17th World Conference on Earthquake Engineering, 17WCEE
Sendai, Japan - September 13th to 18th 2020

SEISMIC PERFORMANCE OF SLIDING GUSSET PLATE BRACED FRAMES (SGBFs)

Q. Tang(1), X. Wang(2), J. Jing(3), Y. Cui(4)

(1) *Ph.D Candidate, State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology, Dalian, China, tangqi@mail.dlut.edu.cn*
(2) *Graduate Student, State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology, Dalian, China, address*
(3) *Engineer, Architectural Design & Research Institute, Tsinghua University, Beijing, China, jingjie@mail.tsinghua.edu.cn*
(4) *Associate Professor, State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology, Dalian, China, cuiyao@dlut.edu.cn*

Abstract

A Sliding Gusset Plates Braced Frame (SGBF) is an innovative seismic resilient structural system, which consists of a steel frame system equipped with the sliding gusset plate (SG) braces and replaceable fuses. To form an sliding gusset plate (SG) braces, symmetric friction connections between conventional concentric braces and gusset plates are employed. Besides, the replaceable fuses are introduced in the beams at the locations where plastic hinges are expected to develop. Thus, SGBF owns a double resistance mechanism. The performance objectives under different seismic intensities are then proposed. Under service level earthquakes (SLE), the whole lateral system is elastic, and the braces only provide additional stiffness to control elastic story drift. The building remains intact after the earthquake. Under design basis earthquakes (DBE), the friction dampers begin to slide, dissipating energy and providing additional damping. The fundamental period of the system would increase due to stiffness deterioration of braces, which would further reduce the demand. The building can be immediately occupied after checking the workability of shims. Under maximum considered earthquakes (MCE), the friction dampers could dissipate energy in a steady state. Meanwhile, plasticity begins to develop in the link fuses absorbing extra earthquake energy. The earthquake response would be further reduced due to stiffness degradation and damping increment. The damage is concentrated in the replaceable fuses while the main structure remains elastic. Rapid recovery can be achieved by replacing the damaged fuses. To evaluate the seismic performance of the SGBF, a prototype building was designed based on a practical four-story frame following performance-based seismic design procedure. Then, finite element models of SGBF were constructed in OpenSees and nonlinear response history analyses were conducted. The results show that the SGBF has adequate lateral resistance and energy dissipation capacity to achieve the targeted performance objectives under different seismic intensities. The plastic deformations (i.e. structural damage) are concentrated within the symmetric friction gusset plate connection and replaceable fuses while the main structure remains elastic. The use of proper designed SGBF could greatly reduce the economic losses due to earthquake events, and be immediate occupied or rapidly repaired if there is a need. The proposed SGBF system is shown to be a very promising seismic resilient structural system.

Keywords: innovative system, sliding gusset plates braced frame, symmetric friction gusset plate connection, replaceable fuse, seismic performance

1. Introduction

Concentrically Braced Frames (CBFs) are commonly used as the lateral load resisting system in buildings. Compared with Moment Resisting Frames (MRFs), CBFs have higher elastic stiffness, which are suitable for resisting wind and moderate seismic loadings [1]. However, during severe earthquakes, CBFs do not perform well because of higher seismic forces involved and buckling of braces under compression. Therefore, the inelastic behaviour of the CBF systems is very dependent on the effect of inelastic demand on the braces. To avoid the degradation due to the brace buckling in compression, Buckling-Restrained Braced Frames (BRBFs) have been widely studied and applied [2, 3]. The BRBs exhibit a stable hysteretic response and the ability to withstand significant ductility demands. However, the issues, such as large residual deformations after severe earthquakes and the difficulty to identify the damage state of the BRB core material, are challenged the application of BRBFs [4].

