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Experimental Investigation of Special Concentrically Braced Frames with In-plane Buckling Braces for Ductility-based Design

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ABSTRACT

The damage of non-structural components in the concentrically braced frames (CBFs) during the strong earthquakes can reduce the profitability of the braced frame structures. In order to avoid such failure, a new type of connection called in-plane buckling of the braces is introduced in the CBFs system recently. However, due to the limited studies and lack of guidance on the various critical limits states, pre-mature fracture was observed in the past experiments. Special concentrically braced frame (SCBFs) are designed to provide higher ductility as well as higher energy dissipation by avoiding pre-mature fracture in the connections and by achieving the fracture at the mid-location of braces which is the most desired failure mode for the SCBFs structures. In the present study, a brief review of the structural deficiency in the design of the in-plane braced frame system is highlighted. The analytical equations to prevent the highlighted critical limit states were discussed. Experimental studies were conducted on specimens designed based on proposed methodology. The influence of the linear clearance of the knife plate on the performance of the in-plane brace system has been also studied. The other parameters considered in the present studies are displacement ductility, cumulative energy dissipation and failure mechanism. The results showed that by increasing the linear clearance distance of the knife plate (from $3t_p$ to $6t_p$, where t_p is the thickness of the knife plate), both ductility and energy dissipation potential are increased keeping all other parameters as constant. This shows that by reducing the rigidity of the knife plate, the performance of the brace frame can be improved. Hence, the linear clearance of $6t_p$ was suggested in the detailing of connections of the SCBFs frame system with in-plane buckling braces.

Keywords: Knife plate, Linear clearance, Experimental investigation, Design procedure, Gusset plate, Displacement ductility.

INTRODUCTION

Concentrically braced frame (CBFs) are considered as one of the lateral force-resisting systems in the earthquake-prone areas. These frames consist of conventional steel braces arranged in various configurations in such a way that the line of action of brace forces meet at a point on the supporting beam member. Special concentrically braced frames (SCBFs) are the type of CBFs designed in order to achieve the high level of displacement ductility and the better hysteretic energy dissipation [1]. The performance of the SCBF system highly depends on the brace components and their connections because any premature fracture can lead to the undesired performance of the system. Displacement ductility in SCBFs is achieved through the inelastic deformation of braces in tension/compression. The increase in the overall slenderness ratio and the decrease in the width-to-thickness ratio of brace section improve the ductility level of the brace system. The post-buckling behavior of compression braces also greatly influences the displacement ductility. The flexural buckling of compression braces induces the formation of plastic hinges at three locations, i.e., at both ends and mid-length of braces. Allowing the plastic hinges to form in the end connecting (or gusset) plates, rather than in braces, increases the energy dissipation and deformability under cycle loading. The formation of flexural plastic hinges in the gusset plates allow the out-of-plane buckling of the compression braces. The in-plane buckling (IPB) brace system is introduced recently [2] to limit the damage of the non-structural components in SCBFs. In case of the IPB brace system, the knife plates between the brace component and the gusset plate are allowed to undergo the inelastic felxural displacments while the gusset plates are designed to remain elastic. If the braces are directly connected to the beams/columns of SCBFs, all three plastic hinges are formed in the brace components. Figure 1 shows the three possible types of brace connections in SCBFs and the potential locations of plastic hinges in these arrangements. Limited studies have been conducted to understand the cyclic performance of the IPB brace system [3]. Adopting a balanced design procedure with the rectangular elliptical clearance of 8 times thickness of plate (t_p) in the detailing of corner gusset plates can significantly improve the seismic performance of SCBFs with the out-of-plane buckling braced connection [4].

