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Advances and Challenges in Design of Connections in Steel-Braced Frame Systems with In-Plane Buckling Braces

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Abstract: A new type of connection has been developed for steel-braced frame systems that allows the brace members to undergo compression buckling in the in-plane direction. In addition to the inherent benefits of in-plane buckling (IPB) braces that help in reducing the extent of damage to the non-structural components, the IPB brace system is also considered to be an efficient way of retrofitting existing seismically deficient structures. The use of the compact and thicker gusset plate prevents the distortion of the free edges and the additional torsional force demand on beams and columns. However, IPB braced frame systems are not frequently used in practice, primarily due to the absence of limit state design criteria. As a result, some prominent failure modes observed in IPB frame systems are out-of-plane brace buckling, yielding of gusset plates, interface weld failure, and fracturing of knife plates. Recent studies on the IPB braced system have resolved some of these problems, such as design criteria being developed to prevent OOPB (out-of-plane buckling) of the IPB braced system. Other challenges need to be studied to achieve reliable performance of the braced frame system. This study focuses on recent advances and potential areas of improvement to achieve an efficient IPB braced system in highly seismic areas.

Keywords: limit states criteria; gusset plate; ductility; interface weld; seismic performance; uncertainties in buckling modes

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1. Introduction

The seismic design of structures requires reliable estimation of the behavior of the components that are expected to resist the lateral load. Premature failure of any such components below the design load or ductility demand will change the structural performance level. In the case of a special concentrically braced frame (SCBF) system, the brace components act as a fuse element, dissipating the earthquake energy and minimizing the damage to the gravity-resisting elements. Braces are designed to accumulate inelastic deformation due to the buckling and yielding under cyclic axial loading in the event of earthquakes. The primary mode of failure for the SCBF system during the seismic event is fracture at the middle of the brace members for its optimum performance. Past earthquakes, e.g., the 2011 Christchurch Earthquake, the 1995 Kobe Earthquake, the 1994 Northridge Earthquake, and the 1985 Mexico City Earthquake, have shown that brace frame systems are susceptible to premature failure. The various undesirable failure modes observed are fracture of interface weld of gusset plate, tearing of gusset plate, buckling of gusset plate, net section failure of brace cross-section, premature failure of brace section, and block shear failure of brace or gusset plate [1–8]. Because most of the steel-braced frames were constructed before the incorporation of the ductility-based design concepts, failure modes are mostly related to lower brace strengths and limited ductility capacity. Recent studies conducted in the United States and Canada have also highlighted these deficiencies and their consequences for the overall seismic performance of these systems [9,10].

The connections of these lateral load resistance systems are the most critical components of the structure because of the associated complexity involved in designing and detailing the connection to withstand large inelastic drift without undergoing premature fracture. The concentrically braced frame (CBF) system is the most prominent lateral load-resisting system, used widely because of the ease of constructability, low cost, and high strength-to-weight ratio. The CBF system designed in high seismic zones to withstand large inelastic drift is called the special concentrically braced frame (SCBF) system. Research on the connection design for the SCBF system is not explicitly coded like that of the moment resistance frame [11]. This can be attributed to the complex stress state of the gusset plate, whose behavior is difficult to predict, as well as limited experimental studies compared to other connection types. Mostly, the design of these connections is based on empirical formula to predict their performance at lower inelasticity demand. However, the performance of these connections at higher lateral drift needs to be verified.

Thornton [12] proposed a linear clearance of $2t_p$ (t_p = thickness of gusset plate) in the tapered gusset plate to facilitate out-of-plane buckling of the brace member to dissipate higher energy and withstand higher drift. These types of braced systems are called out-of-plane buckling (OOPB) braced systems. Before that, the gusset plates were directly connected to the end connection and called direct connection (DC) braced systems. Research conducted by Lehman et al. [13] proposed the rectangular gusset plate with elliptical clearance. It is observed that by reducing the gusset plate's flexural rigidity, the braced frame's ductility can be increased. Predicting fracture ductility of brace specimens is the most important yardstick for the collapse assessment of special concentrically braced frames (SCBFs). Most empirical formulations have neglected the effects of end connections in quantifying brace performance.

