EXPERIMENTAL INVESTIGATION OF BOLT-CONFIGURED NATURALLY BUCKLING BRACE WITH GUSSET PLATE CONNECTION

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Abstract

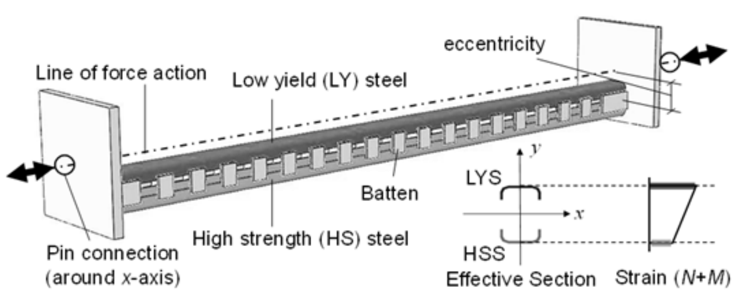
The Naturally Buckling Brace (NBB) is a steel brace developed by the writers, which consists of a high-strength and low-yielding steel channel arranged in parallel with an intentional eccentricity along the brace length. The NBB deforms with a novel mechanism providing ductile seismic behavior, and overcomes the deficiencies of conventional steel braces. To further improve the construction of NBB for practical applications, the present study examines the following configurations: 1) use gusset plate connections designed to accommodate inelastic rotations instead of mechanical pins; 2) use bolts instead of welding to connect the two channels together; 3) apply intentional eccentricity along the brace length with the aid of a steel block or steel knife plate. The efficiency of these suggestions was evaluated by conducting cyclic quasi-static tests in three specimens. The test results showed that the proposed configurations keep the beneficial seismic performance of the original NBB configuration, experiencing similar cyclic responses mainly up to 2% story drift.

Keywords: Steel brace; Gusset plate; Eccentricity; High strength steel; Low yield steel

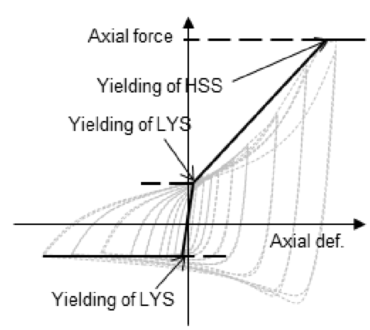
1. Introduction

Steel concentrically braced frames (CBFs) are commonly used as seismic resisting systems in buildings in regions of high seismic activity. CBFs can be classified as conventional buckling braced (CBBs) frames, also called special concentrically braced (SCBs) frames. However, CBBs have several weaknesses: a) they inherently provide large stiffness and strength which increase the seismic acceleration and therefore, the base shear in the structures; (b) damage concentrates at the mid-length of the brace, which results in intense local buckling, followed by premature fracture [1]; (c) they provide very limited post-yielding stiffness, which inherently results in a rapid increase of the inelastic deformation under a strong seismic loading and thereby, the possibility of occurrence of the soft-story collapse mechanism increases [2]. To overcome these deficiencies, the writers have proposed a new brace design which deforms with a novel mechanism, called the naturally buckling brace (NBB). The NBB simultaneously overcomes those three weaknesses providing reduced initial stiffness, large post-yielding stiffness and high ductility capacity, and thus becomes an alternative for steel bracing frame systems [3].

As shown in Fig. 1 (a), the original NBB configuration consists of a high-strength (HS) and a low yield (LY) steel channel arranged in parallel and bound together with a series of battens, while a specified eccentricity through the brace length is applied. Owing to the moment contribution caused by the eccentrically applied axial force, the strain distribution along the cross-section is not constant unlike conventional braces. The LY steel segment starts yielding under a low axial force and plays the role of the energy dissipater capable of sustaining large strain demands (Fig. 1 (a)). On the contrary, the HS steel channel remains elastic and undamaged until very large deformation, since the values of strain in HS segment remain at low levels (Fig. 1 (a)). Because of this “cooperation” between the LY and HS steel channels, NBBs exhibit an advanced hysteresis loop, as shown in Fig. 1 (b). Under tension, the NBB displays tri-linear behavior, while under compression displays bi-linear behavior. Six specimens subjected to cyclic loading up to 4% story drift were examined in the previous series of tests [3], where mechanical pins were used to connect the specimens to the surrounding loading frame. However, NBB configuration still has some difficulties for practical application in terms of construction efficiency. The present papers experimentally investigates improvements on the original NBB’s configuration characterized as follows: a) the improved NBB is connected to the surrounding steel frame using gusset plates (GP) instead of mechanical pins; b) the two NBB’s channels are connected together along the brace length using bolts instead of welded battens; and c) the intentional eccentricity along the brace length is applied with the aid of a ‘steel knife plate’ or ‘steel blocks’ instead of end plate connections. A total of three half-scaled specimens were subjected to cyclic loading protocol up to the 4% story drift to evaluate the efficiency of the aforementioned configurations.