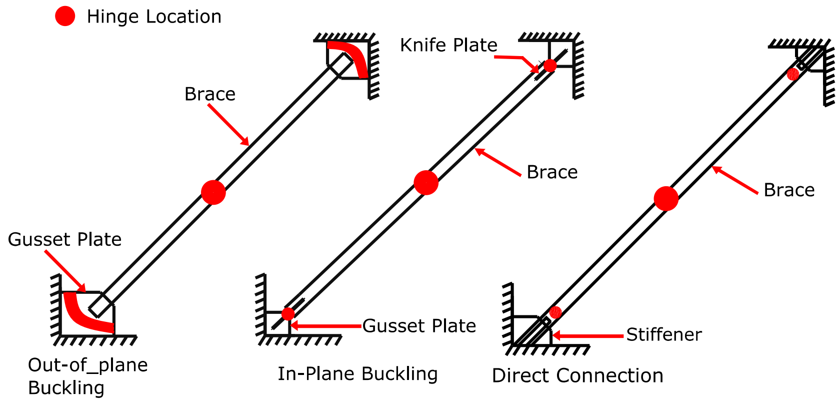


Figure 1. Locations of plastic hinges in different type of connection of the SCBF system.

Out of the three types of connections, the IPB brace system buckles may help in reducing the damage to the non-structural components under seismic loading. The first experiment on the in-plane buckling brace system was conducted by Lumpkin[5]. The linear clearance of $2t_p$ was provided in the knife plate for the formation of the secondary hinges. Further studies highlighted the areas of improvement in the design of IPB brace system in order to avoid the premature failure and to achieve the desired performance. A review of past studies has been presented in the next section.

In the present study, two large-scale IPB brace systems were tested under the displacement-controlled quasi-static loading. The tested specimens were designed using the newly proposed design procedure to prevent the failure from the critical limit states, such as, the out-of-plane bending of the gusset plate and the failure of the interface weld of the gusset plate to beam-column junctions. The linear clearance of the knife plates was varied from $3t_p$, where t_p was the thickness of the knife plate as recommended by ASIC 341-16[1] to $6t_p$ in the connection detailing to study the influence of the clearance of the knife plate on the fracture ductility and cumulative energy dissipation. The performance of the knife plate, gusset plate and brace at different story drift level were also documented.

REVIEW OF PAST EXPERIMENTAL STUDIES

Most of the research in the past was focused on the performance of the out-of-plane buckling brace system. Various guidelines were provided to avoid premature fracture for the out-of-plane buckling brace system. A balanced design procedure was proposed by Roeder *et. al.* [4] to increase the performance of the brace frame system by maximizing the inelastic drift of the out-of-plane brace system. One of the major problem observed in the out-of-plane buckling brace system is that the out-of-plane displacement of the braces are about 500 mm at a lateral drift of 4% [6]. Due to this very high out-of-plane displacement, many non-structural components may get damage and increase the downtime of the building in the major seismic events. IPB brace system can limit the damage to the non-structural components due to the reduced brace displacements [7].

Very limited studies have beeen conducted on the IPB brace system till date. All the limit states for the design of the IPB brace system also not considered in the studies which lead to premature fracture that was observed in the past experimental studies. Figure 2(a) shows the in-plane buckling of braces [7]. One of the major problems for the IPB brace system is the out-of-plane bending of the gusset plate as shown in Figure 2(b). There is also no such limit state available in the design guidelines to prevent the out-of-plane buckling of braces in the in-plane brace system. In case of the IPB brace system, the knife plate acts as the hinge plate, and secondary hinges accommodate in it. The gusset plate of the IPB brace system was designed to remain elastic. But unknown demand on the gusset plate because of the in-plane buckling of the IPB brace system, inelasticity can introduce in the gusset plate connection. Figure 2(a) and (b) shows the failure of the gusset plate due to the out-of-plane bending of the gusset plate. Figure 2(c) and (d) shows the failure of the gusset plate connection at the beam-column junction. This creates a question on the efficiency of the predicting the edge forces of the IPB brace system. Figure 2(e) and (f) shows the crack in the knife plate for the linear clearance of $2t_p$ and $3t_p$ respectively. The failure of the knife plate signifies two things, i.e., (i) the knife plate is rigid which leads to the failure, or (ii) the knife plate is less stiff to take loads of the brace system. The first case will reduce the displacement ductility, and vice-versa. AISC 341-16[1] recommends $3t_p$ linear clearance for the IPB brace system. However, the crack in the knife plate will not create a problem if it is stable and does not initiate the fracture. The next section shows the different limit states that need uttermost care for the better performance of the brace frame system.

