ANALYTICAL STUDY OF SHEAR SLOTTED BOLTED CONNECTION IN MOMENT RESISTING FRAMES

M. T. Nikoukalam¹, S. R. Mirghaderi² and K. M. Dolatshahi³

ABSTRACT

Slotted Bolted Connections (SBCs) and Rotational Slotted Bolted Connections (RSBCs) are two types of friction dampers that have been employed over the years in braced frames and moment resisting frames, respectively. Friction dampers are one of the most desirable energy dissipating systems due to their high potential to dissipate energy with a non-destructive mechanism and stable hysteresis behavior. However, the application of SBC and RSBC is limited mainly to members with axial and flexural dominated behavior, respectively. Shear Slotted Bolted Connection (SSBC) is developed in this paper to provide a non-destructive energy dissipation system for lateral load resisting systems with predominant shear behavior members that dissipate energy through yielding mechanism. SSBC dissipates the input energy to the structure via friction which is activated by shear. In this paper the details and applications of SSBC in various lateral load resisting systems are described. Moreover, the cyclic behavior of SSBC in Moment Resisting Frames (MRFs) is investigated using finite element models developed in ABAQUS. Finally, an existing two dimensional nine story moment resisting frame is modeled and equipped with SSBC and the behavior and performance level of the two frames are evaluated and compared through nonlinear static and dynamic analysis.

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Slotted Bolted Connections (SBCs) and Rotational Slotted Bolted Connections (RSBCs) are two types of friction dampers that have been employed over the years in braced frames and moment resisting frames, respectively. Friction dampers are one of the most desirable energy dissipating systems due to their high potential to dissipate energy with a non-destructive mechanism and stable hysteresis behavior. However, the application of SBC and RSBC is limited mainly to members with axial and flexural dominated behavior, respectively. Shear Slotted Bolted Connection (SSBC) is developed in this paper to provide a non-destructive energy dissipation system for lateral load resisting systems with predominant shear behavior members that dissipate energy through yielding mechanism. SSBC dissipates the input energy to the structure via friction which is activated by shear. In this paper the details and applications of SSBC in various lateral load resisting systems are described. Moreover, the cyclic behavior of SSBC in Moment Resisting Frames (MRFs) is investigated using finite element models developed in ABAQUS. Finally, an existing two dimensional nine story moment resisting frame is modeled and equipped with SSBC and the behavior and performance level of the two frames are evaluated and compared through nonlinear static and dynamic analysis.

Introduction

In traditional Lateral Load Resisting Systems (LLRSs) such as Moment Resisting Frames (MRFs), Eccentrically and Concentrically Braced Frames (EBFs and CBFs), the input seismic energy to the structure is mostly dissipated through the formation of plastic hinges in different components of the structure. However, this traditional energy dissipation mechanism is accompanied by cumulative damages which increase post-earthquake losses and repair costs. Damage resistant design of steel structures has been developed most recently in order to reduce the possibility of significant damage to main lateral load resisting systems of structures during earthquake excitations. Several innovative earthquake-resistant systems have been developed having the potential to control damages to the structure and raise the seismic performance level. These modern control systems can be categorized mainly into damping and isolation systems. Damping systems improve the energy dissipation potential of the structure by adding

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supplemental damping that can be divided into passive systems and semi-active/active systems. Friction dampers are one of the passive control systems which have been utilized in damage resistant design of steel structures.