(a)



(b)

Fig. 1 - Introduction of previous NBB: (a) configuration; (b) hysteresis loop and backbone curve [1]

2. Proposed Brace Configuration

2.1 Pin behavior adopting gusset plate connection

AISC [4] suggests the use of appropriately designed GP to allow out-of-plane rotation of brace. Since the performance of original NBB was investigated by adopting mechanical pins at the brace ends, to simplify the brace connections further, GPs are proposed in this study.

According to the AISC [4], the fold line between the brace ends and beam-column restrained part is called "clearance distance" (Fig. 2), and should be able to accommodate out-of-plane rotations of steel braces. More specifically, a 2*t* (twice of the GP thickness *t*) clearance distance is recommended for a better strain distribution within the folded area. Although it is known that larger clearance distance reduces the strain demand in folded area [5], extremely large value may result in buckling failure within the clearance distance [6].

Compared to CBB, the NBB naturally buckles out-of-plane at small story drifts under both tension and compression, due to the additional moment caused by the eccentric applied force (Fig. 1(a)). This behavior indicates that clearance distance larger than 2*t* may be needed to prevent the GP from high concentration of cumulative strains due to cyclic loading. In this study, the GPs were designed according to AISC [4] recommendations, adopting 3*t* clearance distance for the specimens. Since there is no example of application of GP connection to brace with intentional eccentricity, this clearance distance width was chosen based on extensive nonlinear finite element analyses.

2.2 Cross-section configuration

In the NBB concept, two channels of HS and LY steel are connected together to form a built-up compact cross-section and therefore, when the brace deforms, the plain sections remain plain. For this reason, a conservative connection way had been adopted in the original NBB configuration [3], where a sufficient number of welded battens were used to connect the two channels, as shown in Fig. 3 (a). Instead of that, a new section configuration using bolts is proposed in this study (Fig. 3 (b)) to avoid the "multi-point" welding around each batten area. The shape of channel is modified to a new shape, which has an extended part at the web side with wing-shape cold-formed by a press bending machine. First, the steel plate is CNC cut into shape with "wings" at all original batten locations, and then, is bent to form the wing-shape channel. The two channels are connected together using four bolts (two at each side), as shown in Fig. 3 (b).

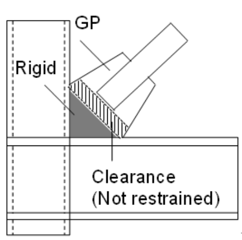


Fig. 2 – Clearance distance of GP [4]

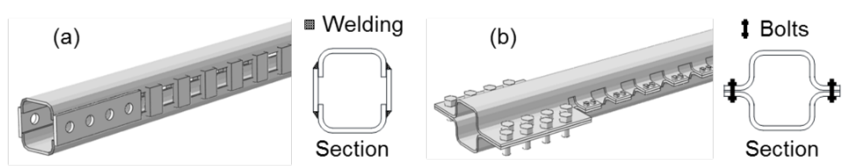


Fig. 3 - Channel connection: (a) original design; (b) modified design

2.3 Applying eccentricity

Although GP connections have been developed and adopted by many researchers [7, 8] in bracing frames, there is no application to date to incorporate intended eccentricity. Considering that eccentricity can be accomplished by means of GPs, two different GP connections are proposed in this study, as shown in Fig. 4.