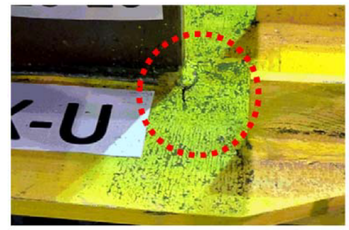
(a) In-plane buckling of IPB brace system [7]

(b) Out-of-plane buckling of IPB brace system[7]

(c) Weld failure of gusset plate[7]

(d) Bolt failure of gusset plate[7]

(e) Crack in knife plate(LC-2t_p)[4]



(f) Crack in knife plate(LC-3t_p)[2]

Figure 2. Mode of failure of past experiments of IPB brace system

CRITICAL LIMIT STATES

Most of the code around the globe provide the guideline for the design and detailing of the out-of-plane buckling braced system. Despite the merits of the IPB brace system, their uses in the real structures are very limited. This may be due to the premature fracture (as shown in Figure 2) and the limited experimental study on the IPB brace system. AISC 341-16[1] has introduced the IPB brace system in their newly published provision in 2016. However, the design limit states such as to prevent out-of-plane displacement of gusset plate, and failure of the interface weld of the gusset plate were absent from the code. Table 1 shows the various limit states for the design of the IPB brace system. The difference between out-of-plane and in-plane buckling brace system is that the former used the gusset plate and later used the knife plate for the formation of the secondary hinges. The design of the IPB brace system was done for the various limit states as mentioned in Table 1 and using the proposed design procedure by the authors [8] for the critical limit states mention in serial no. 9 and 13 of Table 1. At the end of the experiments, the performance of the proposed procedure were checked. A detailed discussion of these limit states can be found elsewhere [8]. The proposed design procedure has been briefly presented in this paper.

The out-of-plane bending of the gusset plate will be prevented if the capacity of the out-of-plane bending moment of the gusset plate is greater than that of plastic moment of the knife plate. In order to calculate the out-of-plane bending capacity of the gusset plate, the edges forces on the gusset plate are calculated. Two critical cases are considered. First one assumes the connection is loaded with the tensile capacity of the brace and in the second case, the connection is subjected to a force equal to the buckling strength of the brace plus the plastic moment of the knife plate. A new equation is proposed to calculate the edge forces due to the plastic moment of the knife plate which are added to the edge forces due to the maximum compressive load [8]. Once the edge forces are calculated, the out-of-plane bending moment is calculated using the interaction equation as follows [9] :

$$\left(\frac{P_u}{\beta R_y P_y}\right)^2 + \left(\frac{V_u}{\beta R_y V_p}\right)^4 + \left[\left(\frac{M_{ux}}{\beta R_y M_{px}}\right)^{1.7} + \left(\frac{M_{uy}}{\beta R_y M_{py}}\right)^{1.7}\right]^{0.59} \leq 1 \tag{1}$$

where P_u is the compression force at the gusset edge due to brace compression specified in AISC 341-16, V_u is the shear force at the gusset edge due to brace compression force specified in AISC 341-16, M_{ux} is the in-plane moment at the gusset edge due to brace compression as specified in AISC 341-16, M_{uy} is the out-of-plane moment at the gusset edge due to deformation from brace buckling, β is the resisting factor, R_y is the ratio of the expected yield stress to the specified, $\beta R_y P_y = 0.9 R_y F_y L t_p$ is the gusset plate edge expected compression strength, $\beta R_y V_p = 0.9(0.6 R_y F_y L t_p)$ is the gusset plate edge expected shear strength, $\beta R_y M_{px} = \frac{0.9 R_y F_y L^2 t_p}{4}$ is the gusset plate expected flexural In-plane strength, $\beta R_y M_{py} = \frac{0.9 R_y F_y L t_p^2}{4}$ is the gusset plate expected flexural Out-of-plane strength, F_y is the specified minimum yield stress, L is the length of fillet welds on gusset plate edge and t_p is the gusset plate thickness. The gusset plates need to be redesigned if the moment capacity of the gusset plate is less than that of plastic moment of the knife plate. The end connection of the gusset plate to the beam and column junction is calculated based on the calculated edge forces.