Conventional seismic-resistant steel frames designed according to current seismic provisions prevent collapse and ensure life safety under the design earthquake [5]. A well designed and detailed ductile structure will experience significant inelastic deformations in main structural members and residual story drifts after strong earthquake [6]. However, it might be significantly damaged requiring major repair or demolition. An effective strategy to overcome the issue of reparability of structural members is to concentrate damage in carefully designed replaceable elements. Considering the above-mentioned unsatisfactory response of the CBF systems in compression, and the requirement of reducing economic cost due to seismic events, a great need is recognized to develop the low-damage or resilient structures [7]. In particular, the goal is to develop low cost connections with supplemental and repeatable mechanisms for energy dissipation that are easy to repair/replace after sever earthquakes.

Friction connections offer efficient seismic energy dissipation because they are cheap and easy to fabricate and install. Moreover, friction connections present a high level of resilience as they enable rapid damage assessment and relative ease of repair, reducing the economic cost to restore building function after severe seismic event. Several studies have been carried out exploring the possibility of applying friction connections as energy dissipaters in structural systems. Analytical results of Pall show that steel braced frames including sliding friction devices have superior seismic performance compared with conventional steel frames [8]. Experimental and analytical results carried out by Tremblay and Grigorian on symmetrical friction connections revealed that a stable response can be achieved [9, 10]. Another alternative of applying friction connections as energy dissipaters is the concept of Asymmetrical Friction Connections, initially developed to be applied in moment resistant steel frame connections by Clifton [11]. The application of asymmetric friction connections (AFCs) in braced frames was proposed by Butherworth and MacRae [12-14]. Analytical results show that by placing the connection within braces the frame is enabled to dissipate a significant amount of energy and minimal damage is expected in the structure after a major earthquake.

This paper proposes an innovative CBFs, denoted as Sliding Gusset Plate Braced Frames (SGBFs). It is a concentrically braced frames (CBFs) equipped with the symmetric friction connections in the gusset plate connections and replaceable fuses at the locations of the beams where plastic hinges are expected to develop. A prototype building is designed according to the provisions of GB50011-2010 using the proposed SGBF [15]. The seismic performance of the SGBF is then evaluated using numerical simulations.

2. Sliding Gusset Plates Braced Frames (SGBFs)

2.1 Components of SGBFs

Fig. 1 shows the configuration of the proposed SGBF system, which is mainly composed of sliding gusset plates, replaceable fuses, and main frames. In the SGBF, the symmetrical friction connection is placed at the end of the brace where the gusset plate has slotted holes and is welded to the beam column joint as described in Fig. 1. The symmetrical friction connections have stable hysteresis and excellent energy dissipation capacity. Replaceable fuses are placed in the main beams immediately after the gusset plates, where plastic hinges are expected to develop, as shown in Fig. 1. They are designed following the same concept of the replaceable link proposed by Shen et al. [16]. The fuses are welded on strong end plates, which are bolted on the main beam (Fig. 1).

The slotted holes in the symmetric friction connection enhance the deformation capacity of the brace, especially the brace buckling under compression is avoided. Since the strength of the connection can be reliably predicted and tuned, the maximum forces in the frame can be reliably predicted. As a result, no damage is expected in the SGBF frames. The proposed frame can be designed to provide: a) high initial stiffness resulting in effective control of storey drifts; b) elimination of structural damage by concentrating plastic deformations in the symmetric friction connection and the replaceable beam fuses.