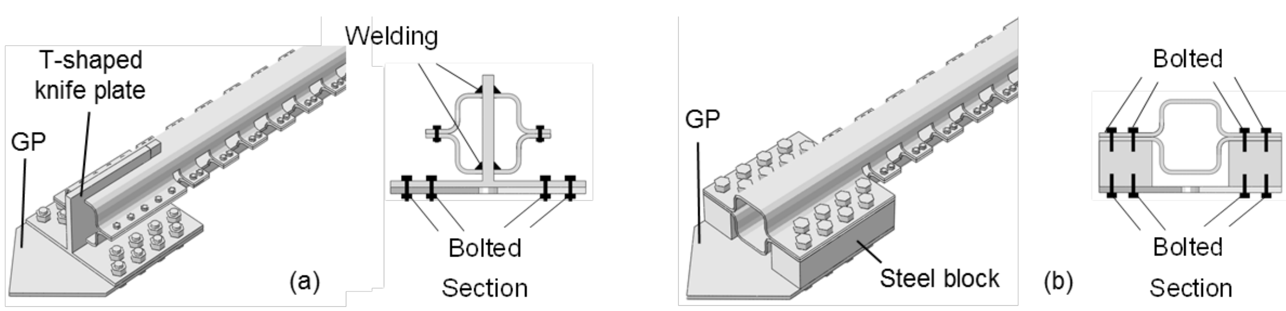


Fig. 4 - Detail configurations of the proposed connection: (a) T-shaped connection; (b) steel block connection

First, a relatively popular connection by using a knife plate illustrated in Fig. 4 (a) is proposed. In this configuration, a T-shaped knife plate is fabricated using two steel plates perpendicular welded each other. The T-shaped steel is inserted to the brace ends through slots and is welded to the NBB in the slots. Then, the T-shaped knife plate is bolted to the GP, and the T-shaped connection is created. As an alternative to knife plate, a steel block (Fig. 4(b)) is used to construct bolted connections, thus avoiding entirely the welding areas. The steel block connection shown in Fig. 4 (b) is fabricated by inserting two steel blocks between the brace end and GP, and then they are bolted together.

3. Test Specimens and Setup

To examine the proposed NBB configurations, three half-scaled test specimens were subjected to quasi-static cyclic loading. Details on dimensions of specimens are shown in Fig. 5, and basic information of each specimen including material properties is summarized in Table 1. In Table 1, the quantities t, F_y and F_u denote thickness of GP, yield stress and tensile strength, respectively. The primary test parameters were the following: 1) Support (GP or Mechanical pin); and 2) Brace end connection type (end plate, steel block, or knife plate). In all specimens, HS and LY steel channels are connected by bolting in 'wing' portion. Each letter in the specimen nomenclature of Table 1 indicates the support (G for gusset plate and P for mechanical pin) and the connection type (E for end plate, B for steel block, and K for knife plate), respectively. The exterior radius of the rounded corners of the steel channels was equal to three times the steel plate thickness. All specimens were designed to have identical