Table 1. Different limits states for design of IPB brace system

Sl. No.	IPB system
1	Yielding of knife plate
2	Failure of brace net-section
3	Failure of brace to knife plate weld
4	Failure of brace to knife base material
5	Block shear
6	Fracture of knife plate
7	Knife plate buckling
8	Gusset plate buckling
9	Failure of knife plate to gusset plate weld
10	To prevent out-of-plane disp. of gusset plate
11	Yielding of gusset plate
12	Fracture of gusset plate
13	Failure of interface welds of gusset plate

EXPERIMENTAL INVESTIGATION

In the present study, two large-scale experiments were conducted to evaluate the performance of the IPB brace system of the SCBF structure. The first specimen, i.e. IP-1 had a linear clearance of $3t_p$ in the knife plate for the formation of the secondary hinges. The gusset plate was designed to remain elastic, and the knife plate was excepted to accommodate the inelasticity in the seismic event so that the premature fracture could be avoided in the connection. The critical limit states, such as, the out-of-plane bending of the gusset plate and the failure of the interface weld of the gusset plate were cosnidered using the proposed design procedure as discussed above. This study will also help to quantify the performance of the proposed limits states. The second specimen, i.e. IP-2 was tested to study the influence of the clearance of the knife plate in the performance of the IPB brace system. The linear clearance that was adopted in the IP-2 was $6t_p$. Hollow circular sections (HCS) were adopted as braces. The geometric properties of braces are provided in Table 2. The main parameters studied were the displacement ductility, the cumulative energy dissipation, and the failure mechanism. The yield hierarchy was also observed and the performance of the in-plane brace system has been documented. This section will discuss the material properties, loading history, test setup and instrumentation used in the conducting the experimental studies.

Test specimen

The specimens were applied quasi-static displacement-controlled reversed cyclic loading up to the fracture of braces. The fracture at the mid-location of braces is considered as the desired failure mode for the SCBF structure. HCS braces used in this study conform to the Indian Standard specification of IS 1161[10]. Table 3 shows the structural details of the test specimens. The length of the brace was taken as the free length of the brace, i.e. end to end distance. The length of IP-1 and IP-2 are 2160 mm and 2264 mm, respectively. A slight variation in the length was observed due to the change in the knife plate size and the angle of the brace with the horizontal axis. The effective length factor (K) of the brace was taken as 1. The width-to-thickness ratio of the brace was 26 which satisfied the requirement of the highly ductile member as per AISC 341-16[1]. The slenderness ratio of the specimen IP-1 and IP-2 are 83 and 87, respectively. The slenderness ratio and the compactness ratio of the test specimen were compared with the limiting values provided in AISC 341-16[1] and found to be within the permissible limit as shown in Table 3.

Table 2: Geometric Properties of the Specimens Tested

Section	D (mm)	t (mm)	A (mm^2)
HCS 76.1x2.9	76.1	2.9	667

Coupon test results

Three ccoupons were taken from the various locations of the brace specimens. The brace used in the study was of the grade of Yst 210. The ultimate tensile strength of the brace of Yst 210 was 330 MPa with a minimum elongation of 20%. The coupon tests were conducted in accordance with ASTM E8/E8M-09[11] guidelines. Table 4 shows the average yield stress, ultimate yield stress and the percentage elongation of the brace. The material over strength factor (R_y) was found to be 1.33 from the coupon test results.