The knee-braced system (KBS) does not allow the brace members to buckle but provides energy dissipation with the help of the knee anchor yielding in flexure [14]. A recent experimental study on KBS observed stable hysteresis response and higher lateral drift capacity. The connection of the knee-braced system is designed to prevent buckling of the brace member [15,16].

However, in the case of the SCBF system during an earthquake, the gusset plate bends to accommodate buckling, and the brace undergoes out-of-plane displacement. The out-of-plane displacement is found to be very large and can go from 500 mm to 700 mm depending on the slenderness ratio of the braces. To avoid large out-of-plane displacement, a new type of connection is proposed such that the brace will undergo in-plane buckling: the in-plane buckling (IPB) braced system. Figure 1 illustrates the different detailing of the end connection of the braced frame system.

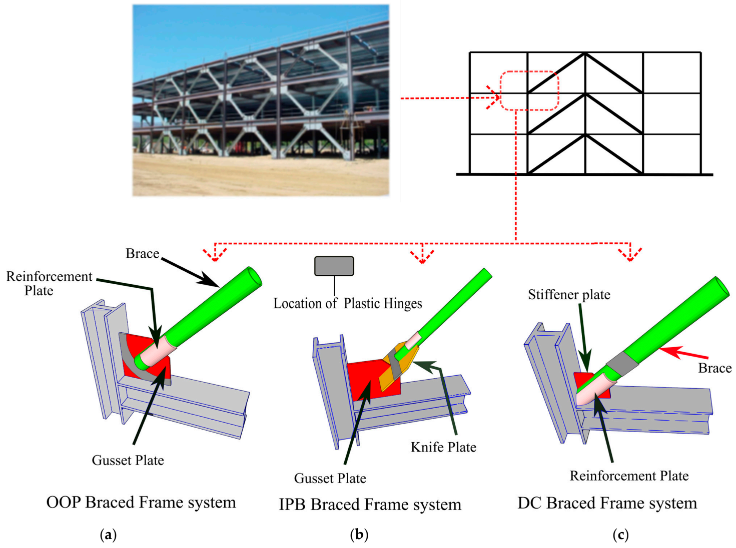


Figure 1. Connection detailing of (**a**) out-of-plane buckling (OOPB), (**b**) in-plane buckling (IPB), and (**c**) direct connection (DC) braced frame systems.

2. Background

SCBF structures built after the incorporation of the Uniform Building Code [17] are designed for a ductile response using a capacity-based design method. However, limited knowledge of the performance of its components and their interaction leads to early strength loss. The premature loss of strength of the brace in the particular story accumulates the inelasticity in that story and forms the soft-story mechanism, which finally leads to the structure's collapse [18]. Hence, the structures need to be designed to avoid premature fracture and to maximize the lateral drift capacity of the brace. Astaneh-Asl et al. [19] first introduced the concept of a tapered gusset plate with linear clearance of twice the thickness of the hinge plate for the restraint-free rotation, which led to the out-of-plane buckling (OOPB) brace system. It was observed that forming hinges on the gusset plate enhances the ductility of the braced frame system. To further improve the performance of the SCBF system, a series of experimental and numerical studies were conducted in the United States, which led to development of a compact rectangular gusset plate arrangement with elliptical clearance [13,20,21]. Research also highlighted the influence of the flexibility of the connection on the ductility of the braced frame system but mostly focused on the OOPB brace system. This also illustrates the balance design procedure that leads to the desired yield hierarchy for the SCBF structures [22]. Roeder et al. [22] investigated the behavior of the gusset plate connections in multi-story X-braced frames and observed that the seismic performance of the braced frame is affected by the design and detailing of the gusset plates.