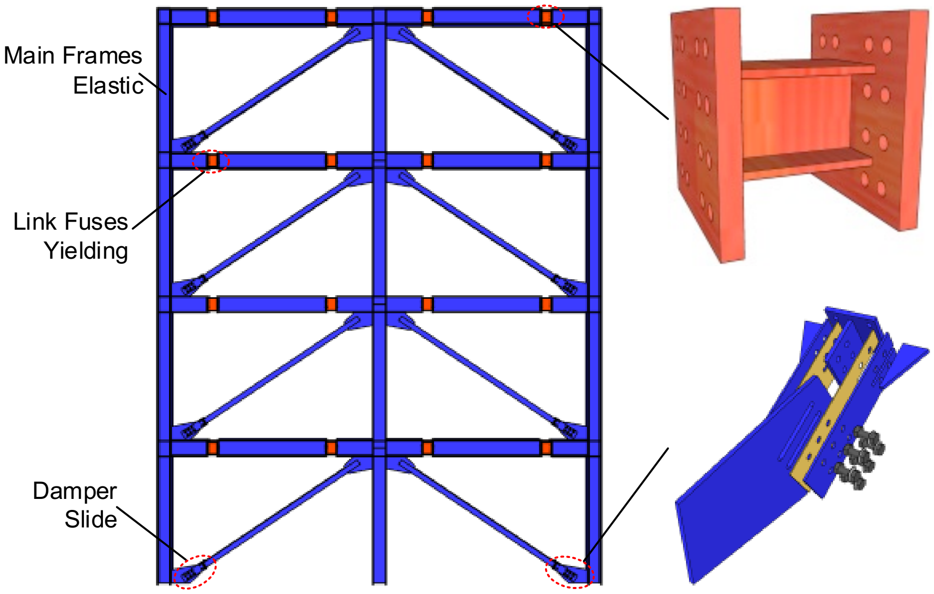


Fig. 1– Components of SGBFs

The relationship between the lateral shear force and roof drift relationship of the SGF is illustrated in Fig. 2. In the service level earthquake (SLE), the symmetric friction connections do not slip, the braces provide lateral stiffness, and the main frame remains elastic. The seismic performance is similar to the CBFs and it can be used immediately after the earthquakes. After SLE, the symmetric friction connections begin to slip, and the axial force of the brace keeps as a constant of the slip load. With proper design, the compression buckling of the braces can be avoided, and the stable energy dissipation in friction can be achieved. The main frame still remains elastic. After the earthquake, only the friction material needs to be check and replaced if it is necessary. After the maximum considered earthquake (MCE), the replaceable fuses begin to yield and dissipate energy with the symmetric friction connections at the gusset plate. The introduction of replaceable fuses reduces the strength demands on columns and beams and ensures the ductile failure mode of strong column and weak beam. After the earthquake, the quick recovery could be achieved by the replacement of link fuses and minor maintenance the friction material.

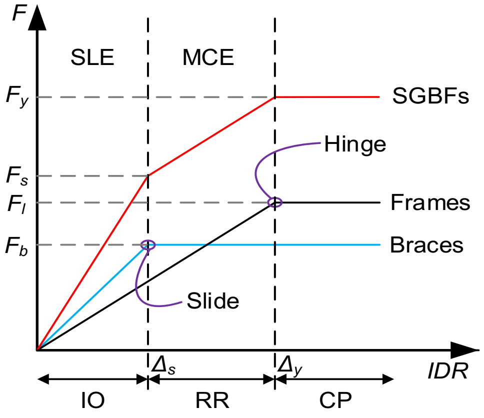


Fig. 2 – Force versus inter-story drift ratio relationship

2.2 Cyclic behavior

The resistance mechanisms of SGBF response to lateral force in cyclic load are illustrated in Fig. 3. The solid grey line represents the behavior of braces with symmetric friction gusset plate connections, the dashed grey line stands for the replaceable fuses, and the solid black line shows the behavior of the SGBF system.

