs) are light and flexible bracing elements that are capable of mitigating seismic response as a result of longer structural period. But because of highly pinched hysteresis, TOBs have to be backed up by a favourable energy dissipation mechanism if they are designed to be used in areas of high seismicity. To address the aforementioned concern, the SC-TOB system, taking advantages of the seismic resilience of SCBs and load mitigation of TOBs, has been developed\cite{10-11}. In this paper, multistory steel frames built with SC-TOBs are numerically investigated in terms of internal force, inter-story drift, and energy dissipation.
2. SC-TOB concept
As illustrated in Figure 1(a), the SC-TOB system consists of PT tendons to provide SC, a frictional device for energy dissipation, and a high strength steel cable as the main bracing element. Detailed mechanics of the SC-TOB can be found in [11]. Three types of SC-TOBs with different hysteresis shown in Figure 1(b) are selected for the analysis, where the bracing types with cable diameters $\phi=70\text{mm}$, $80\text{mm}$, and $90\text{mm}$ are installed in stories 1-3, 4-6, and 7-9, respectively.

![SC-TOB system configuration](image1)

![Hysteretic responses](image2)

Figure 1. SC-TOB system: (a) configuration; (b) hysteretic responses.

3. Prototype building design
The prototype building is the SC-TOB frames (SC-TOBFs) as illustrated in Figure 2, where the dotted lines indicate the braced bays. The load information is listed in table 1.

![Prototype building plan view](image3)
![Prototype building elevation view](image4)

Figure 2. Prototype building: (a) plan view; (b) elevation view.
Table 1. Load information.

| Gravity loads  | Floor        | Dead   | 4.5 kPa | Live   | 4.0 kPa |
|----------------|--------------|--------|---------|--------|---------|
|                | Roof         | Dead   | 5.0 kPa | Live   | 2.0 kPa |
|                | Exterior walls| Dead   | 10 kN/m |        |         |
| Seismic load data | Basic acceleration of ground motion | 0.20 g |

4. Pushover analysis
The parabolic lateral load distribution is adopted for the pushover analysis and the target roof displacement is set at 2% times the building height. As shown in Figures 3 and 4, both the axial force of the cables and the inter-story drifts exhibit a bilinear response as the roof drift increases and decrease over the building height. The energy dissipation in each story stably increases as the roof drift increases as long as the SC-TOBs are triggered (see Figure 5). Figure 6 counts the cumulative energy dissipation of each story. It is shown that the lower stories generally dissipate more seismic energy than the rest of the structure do, and almost no energy dissipation is observed in the top story.
5. Nonlinear dynamic analysis

The 1940 El-Centro ground motion was scaled to four hazard levels with a peak ground acceleration 0.07 g, 0.22 g, 0.41 g, and 0.52 g to conduct the time history analysis denoted as TH1, TH2, TH3, and TH4, representing the minor, moderate, severe, and extremely severe earthquakes, respectively. As shown in Figures 7 and 8, with the increase of intensity of ground motions, the distributions of cable axial force and the inter-story drift show the same tendency once the SC-TOBs get activated. The maximum inter-story drift initiates at the bottom story under all the four hazard levels without in excess of the code-prescribed plastic limit of 2.0%.

Figure 9 counts the cumulative energy dissipated by each type of SC-TOBs adopted for every three stories. The SC-TOBFs dissipate no seismic energy when subjected to the minor earthquake excitation. As the intensity of ground motions increases, energy dissipation initiates and enhances gradually. It is also revealed that the seismic energy dissipated in the higher part of the building is not as much as in the middle and lower parts of the structure.
Figure 7. Response envelopes of cable axial force.

Figure 8. Response envelopes of inter-story drift.

Figure 9. Energy dissipation distributions.
6. Conclusion
A numerical investigation was conducted to examine the seismic behavior of the steel frames built with self-centering tension-only braces (SC-TOBs) through pushover and nonlinear dynamic analysis. The results indicate that the SC-TOBs can be designed to perform as conventional TOBs just offering required lateral stiffness to the structure under minor earthquakes and to function with excellent energy dissipation and recentering capabilities during significant earthquakes. Because of their advantages of seismic resilience and load mitigation, the SC-TOBs are promising bracing members that have the potential to minimize the repair costs and operation disruption after earthquakes.

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