The connection of the CBF system is observed to be the most critical component that not only dissipates the forces to other members of the structure but also helps enhance the system's performance and ductility. However, most of the research in the past two decades has focused on the design and detailing of the OOPB braced system to avoid premature failure and to have the desired yield hierarchy. Recently developed IPB braced systems designed for in-plane buckling have attracted industry and researchers as good, efficient alternative connections for increasing the resilience of the braced frame system. Past experimental research on the full structure of the OOPB system has shown that the brace member's out-of-plane deflection can go up to 500–700 mm before the final fracture. The large deflection may lead to potential damage to the surrounding cladding, non-structure components, partition, etc. It also has the potential to increase falling debris, which is the most prominent cause of mortality in earthquakes. The recently developed flexible design framework aims to reduce earthquake forces on the non-structural components [23], which in fact needs the brace members to buckle in the plane of the system. Mostly, the out-of-plane buckling starts at a lower inter-story drift, and it can go up to 700 mm; severe non-structural damage can occur. For the CBF system, buckling usually starts at a very low drift of about 0.3% to 0.5% [24]. It is expected that in the design-based earthquake (DBE), most of the brace members will show out-of-plane displacement, which will increase the chance of falling debris.

3. Need for the IPB Connection in Braced Frame System

Along with the inherent benefits of the in-plane buckling braces to prevent damage to the non-structural component, IPB brace systems are also considered to be an efficient way of retrofitting existing seismically deficient braced frame systems by accumulating the inelasticity in the knife plates [10]. The process of replacing the brace and strengthening the gusset plate may efficiently enhance the feasibility and constructability. Gusset plates of OOPB brace connections are subjected to frame action at the interaction of the beam–column junction. This requires the use of thicker gusset plates to prevent distortion of the free edges. The thicker gusset plates also increase their rotational rigidities, reducing the ductility. The additional torsional force demand on beams and columns due to brace buckling or the post-buckling residual out-of-straightness of braces can be minimized by forcing the braces to buckle along the plane of the frame. The flexural rigidity of knife plates of the IPB brace system is smaller than that of the gusset plate connections in the OOPB systems. Therefore, the IPB braces exhibit a lesser accumulation of plastic strain and a higher displacement ductility [24].

4. Limit States Criteria

SCBFs are designed as concentric truss members, and the frame bending and brace buckling effect are neglected. They are designed for higher inelastic capacity, which is introduced through the buckling and yielding of the brace. The compactness of the brace member should satisfy the criteria for the highly ductile member for the SCBF system. The slenderness limit of the brace member is restricted to 200 as it precludes the dynamic effect related to the extremely slender braces. In the design, it is expected that the brace should resist 30% to 70% of the total horizontal force in tension. The buckling of the brace is expected at the story drift of 0.3% to 0.5%. The braces in the SCBF system are designed to have axial deformation of 10 to 20 times the yield displacement of the brace. The capacity-based design methodology is used for the design of the beam, column, and connection of the SCBF system. The required resistance of the brace for tension and compression in the capacity design method is taken as $P_{bt} = R_y F_y A_g$ and $P_{bc} = (1/0.877) F_{cre} A_g$ respectively. The excepted post-buckling strength of the brace is taken 0.3 times the excepted compressive strength of the brace. In the expression, P_{bt} and P_{bc} are the excepted tensile strength and compressive strength of the brace, R_y is the ratio of the excepted yield strength to the minimum specified yield strength (F_y),A_g is the gross cross-sectional of the brace, and F_{cre} is the critical stress associated with the brace buckling. A factor equal to 1.1 was applied to calculate the expected buckling strength in the earlier edition of Seismic Provision AISC 341-10 [25] and was removed from the current edition of AISC 341-16 [26] to include the effect of the conservative column curve equation. The effective length coefficient (K) is taken as 1 to calculate the critical buckling stress as per AISC 341-16 [26]. The brace length used to calculate the effective length is the length from brace end to brace end. The columns are designed for the inelastic capacity of the brace based on the plastic mechanism discussed in AISC 341-16 [26]. The column splices are designed to develop at least 50% of the lesser connected member’s plastic flexural strength (MP). The connection, which plays an important role in transferring the forces from the brace to the beam–column junction, is required to bear the high inelastic demand of the SCBF system. As discussed earlier, the inelasticity demand on the SCBF system is fulfilled by the hinges on the prescribed location. The various limit states design criteria for the IPB braced system are shown in Figure 2. In order to have the desired yield hierarchy and to avoid premature fracture, the connection of the IPB braced system has to satisfy all the design limit state criteria. The design of the IPB braced system has more limit states and requires a lot more calculation than the OOPB braced system. This is due to the extra element introduced to the IPB braced system called the knife plate. The seismic load path of both types of connections is explicitly different due to the inherited different detailing and yielding zone. The limit states for the IPB braced system were not explored much compared to the OOPB braced system, which led to the premature structure failure observed in the recent experimental studies [10,27]. In the absence of that, the design of the IPB brace system is carried out based on the prescribed limit state of the OOPB braced system or not considered in the design.