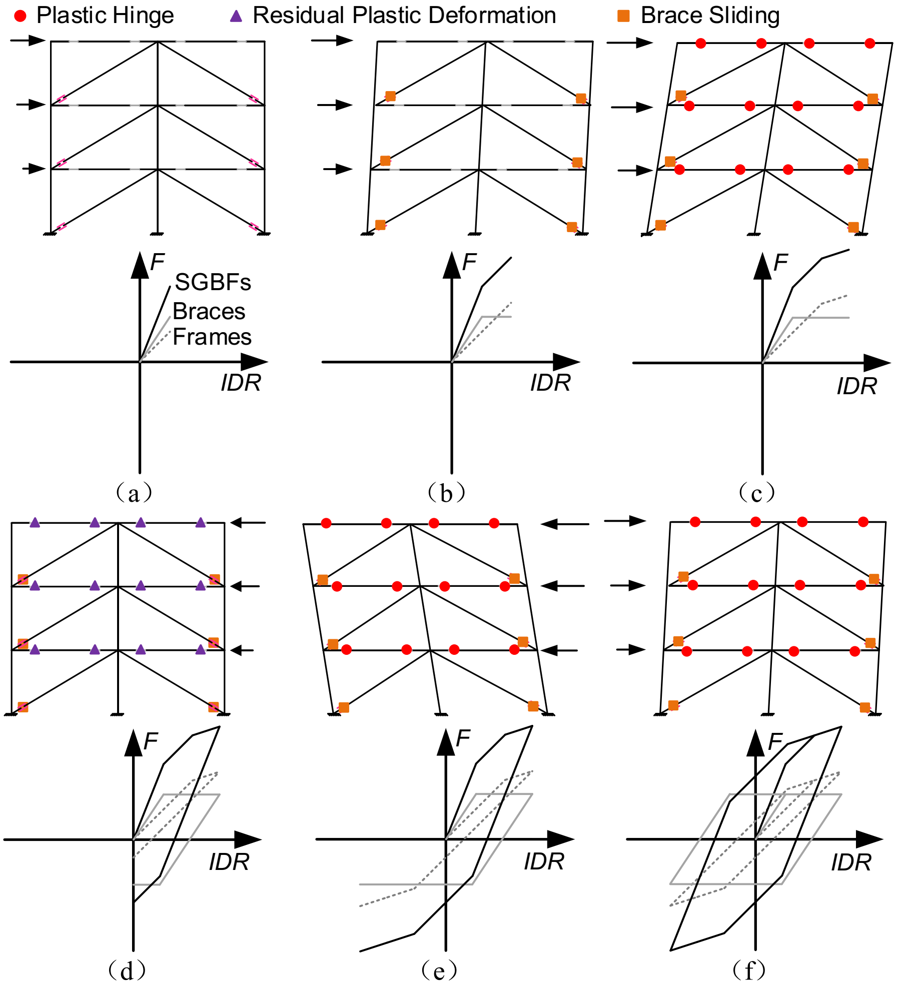


Fig. 3 – Cyclic behavior of SGBFs

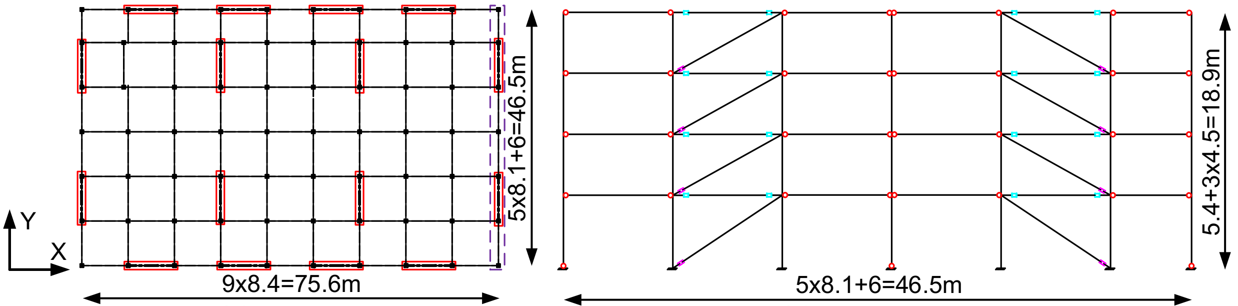
Before the lateral load reaches SLE, the symmetric friction gusset plate connections don't slip, therefore braces only provide the lateral stiffness, and the whole system remains elastic, as shown in Fig. 3 (a). When the lateral force reaches SLE, the axial force in braces reaches the slipping load of the symmetric friction gusset plate connections, and the axial force of braces remains a constant after sliding. The seismic input energy is dissipated by the friction mechanism, as shown in Fig. 3 (b). After the lateral force reaches MCE, the replaceable fuses yield, and dissipate the earthquake input energy together with the symmetric friction gusset plate connections. The main structure remains elastic, as shown in Fig. 3 (c). When the system subjects to reverse load, the system first recovers to the initial position, the symmetric friction gusset plate connections is still in the sliding state, and the structural damage, i.e. the residual plastic deformation, is all concentrated in the replaceable fuses. Other frame elements are still elastic, as shown in Fig. 3 (d). When the reverse load reaches MCE again, the replaceable fuses yield again, as shown in Fig. 3 (e). After the completion of one cycle, the resulting hysteretic curves are shown in Fig. 3 (f).