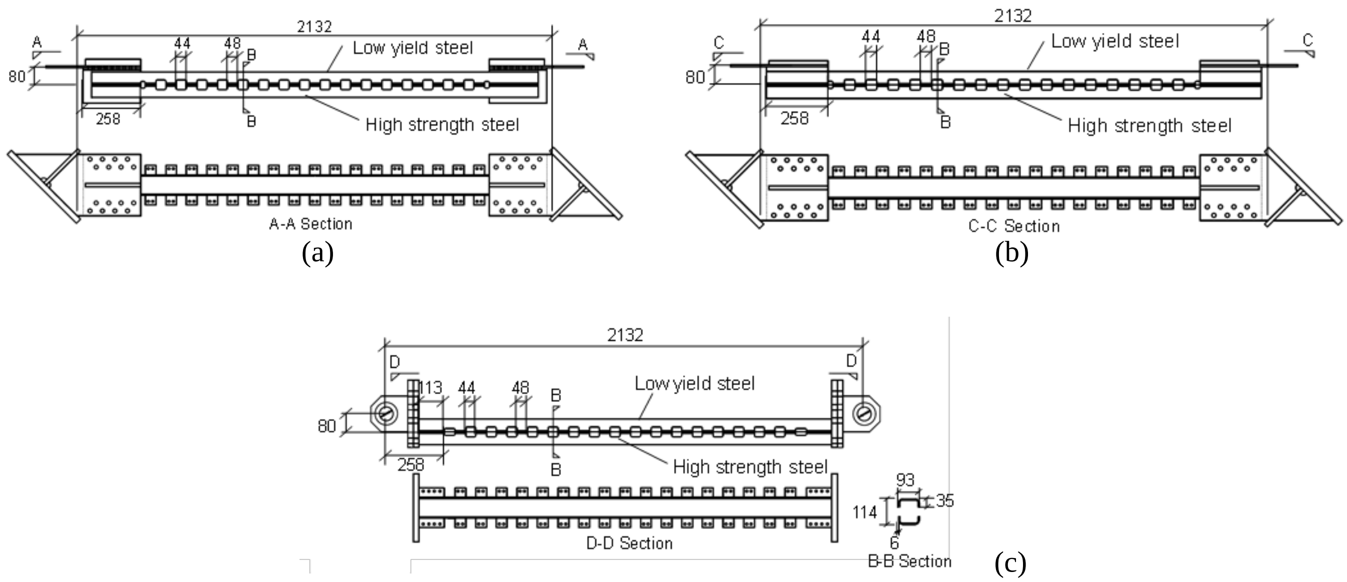


Fig. 5 - Dimensions of all specimens: (a) G-K; (b) G-B; (c) P-E

Table 1 - Dimensions and material properties of test specimens

Specimen	Section config.	Support	Connection	Channels			Gusset Plate		
				Steel type	F_y/F_u (MPa) HS	F_y/F_u (MPa) LY	Steel type	F_y/F_u (MPa)	t (mm)
G-K	Wing	GP	Knife plate	HS/LY	548/619	59/239	CS	333/468	9
G-B	Wing	GP	Block	HS/LY	548/619	59/239	CS	333/468	9

P-E	Wing	Pin	End plate	HS/LY	548/619	59/239	N/A	N/A	N/A

characteristics, such as pin-to-pin length, eccentricity, and rigid length of brace ends. The GPs were designed to have the 3*t* clearance distance as explained in previous section and 9mm thickness. It should be noted, that the connection examined in this study (use of knife plate, steel block, and end plate) were designed to behave in a rigid manner.

The slenderness ratio λ (=KL/r) of specimens calculated for buckling around the major *x*-axis and around the minor *y*-axis are λ_x=44.1 and λ_y=31.1, respectively (each axis shown in Fig. 1 (a)). The coefficient *K* defines the effective length which is equal to 1.0 around *x*-axis and equal to 0.5 around *y*-axis, considering the different boundary condition. The parameters *L* and *r* denote the pin-to-pin length and the radius of gyration of the brace.

The channel segments of specimens were fabricated by high strength steel named WEL-TEN590RE and low yield steel named JEF-LY100, while the GP was fabricated by conventional steel named SS400. The material properties are shown in Table 1.

Fig. 6 shows the loading system. The NBB specimens were installed into the four-pin frame with 45 degree angle, where only the steel brace can resist to the applied force. The loading frame was controlled by an oil-jack connected to the top of the frame. A cyclic loading protocol with increasing amplitudes from a story drift angle of 0.1 to 4.0% radians with two cycles imposed at each drift level was adopted. The lateral displacement was calculated based on the axial measured displacement, and then was divided by the story height (= inside measure of four-pin frame) to define the story drift angle. Five LVDTs to measure the deformed shape of the brace and two LVDTs to measure the axial displacement located on both sides of brace were used. The axial displacement was calculated as the average value of both measurements.