Table 3. Structural Details of the Specimens

Specimen	Section	Length (mm)	K	Slenderness ratio ($\lambda_{Spec.}$)	Compactness ratio $(D/t)_{Spec.}$	Theta (θ)	$\lambda_{Spec.}/\lambda_{AISC(\lim)}$	$(D/t)_{Spec.}/(D/t)_{AISC(\lim)}$
IP-1	HCS 76.1x2.9	2160	1	83	25.9	45	0.42	0.69
IP-2	HCS 76.1x2.9	2264	1	87	25.9	35	0.44	0.69

Table 4: Coupon Test result

Specimen	Material grade	Yield stress	Ultimate stress	Elongation	Over strength factor(Ry)
IP-1	Yst 210	284	341	20.1	1.33

Test setup and instrumentation

Figure 3 shows the experimental test set-up used for the conducting the tests. The test set-up was designed in such a way that the stiffness of the column-beam should not act when the lateral load was applied. This has been done in order to correctly predict the behaviour of the IPB brace system to the applied lateral drift. But the interaction of the gusset plate to the beam-column junction was taken in the test in order to evaluate the welding capacity of the gusset plate to beam-column junction. The focus was on the measurement of axial strain in the brace. The orientation of the brace with respect to the vertical axis should not affect the cyclic performance of the brace as the stiffness of the beam-column was not considered during the test. However, in order to simulate the real field condition, the gusset plates were welded to the beam and column as shown in Figure 4. This would help to determine the demand on the welding of the gusset plate in the beam-column junction.

Loading protocol

Quasi-static test were conducted to quantify the performance of the IPB brace system. The cyclic loading protocol was applied in the test specimens as per ACT-24 [12] with suitable modification. The loading protocol used in the experiment is shown in the Figure 5. Loading was not provided beyond 5% lateral drift, and the number of cycles at 5% lateral drift was 20 or the fracture of the brace, whichever was earlier. The lateral drift was converted into the axial deformation by using the following expression:

$$\Delta = \cos\theta \sin\theta L_B \alpha \tag{2}$$

where Δ is the axial deformation of the brace, θ is the angle the brace make with the horizontal axis measured anti-clockwise, L_B is the length of the brace and α is the lateral drift express in radian.

TESTS RESULTS

Displacement control test were conducted with having quasi-static loading protocol. The lateral drift was applied, and the lateral force was recorded from the actuator. Then, these components were converted to the axial force and axial displacement of the brace to study the performance of the brace. In this section, the summary of the experimental result of the IPB brace system were presented.

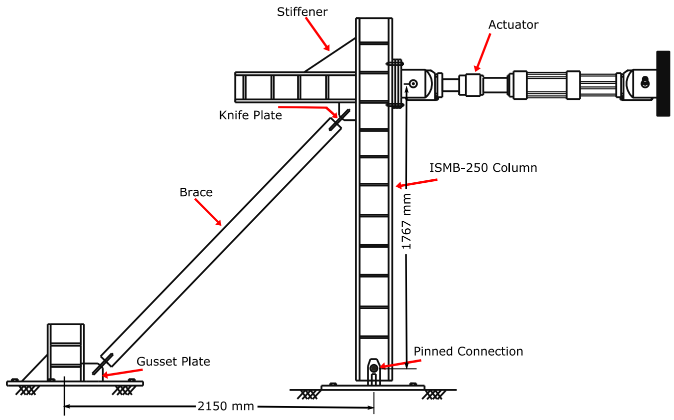


Figure 3. Test setup used in the Experiment

Figure 4. Detail of test setup and instrumentation

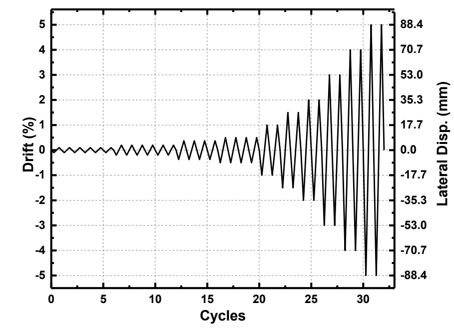


Figure 5. Loading Protocol

Hysteresis Response

Figure 6 shows the axial deformation and axial force (hysteretic) response of the IP-1 and IP-2 specimen under the applied lateral load. The buckling load of the IP-1 and IP_2 were found out as 143.3 kN and 114 kN, respectively. The drifts at which the buckling of the specimen IP-1 and IP-2 observed were noted as 0.36% and 0.34%, respectively. IPB-2 final fracture occured at the second cycle of 3% lateral drift, whereas the final fracture in specimen IPB-1 was noted at the first cycle of 2% lateral drift.