In the cyclic protocol, the symmetric friction gusset plate connections are assumed to exhibit stable and non-deterioration hysteresis loops. Compared with the conventional CBFs, the braces with the symmetric friction gusset plate connections exhibit the same tensive and compressive behavior with full and stable hysteresis curves. In severe earthquakes, the damage is concentrated in the replaceable fuses while the main structure remains elastic in SGBFs, which can be rapidly repaired after earthquakes.

3. Case Study

3.1 Building information

In order to perform a preliminary assessment of the behavior of SGBFs, it was designed for a four-story archetypical hospital building located in Beijing. The plan of the building that was considered is shown in Fig. 4. According to the Chinese seismic design code GB50011-2010 [15], the seismic fortification category is 8 and the Peak Ground Acceleration (PGA) of the design basis earthquake is 0.2g. Q355 steel, with the nominal yield stress of 355 MPa, is adopted for the system. The frame in Y-direction as indicated in Fig. 4(a) is chosen for the following discussion. As shown in Fig. 4(b), the frame in Y-direction consists of two braced frames and gravity frames which are pin-connected to foundation and SGBFs. The story height of first floor is 5.4m, and 4.5m for other floors. The dead load is taken as 5 kPa, and the live load was taken 2.5 kPa. For this building and the assumed loads, the seismic weight acting at all the level was calculated as 2440 kN.



(a) Plan View (b) Elevation View

Fig. 4 – The plan and elevation view of the archetypical building

The symmetric friction gusset plate connections were set to slip at the story drift ratio of 0.001rad in the SLE. After the MCE, the replaceable fuses began to yield at a story drift of 0.01rad. The displacement-based method was used in the design process. The MDOF system was first transferred into a SDOF system. The equivalent period was calculated based on the performance objectives. Then the base shear was computed and SGBF was design as an equivalent CBF at SLE. In MCE, the beams and columns of SGBF were designed as an MRF with increased damping ratio. Then, according to assumed stiffness ratio of 25% between moment frames and braces, the cross-section areas of braces were determined. Finally, the slip load is calculated based on the lateral force distribution in SLE. The resulting components are shown in Table 1 and Table 2.

Table 1 – Selected members for the prototype frame

Floor level	**SGBFs**			**Gravity frames**	
	Beam section	**Column section**	**Replaceable fuse section**	**Beam section**	**Column section**
4	H700×300×13×24	H400×400×11×18	H600×300×12×20	H450×200×9×14	H350×350×10×16
1-3		H500×500×20×30			

Table 2 – Information of symmetric friction gusset plate connections

Floor level	**1**	**2**	**3**	**4**
Brace section	□200×15	□150×10	□150×10	□140×8
Brace axial stiffness (kN/m)	238891	118081	118081	84028
Slip load (kN)	592	501	386	219

3.2 Numerical model

The 2D numerical model was conducted to investigate the seismic behavior of the porposed SGBFs by using the OpenSees [17]. The beams and columns were modeled using force-based beam column elements while the braces equipped with the symmetric friction gusset plate connections were modeled as two node link elements. The uniaxial bilinear steel material with kinematic hardening Steel02 was assigned to the beams and columns. The yield stregnth is 355MPa and the strain hardening ratio was set to be 0.01. An elasic perfectly-plastic uniaxial material was adopted for braces with axial stiffness of braces and equivalent yield strength same as the slip load of symmetric friction conenctions as listed in Table 1. The P-Delta effects were considered. Rayleigh damping was applied using 4% damping in the first mode.