Friction dampers can dissipate the input energy to the structure with a non-destructive mechanism and stable hysteresis loop, increasing the seismic sustainability of structure and minimizing repair costs and also downtime of structures. Many types of energy dissipating devices using friction as a means of energy dissipation have been tested and studied by researchers [1-5], requiring precision manufacturing, odd materials and specialized training for installation have limited their application in practice. Slotted Bolted Connection (SBC) that has been employed in bracings is a common type of friction dampers in which the friction is activated by axial forces in the brace [6-8]. In order to employ the benefits of SBCs in moment resisting frames, which are desirable mostly due to aesthetic and functional reasons, Rotational Slotted Bolted Connection (RSBC) are proposed as a rotational friction damper by Yang and Popov [9]. In RSBC two equal-capacity SBCs are placed on top and bottom flanges of a beam in which the friction force is activated by the beam rotation [9-13]. However, the applications of RSBC are mainly limited to MRFs with flexural dominated behavior beams. Shear Slotted Bolted Connection (SSBC) is proposed by the authors as a new type of friction dampers to employ the benefits of slotted bolted connection in some lateral load resisting systems such as framed-tube structures, Eccentrically Braced Frames (EBFs) and Coupled Concrete Shear Walls (CCSWs) [14]. In these systems the main lateral load resisting members have a high shear demand and the input energy to the structure is dissipated mainly by material yielding in flexure or shear. SSBC is designed to act as a mechanical shear fuse in these structural systems, capable of improving the seismic performance level of the structure by decreasing the plastic deformation demands.

In this paper the details and applications of SSBC are introduced. Moreover, the behavior of SSBC in a portal MRF with 4.75m beam length is investigated through finite element models developed in the commercially available software package ABAQUS [15]. In addition, the effectiveness of SSBC in improving the performance of MRFs is investigated by retrofitting a nine story framed tube structure with SSBC and assessing the performance of the existing and retrofitted structures through Nonlinear Static Procedure (NSP) using the PERFORM-3D computer Program [16]. Finally, nonlinear time history analysis is conducted to verify the effectiveness of SSBC in decreasing deformation demands and improving the seismic performance of the structures.

Details and applications of SSBC

The general detail of an SSBC assembly with the exploded view is shown in Figure 1. SSBC generally consists of three metal plates, two U shape clamps (U-clamps), and a number of fastener bolts with nuts. The end plate flanges are from steel; one end plate has two long slotted bolt holes while the holes in the other are of standard type. To provide a constant friction, a three millimeter brass shim with standard bolt holes is sandwiched between the flanges. According to the experimental results, sliding between mild steel and brass is stable while sliding between two similar mild steel surfaces results in fluctuations of sliding force [7]. The three plates are embraced by two U shape clamps with standard bolt holes. The normal force required to develop friction during sliding is provided by pre-tensioned bolts.
In Figure 2, the applications of SSBC in EBFs, MRFs, and CCSWs are introduced. As shown, SSBC is designed to be placed as a non-destructive structural fuse in the middle of link beams in EBFs, beams in MRFs and steel coupling beams in CCSWs where the flexural demand due to the lateral load is minimal and the shear demand is high and constant all over the member.

Finite element study

In this section the behavior of SSBC in a portal MRF with 4.75m span length is investigated through finite element models developed in the general-purpose finite element analysis program ABAQUS [15]. The frame is selected from a nine story framed tube SAC building, with the plan and elevation data shown in Figure 3 (complete details are given in [17]). MRFs with various beam lengths equipped with SSBC are also studied by the authors in [14], where full details of the design and modeling approach, mesh sensitivity study and verification of the model are presented. The main design parameters of an SSBC are the slippage force that could be controlled by changing the bolts pre-stress load, and slippage length that controls slots length. Herein, The SSBC is designed so that the slippage occurs before the formation of flexural plastic hinges in the beam ends. According to Figure 3(c), a displacement-controlled cyclic analysis is conducted while the beam ends are constrained up to the ultimate story drift of 3% following the SAC protocol which is presented in [18].
Figure 3. Nine story SAC model structure: (a) elevation view; (b) plan view; (c) loading condition.

The Von Mises stress on deformed shape of the frame in +3.0%, -3.0% drift, and final step of cyclic pushover analysis are presented in Figure 4. As shown, corresponding to lateral displacement of 120 mm (3% drift), a relative displacement of 50 mm has occurred in each flange of SSBC. According to the stress distribution, no yielding has occurred as expected. As shown in the final step of the analysis, a residual displacement of 49 mm is remained in SSBC. However, in practice it is expected that after structural loading the residual displacement left in an SSBC would be recovered by slackening, re-aligning, and re-tightening the bolts [11].