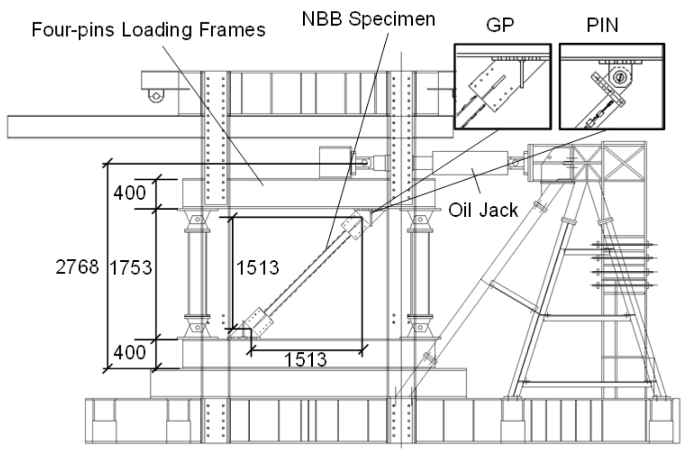


Fig. 6 – Test setup and loading system (unit: mm)

4. Experimental Results

4.1 Discussion on hysteresis behavior of NBBs

The hysteretic responses of the three test specimens are shown in Fig. 7. All specimens started yielding from small story drifts (yielding on LY steel flange was observed near to 0.03%~0.05% story drift in all specimens), and up to 3% story drift, their behavior was stable without pinching phenomena or significant strength deterioration. Because of the existence of HS steel channel which remained in its elastic range, large post-yielding stiffness of almost 15% of the initial stiffness was achieved under tension. The specimens continued to increase their tensile strength up to 4% story drift which is a large story drift in seismic design. Under compression, the specimen transitioned smoothly into post-buckling behavior, avoiding a severe drop in compressive strength, and an almost elastoplastic behavior was observed up to 2~3% story drift. In the second compression cycle of 3.0% drift, local buckling was observed in all specimens, leading to pinching and deteriorating behavior. The tests were completed without observing any fracture in all specimens. According to the aforementioned seismic performance, all specimens exhibited the desired and beneficial behavior that characterizes the original NBB configuration [1]. These results indicate that the proposed bolted wing-shaped cross-section configuration satisfied the assumption that plain section remains plain along the brace length. Therefore, bolted wing-shaped cross-section can be considered as a handy alternative for the NBB configuration. Finally, it was also observed that GP properly behaved as a pin, as shown in Fig. 8. A plastic hinge was formed along the GP clearance distance which rotated uniformly, following the brace deformation under both tension and compression. No discernible damage (e.g. fracture) was observed in GP and welds.

4.2 Influence of gusset plate

Fig. 9 shows comparisons between the hysteretic loops of the specimens with GP (G-K and G-B) connections and that with mechanical pin (P-E). Although the connections of the brace ends to the GP are different (end plate, knife plate, and steel block), their influence on the hysteretic loop is found to be negligible since they behaved as rigid portions.

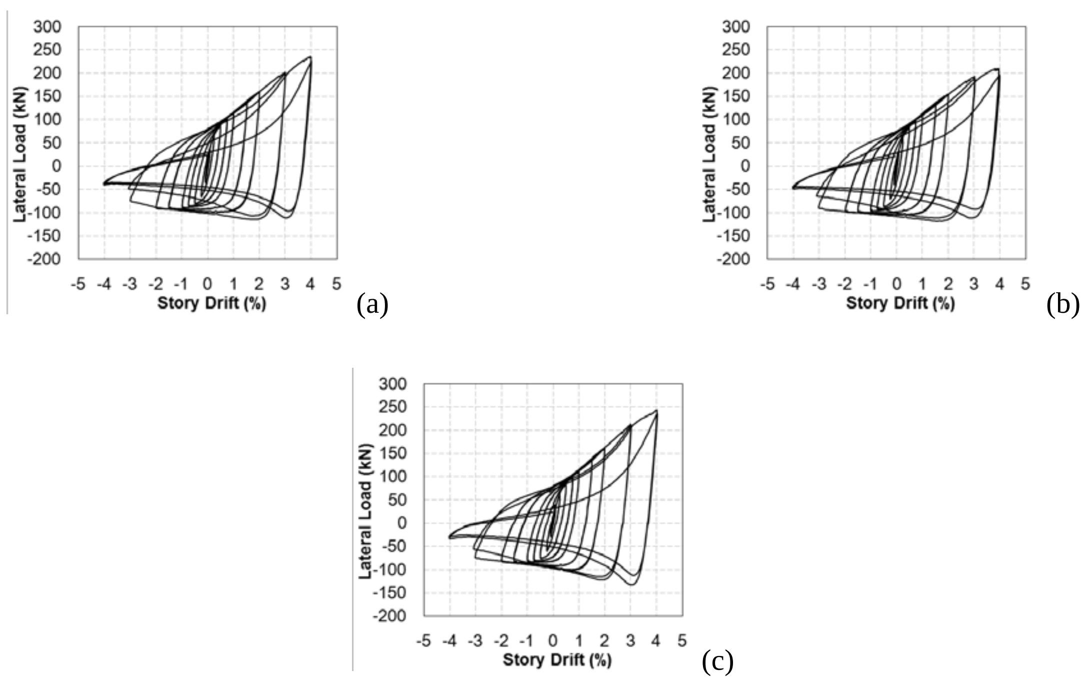
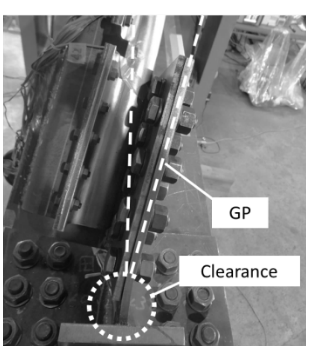