The ground motion records of Takatori, Kobe, and Northridge earthquakes were used in this study. For SLE, the PGA was scaled to be 0.071 g. As for MCE, the PGA was scaled to be 0.4 g. The spectra of the selected ground motions compared with design spectrum in GB50011-2010 [15] were shown in Fig. 5.

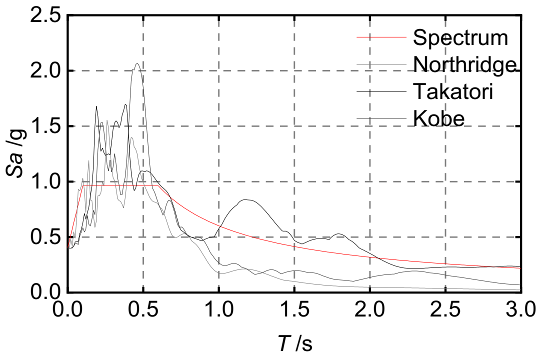
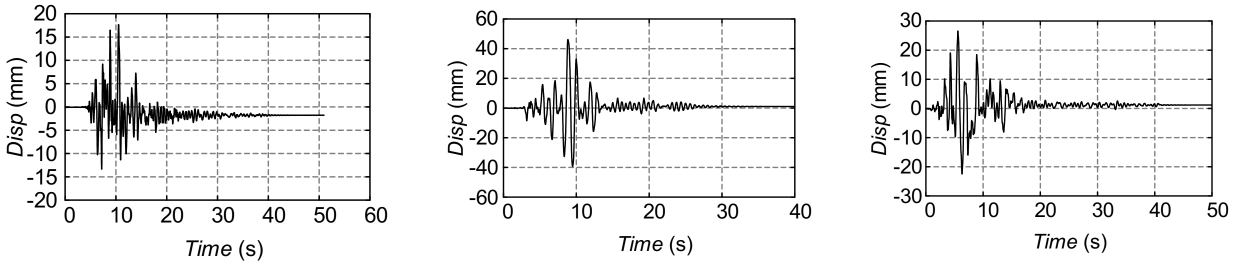