<table>
<thead>
<tr>
<th>+3% Drift</th>
<th>-3% Drift</th>
<th>Final step</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.jpg" alt="Image" /></td>
<td><img src="image2.jpg" alt="Image" /></td>
<td><img src="image3.jpg" alt="Image" /></td>
</tr>
</tbody>
</table>

Figure 4. Von Mises stress on the deformed shape of SSBC-MRFs and MRFs with plastic hinge.

Figure 5 shows the base shear versus story drift hysteresis from the cyclic pushover analysis. According to Figure 5, a hardening of 27% has taken place in the system. This is mainly due to axial force induced in the beam due to the beam elongation tendency during slippage while the beam ends are fully constrained which increases the normal force between the flanges. This additional normal force can be developed only if two sides of the frame have an equal lateral displacement which requires the concrete slab over the beam to behave rigidly and fully connected to the beam. In practice, similar to eccentrically braced frames, it is anticipated that the slab rigidity deteriorates rapidly during the cycles of large inelastic deformations at the SSBC. Thus, in the remainder of this paper, the behavior of SSBC is considered Elastic-Perfectly Plastic (E-PP).
The behavior of SSBC in MRFs and its effect on the performance of the structure is studied in this section. The behavior, response, and performance assessment is carried out for the nine story SAC building located in Los Angeles described before. The original structure is designed to meet the code (UBC 1994) strong column-weak panel zone criterion [17]. Thus the strength of the structure is controlled by yielding in panel zones, which prevent the development of bending strength in beams and columns. Two-dimensional nonlinear analytical models for the MRF in the north-south direction of the prototype SAC building structure are developed using the PERFROM-3D computer program [16]. The frame is given half the seismic mass of the structure at each floor level. The details of seismic weight and mass properties for the structures are given in [17].

Element behavior and Modeling

The beams and columns are modeled by elastic beam elements bounded by inelastic rotational springs at the ends to represent the beam’s nonlinear behavior. the springs follow the generalized load-deformation curve given in FEMA-356 [19]. Panel zones are explicitly modeled with the trilinear behavior curve using the approach of Gupta and Krawinkler [17].

The possibility to simply adjust the activation load of SSBC by changing bolts and their pre-tension load (see details shown in Figure 1) provides a great means to control and adjust the performance level of the structure for the Performance Based Design (PBD) and rehabilitation of the structures. In this research, SSBCs are so designed to keep the performance level of the structure at the desired level, namely Immediate Occupancy (IO) and Life Safety (LS), by limiting the plastic deformation demands in panel zones below $1\gamma_y$ and $8\gamma_y$ ($\gamma_y$: yield shear strain in the panel zone), respectively. As described before, in this study SSBC is modeled with simplified E-PP shear hinge.

Nonlinear static analysis

Nonlinear static analysis is conducted to estimate the inelastic deformations in different components, and assess the performance of both original and retrofitted structures. The pushover analysis has been carried out following the load pattern given in [17] which is suggested in the
FEMA 222A document [20]. The structures are first subjected to the full dead load plus reduced live load followed by the lateral load including P-delta effects. In this study the FEMA 440 linearization method has been adopted for the performance assessment of structures. Figure 6 shows the pushover response of the original WPZ structure, and retrofitted structures with SSBC for two performance levels IO and LS. SSBC has clearly changed the strength of the system consistent with the performance level for which it is adjusted, with no effect on the elastic stiffness. No hardening occurs in the systems with SSBC during the slippage due to the E-PP behavior of SSBC.