Fig. 7 - Hysteretic responses of specimens: (a) G-K; (b) G-B; (c) P-E



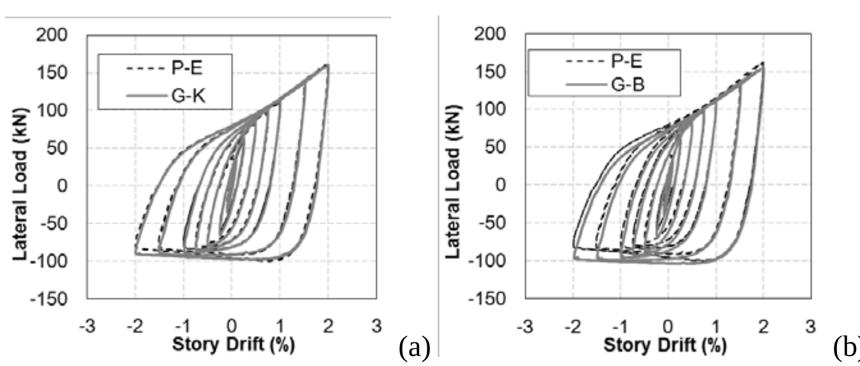


Fig. 8 – Observed GP rotation (G-K)

Fig. 9 - Comparison between specimens with 'GP' and 'Pin': (a) G-K and P-E; (b) G-B and P-E

The test results presented in Fig. 9, show that the specimens with GP connections (G-K and G-B) reached 10~19% larger compressive strength (2% story drift) and had 8~10% larger initial stiffness, while no significant influence was observed in the tensile strength. This increase in the compressive strength and initial stiffness of the member is caused by the rotational end restraint of the brace due to GP, which decreased the effective brace length. The rotational stiffness of GP influenced the behavior of the NBB, but not to such an extend to be considered as significant. The GP thickness affects the rotational stiffness of GP [7] and thereby the performance of the NBB–GP system is a subject for further investigation.

5. Conclusion

This study focuses on the improvement of naturally buckling brace (NBB) construction. Brace connections configured by gusset plate (GP) instead of mechanical pin, bolted built-up cross-section instead of welded one, and two connections for applying eccentricity (knife plate or steel block connection) instead of end plates, were proposed. The efficiency of the new NBB configurations was evaluated by three test specimens subjected to quasi-static cyclic loading. Notable observations are as follows:

1) The tests were completed up to 4% story drift without observing any rupture failure. All specimens appeared the desired and beneficial behavior (dissipation energy at small drifts, large post-yielding stiffness, and high ductility) that characterizes the original NBB configuration.

2) Two different GP connections were developed to accommodate the eccentricity in NBB concept. The GP behaved properly as a pin following the brace deformation under both tension and compression. No discernible damage (e.g. fracture) in GP and welds and no local deformation in connections were observed.

3) The specimens with GP connections reached 10~19% larger compressive strength (2% story drift) and had 8~10% larger initial stiffness. The rotational stiffness of GP influenced the behavior of the NBB, but not to such an extend to be considered as significant.

6. References

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