Fig. 5 – Spectra of selected ground motions compared with design spectrum in MCE

4. Analysis results

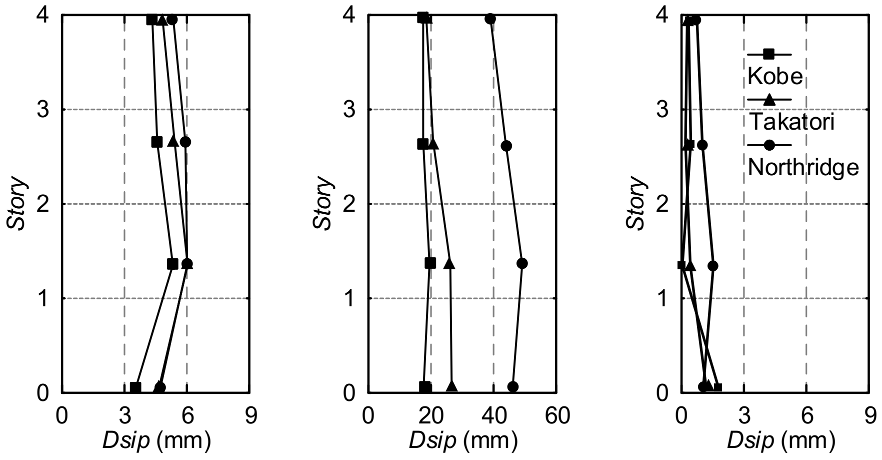
4.1 Maximum story drift

The displacement time history curves of the first floor under MCE level input are shown in Fig. 6. It is noted that the residual displacement of SGBF is relatively small. The maximum story drift distribution of the designed frame under the aforementioned ground motion with the PGA of 0.07g and 0.4 g is shown in Fig. 7. The horizontal axis repents the maximum story drift of the frame while the vertical axis represents the floor of the frame. The peak story drift uniformly distributed along the frame floors. The residual drift of the 1st story is 0.033% rad, 0.034% rad, and 0.022% rad. This value indicate that the shim plate can be easily changed after earthquake if it is necessary. Because residual drift is associated with structural damage, this aspect of the performance of the SGBFs is favorable as a resilience structure.



(a) (b) (c)

Fig. 6 – Displacement time history curves of the 1st floor (PGA=0.4g) : (a) Kobe; (b) Northridge; (c) Takatori

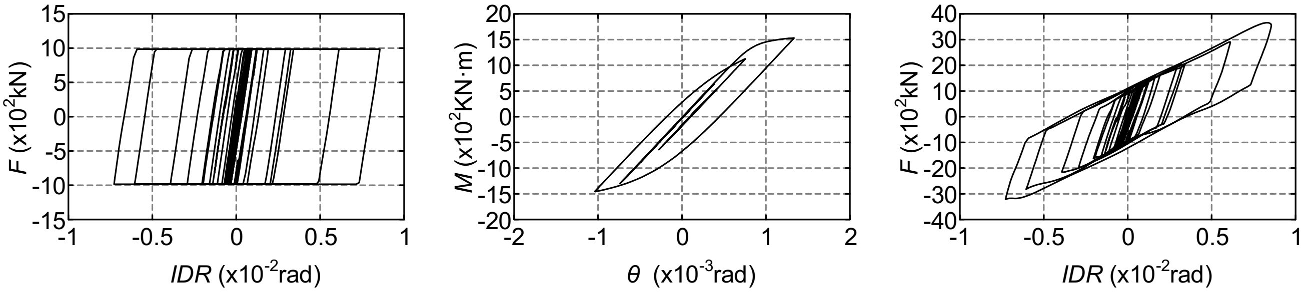


(a) (b) (c)

Fig. 7 – Displacement response: (a) absolute peak drift (PGA=0.07g); (b) absolute peak drift (PGA=0.4g); (c) residual displacement (PGA=0.4g)

4.2 Hysteresis curves

Following the design strategy, the designed SGBF exhibited elastic behavior under the SLE level input, and the symmetric friction gusset plate connections slipped under the MCE level input. Figure 8 shows the response hysteresis curves of the designed SGBF under the scaled Northridge input (PGA=0.4g). The hysteresis behavior of the 1st story SG brace, 1st story replaceable fuse, and the 1st story frame were shown. It is noted that the SG braces dissipated energy due to the slippage at the friction gusset plate connection, and the buckling of brace is therefore avoided in compression. The replaceable fuse also yielded and the beams and columns were still elastic.



(a) (b) (c)

Fig. 8 – Hysteretic curves of 1st story components and frame under Northridge input (PGA=0.4g) : (a) SG brace; (b) replaceable fuse; and (c) 1st story

5. Conclusions

In this work, a seismic-resistant system (denoted as SGBF) consisting of a steel concentrically braced frame equipped with symmetric friction gusset plate braces and replaceable beam fuses was presented and numerically evaluated. The seismic performance of the SGBF was discussed based on the time history analysis. Based on the results presented herein, the following conclusions are drawn:

1. The symmetric friction gusset plate connections can ensure the braces of conventional steel concentrically braced frame avoid the buckling in compression. Moreover, the symmetric friction gusset plate connections offer efficient seismic energy dissipation, and the bolts can easily be replaced.