![Figure 6. Comparison of pushover curves between the original and retrofitted structure by SSBC.](image)

The target drift of the structures has been determined for the Maximum Considered Earthquake (MCE) of Los Angeles shown in Figure 8 [21]. In Table 1 the summary of pushover analysis results is provided, and in Figure 7 the distribution of the panel zone plastic deformation and inter story drift demands in the height of structures are presented. Based on the plastic deformation demands in panel zones, the performance level of the original WPZ structure is Collapse Prevention (CP). Also, it is evident that SSBC has effectively improved the performance of the structure as it was designed by decreasing the deformation demands to the limits provided in FEMA-356 [19]. The base shear demand has been also decreased in both SSBC-IO and SSBC-LS about 30% and 5% which is due to the reduced strength of the structures retrofitted with SSBC compared to original structures. Note that Using SSBCs has almost no effect on the expected inelastic drift while it is increased about 10% in SSBC-IO structure. According to Figure 7 SSBC has effectively reduced the plastic shear deformation in panel zone resulting to improvement of the performance of the structure, while slightly increasing the inter story drift angles without affecting the pattern.

<table>
<thead>
<tr>
<th>Computed Quantity</th>
<th>Original</th>
<th>SSBC-IO</th>
<th>SSBC-LS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expected Inelastic Drift (%)</td>
<td>1.50</td>
<td>1.66</td>
<td>1.50</td>
</tr>
<tr>
<td>Base Shear Demand (kN)</td>
<td>3690</td>
<td>2570</td>
<td>3520</td>
</tr>
<tr>
<td>Peak Inter Story Drift (%)</td>
<td>2.346</td>
<td>2.858</td>
<td>2.424</td>
</tr>
<tr>
<td>Max. Beam Plastic Rot. (θp/θy)</td>
<td>3.84</td>
<td>0.00</td>
<td>3.55</td>
</tr>
<tr>
<td>Max. Column Plastic Rot. (θp/θy)</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Max. Panel Zone Rot. (γp/γy)</td>
<td>8.75</td>
<td>0.85</td>
<td>6.98</td>
</tr>
<tr>
<td>Max. SSBC Slippage (mm)</td>
<td>-</td>
<td>105</td>
<td>43</td>
</tr>
<tr>
<td>Structure Performance Level</td>
<td>CP</td>
<td>IO</td>
<td>LS</td>
</tr>
</tbody>
</table>
Nonlinear dynamic analysis

Due to the assumptions and uncertainties inherent in the pushover analysis methods, it is rational to consider the use of time-history analysis to capture the response of the structure and obtain reasonable estimates for the demands on the structure. In this section time history analysis is conducted including P-Delta effects for a set of seven ground motions using PERFORM-3D [16]. Rayleigh damping is used to represent viscous energy dissipation in the structure. Here the damping in the range of $0.2T_1$ and $0.9T_1$, where $T_1$ is the first mode translational period, is adjusted to be approximately 5%. Following the considerations of ASCE/SEI 7-10 [21], seven earthquake ground motions are selected from the Pacific Earthquake Engineering Research Center (PEER) ground motion database [22]. Basic information for the records is given in Table 2.

Earthquake accelerograms are adjusted to match the MCE target response spectrum employed in nonlinear static analysis using the wavelets algorithm proposed by Abrahamson and Hancock et al. [23, 24]. The scaling was performed by SeismoMatch program (SeismoSoft 2013) [25]. The mean matched spectrum is compared to the target spectrum in Figure 8 that clearly match well over the period range of $0.2T_1$ to $1.5T_1$ according to ASCE/SEI 7-10.

<table>
<thead>
<tr>
<th>Earthquake Name</th>
<th>Magnitude</th>
<th>Station Name</th>
<th>Peak Ground Acceleration (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Erzincan</td>
<td>6.8</td>
<td>Erzincan</td>
<td>0.495</td>
</tr>
<tr>
<td>Imperial Valley</td>
<td>6.8</td>
<td>Superstition Mountain</td>
<td>0.109</td>
</tr>
<tr>
<td>Landers</td>
<td>7.5</td>
<td>Amboy</td>
<td>0.115</td>
</tr>
<tr>
<td>Loma Prieta</td>
<td>7.1</td>
<td>Coyote Lake Dam, Downstream</td>
<td>0.16</td>
</tr>
<tr>
<td>Northridge</td>
<td>6.7</td>
<td>Sylmar</td>
<td>0.612</td>
</tr>
<tr>
<td>San Fernando</td>
<td>6.7</td>
<td>LA - Hollywood Stor</td>
<td>0.209</td>
</tr>
<tr>
<td>Tabas</td>
<td>7.4</td>
<td>Dayhook</td>
<td>0.327</td>
</tr>
</tbody>
</table>
Figure 8. Design spectrum for scaling acceleration time histories based on ASCE7-10.