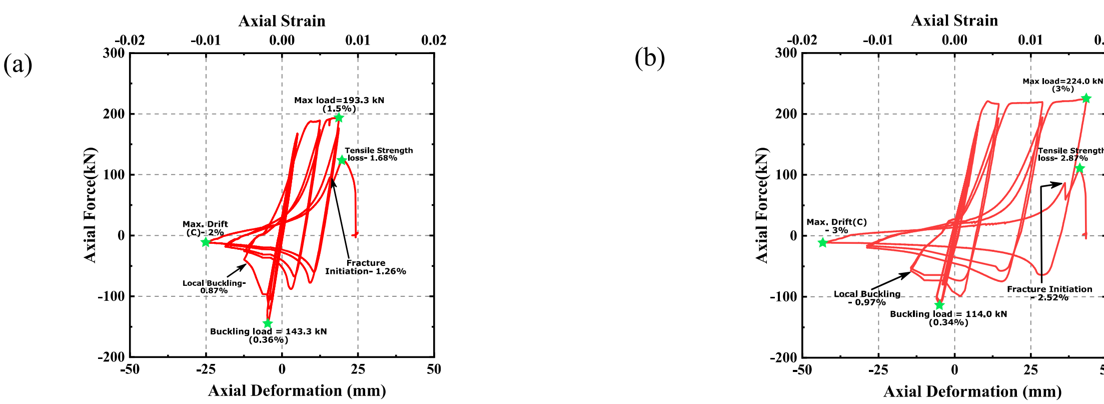


Figure 6. Hysteretic Response a) IP-1 specimen b) IP-2 specimen

Energy dissipation and displacement ductility

The brace after it buckled started to dissipate the energy. The dissipated energy was calculated as the area under the curve of axial force and axial displacement. The energy dissipated on each cycle was added to calculate the cumulative energy dissipated at each story drift. Figure 7 shows the plot of the energy dissipated per load cycle with the axial strain of the IP-1 and IP-2 specimens. The energy dissipation response showed that IP-2 specimen performed better than the IP-1 specimen. The displacement ductility measured the amount of axial force that the brace could undergo before fracture. Figure 8 shows the displacement ductility of the IP-1 and IP-2 specimens. The overall displacement ductility of the IP-1 and IP-2 were found out to be 10.5 and 18.4 respectively. It shows that the IP-2 with $6t_p$ linear clearance performed better than the specimen IP-1 with $3t_p$ linear clearance.