2. In this study, the friction damper is designed to slip after Service Level Earthquakes (SLE). And replaceable fuses are introduced at the beam ends and yield after Maximum Consider Earthquake (MCE) to dissipate energy together with friction dampers and protect other elements from damaging. In the aftermath of severe earthquakes, only to replace the prefabricated and bolted link fuses, the system could be rapidly repaired while the slipping of the braces in friction does not constitute damage

3. Nonlinear time history analyses peforemed show that the proposed design strategy and capacity design rules guarantee that inelastic deformations are concentrated in the symmetric friction gusset plate connections and beam fuses, whereas the main structural components are essentially elastic even for drifts expected under the maximum considered earthquake. The maximum residual drift of the proposed SGBF is negligible under the MCE.

4. The Nonlinear time history analysis results show that the force-displacement response of the sliding gusset plate braces can be described as bilinear with an initial steep segment followed by a flat segment with a force level around to the sliding force of the symmetrical friction connection at the gusset plate connection.

6. References

[1] Bruneau M, Uang CM, Sabelli R (2011): *Ductile Design of Steel Structures.* McGraw Hill Professional, 2nd edition.

[2] Watanabe A, Hitomi Y, Saeki E, Wada A, Fujimoto M (1988): Properties of brace encased in buckling–restraining concrete and steel tube. *9th World Conference on Earthquake Engineering*, Tokyo-Kyoto, Japan.

[3] Iwata M, Kato T, Wada A (2000): Buckling-restrained braces as hysteretic dampers. *3rd International Conference STESSA*, Montreal, Canada.

[4] Sabelli R, Mahin S, Chang C (2003): Seismic demands on steel braced frame buildings with buckling-restrained braces. *Engineering Structures*, **25**, 655-666.

[5] Architectural Institute of Japan (AIJ) (2012): *Recommendations for design of connections in steel structures*, Tokyo (in Japanese)

[6] Bertero VV, Anderson JC, Krawinkler H (1994): Performance of steel building structures during the Northridge earthquake. *Report No. UCB/EERC-94/09*, Earthquake Engineering Research Center, Univ. of California, Berkeley, San Francisco.

[7] Comerio M, Elwood K, Berkowitz R (2011): *The M6.3 Christchurch, New Zealand, earthquake of February 22, 2011.* Oakland: Earthquake Engineering Research Institute (EERI).

[8] Pall AS, Marsh C (1982): Response of friction damped braced frames. *Journal of the Structural Division,* **108**(6), 1313 – 1323.

[9] Tremblay R (1993): Seismic Behaviour and design of friction concentrically braced frames for steel buildings. *Unpublished PhD Thesis,* University of British Columbia, Vancouver, Canada.

[10] Grigorian CE, Popov EP (1994): Experimental and ana- lytical studies of steel connections and energy dissipaters. *Report UCB/EERC-95/13,* Engineering Research Center*,* San Francisco, USA.

[11] Clifton GC (2005): Semi-rigid joints for moments resisting steel framed seismic resisting systems. *Unpublished PhD Thesis,* University of Auckland, Auckland,New Zealand.

[12] Butterworth JW (1999): Seismic damage limitation in steel frames using friction energy dissipators. *6th International Conference on Steel and Space Structures*, Singapore.

[13] MacRae GA (2008): A new look at some earthquake engineering concepts. *M. J. Nigel Priestley Symposium Proceedings*, IUSS Press.

[14] MacRae GA, Clifton GC (2010): New technology applications, recent developments and research directions for seismic steel structures in New Zealand. *Asia Conference on Earthquake Engineering,* Bangkok, Thailand.

[15] GB 50010-2010 (2016): *Code for Seismic Design of Buildings.* China Architecture & Building Press, Beijing, China. (in Chinese)

[16] Shen Y, Christopoulos N, Mansour C, Tremblay R (2011): Seismic design and performance of steel moment-resisting frames with nonlinear replaceable links*, Journal of Structural Engineering,* **137**(10), 1107-1117.

[17] Mazzoni H, McKenna F, Scott MH (2009): *Open System for earthquake engineering simulation (OpenSees) user command-language manual*, Pacific Earthquake Engineering Research (PEER) Center, Berkeley, CA, USA.