The Summary of results from Time history analysis is provided in Table 3. The distribution of mean value of the peak inter story drift and plastic rotations in panel zones are also depicted in Figure 9, and also compared to the results from pushover analysis. From Figure 9, the demands distribution pattern from the nonlinear dynamic analysis is in good agreement with the nonlinear static analysis, whereas in the pushover analysis demands are slightly overestimated. According to Table 3, the performance of the original WPZ structure is found to be LS based on the nonlinear dynamic analysis, thus SSBCs designed to reach LS performance level has only reduced the plastic deformation demand in panel zones about 14%.

Table 3. Mean of the maximum demands from time history analyses.

<table>
<thead>
<tr>
<th>Computed Quantity</th>
<th>Original</th>
<th>SSBC-LS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expected Inelastic Drift (%)</td>
<td>1.24</td>
<td>1.25</td>
</tr>
<tr>
<td>Peak Inter story Drift (%)</td>
<td>2.04</td>
<td>2.06</td>
</tr>
<tr>
<td>Max. Beam Plastic Rot. (θp/θy)</td>
<td>2.84</td>
<td>2.91</td>
</tr>
<tr>
<td>Max. Column Plastic Rot. (θp/θy)</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Max. Panel Zone Rot. (γp/γy)</td>
<td>7.04</td>
<td>6.04</td>
</tr>
<tr>
<td>Max. SSBC Slippage (mm)</td>
<td>-</td>
<td>25</td>
</tr>
<tr>
<td>Structure Performance Level</td>
<td>LS</td>
<td>LS</td>
</tr>
</tbody>
</table>

Figure 9. Comparison of the distribution of demands in height of the structures from nonlinear static and dynamic analysis: (a) inter story drift angle; (b) plastic rotation in panel zones.
Conclusions

In this study the Slotted Bolted Connections (SBCs) are developed for use as a mechanical shear fuse in some conventional lateral load resisting systems such as framed tube structures, EBFs and CCSWs as a new type of friction damper to provide a non-destructive energy dissipation system. After introducing the SSBC system and its applications, the behavior of SSBC in a portal Moment Resisting Frame (MRF) with 4.75m span length is investigated through the finite element modeling in the software package ABAQUS/implicit. Also, SSBC is employed to retrofit an existing 9-story MRF with weak panel zones. The nonlinear static analysis is conducted to assess the performance of the structures using the PERFORM-3D computer Program. Finally, the results of the pushover analysis are evaluated more reasonably by conducting the nonlinear time history analysis. According to the results:

- SSBC could be applied in MRFs to replace the flexural plastic hinges with a mechanical shear fuse. The behavior of SSBC is associated with a hardening that directly depends on the degree of the constraint between two ends of the beam. In the case of MRF with 4.75m span length, when the beam ends are fully constrained, 27% hardening occurs in 3% drift ratio. In conventional buildings the constraint can be only imposed by the slab atop the beam. In case no special detailing is considered to provide sufficient in-plane rigidity for concrete slab, the constraint will not be fully developed.

- SSBC could effectively improve the performance level of an existing structure with MRFs as lateral load resisting system from Collapse Prevention (CP) to Life Safety (LS) or Immediate Occupancy (IO) by working as a structural fuse to control the plastic deformations in structural components. The flexibility in adjusting the behavior of SSBC is provided by adjusting the bolts number and pre-tension load, making it possible to enhance the response of the structures.

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