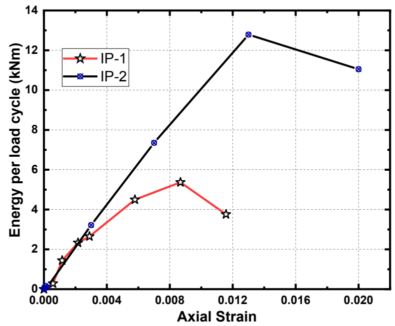


Figure 7. Energy Dissipation response

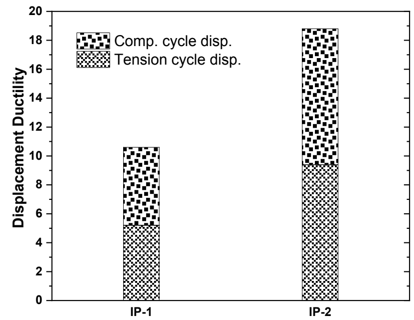
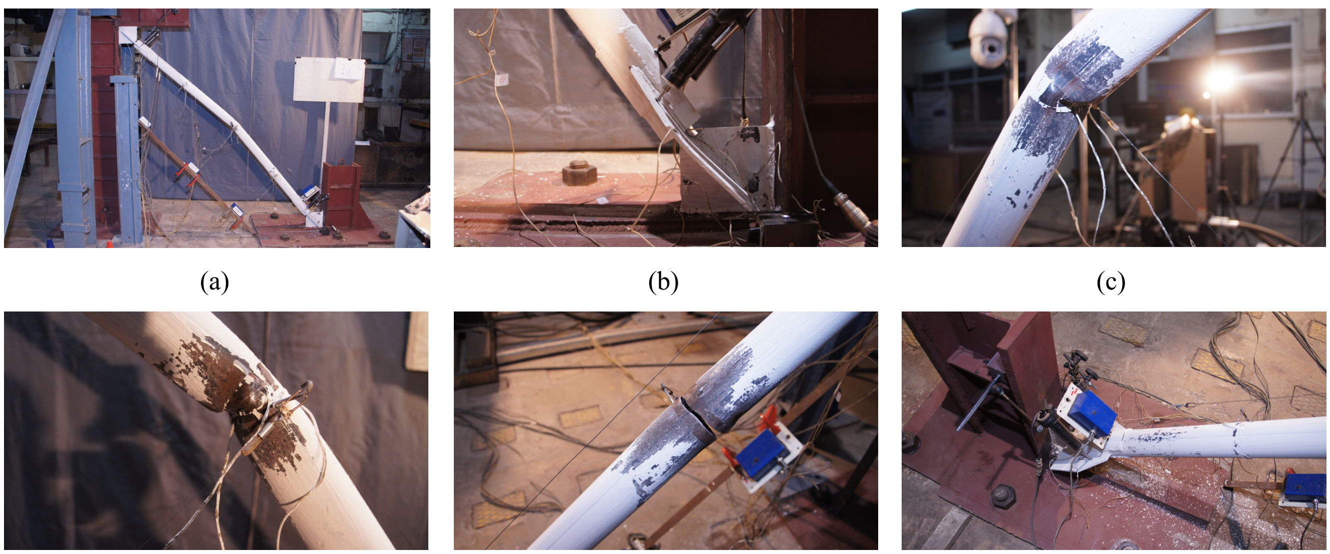


Figure 8. Displacement Ductility



(a) (b) (c)

(d) (e) (f)

Figure 9 (a) Global Buckling (b) Bending of knife plate (c) Local Buckling of brace (d) Fracture Initiation (e) Fracture (f) Yielding of the brace near knife plate

Failure Mechanism

Figure 9 shows the various stages of the IPB brace system that undergo during the cyclic test. The propagation of the various stages started from the global buckling to the final fracture of the brace. One of the primary objectives of the quasi-static test program was to develop the performance-based seismic design (PBSD) tool for the SCBF system with in-plane buckling brace. Therefore, all the failure mechanism and the primary and secondary yielding mechanism were observed and documented during the test.

SUMMARY AND CONCLUSION

The IPB brace system reduces the damage of the non-structural components in SCBF structure during a major seismic event. However, the past experimental studies highlighted the problems in the design of the IPB brace system due to the lack of the proper design guidelines in the present code and literature. In the present study, the performance of the IPB brace system were studied to quantify its behavior when subjected to earthquake-type cyclic loading and a new detailing method has been proposed to improve its seismic performance. The critical limit states, such as, the out-of-plan bending of the gusset plate and the failure at the junction of the gusset plate to beam-column were designed using the proposed design method. The experimental results also highlighted the efficiency of the proposed design method. The test were conducted with the Hollow circular section. The main parameters considered in the present study were displacement ductility, cumulative energy dissipation and failure mechanism. The yield hierarchy was observed during the experiment, and the performance of the in-plane brace system is documented.

It is concluded that the change in the linear clearance of the knife plate from $3t_p$ to $6t_p$ enhanced the cyclic performance of the IPB brace system. In the experiment, the brace yielding near to the knife plate was observed in IP-1 specimen, which is delayed for for IP-2 brace specimen when the linear clearance distance was increased. This shows that by increasing the linear clearance, the rigidity of the knife plate is reduced, which, in turn, helped to achieve the better performance for the brace frame system. The proposed design method based on the critical limit states performed well in the experimental investigation, and no premature fracture was observed in the IPB brace system during the test. Future studies are underway by the authors to generalized the finding for varying slenderness and compactness ratios within the permissible limit of the AISC 341-16 using experimental and numerical investigations.

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