The yielding of the gusset plate and knife plate is measured using the Whitmore width [28] concept. The Whitmore effective width is defined as the projection of a 30° angle from the start to the end of the bolted or welded joint. The buckling capacity of the gusset plate is calculated using the Thornton method [12], which uses the effective length of the gusset plate based on the average centroidal length and the lengths at two ends of Whitmore’s effective width. In the case of the knife plate, the linear clearance is taken as the effective buckling length to calculate its buckling capacity, which is more susceptible to buckling. Figure 3 shows the Whitmore effective width and effective buckling length of the IPB brace system. The effective length factor K = 1.2 is used to calculate the buckling capacity [29,30], which assumed the fixed rotation and translation at the beam–column junction, and fixed rotation and free translation at the brace–hinge plate connection. This relatively conservative value is based on the fact that the middle of the brace moves out-of-plane/in-plane when the brace buckles. However, this needs to be verified using experimental investigation. The interface weld sizes of the OOPB braced system are calculated based on the available shear strength of the plate or the gusset plate's weak axis flexural strength. However, the code is silent about the design of the gusset plate for the IPB braced system, which differs from the OOPB braced system's gusset plate because it is expected to remain elastic during loading.

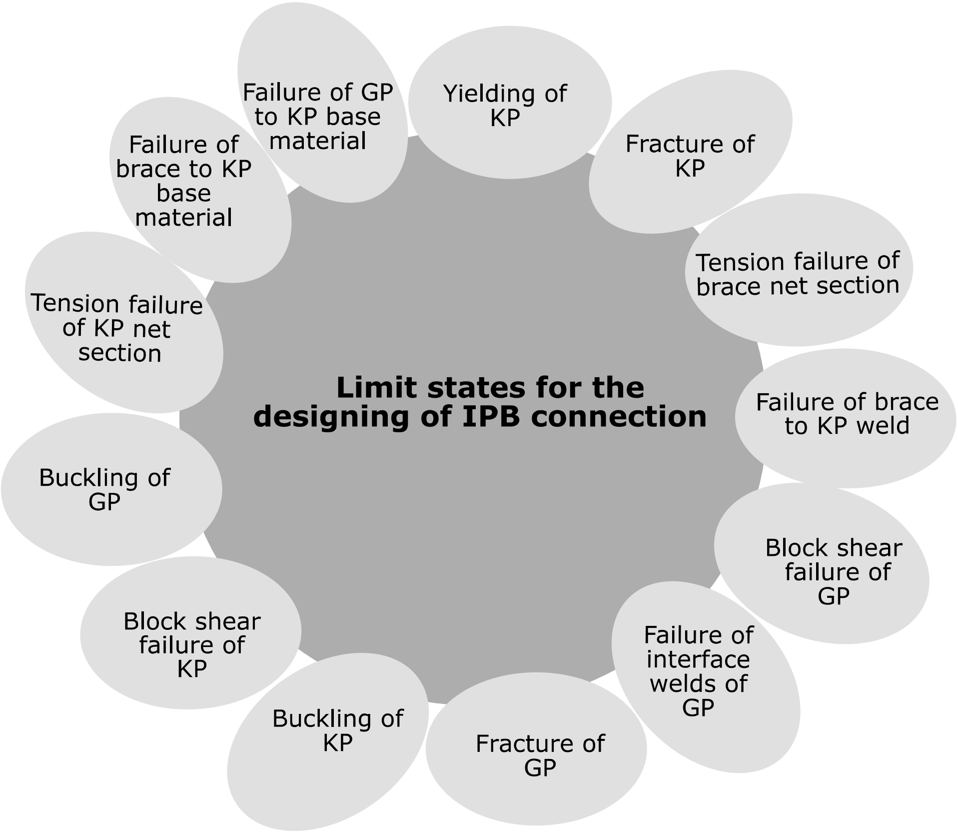
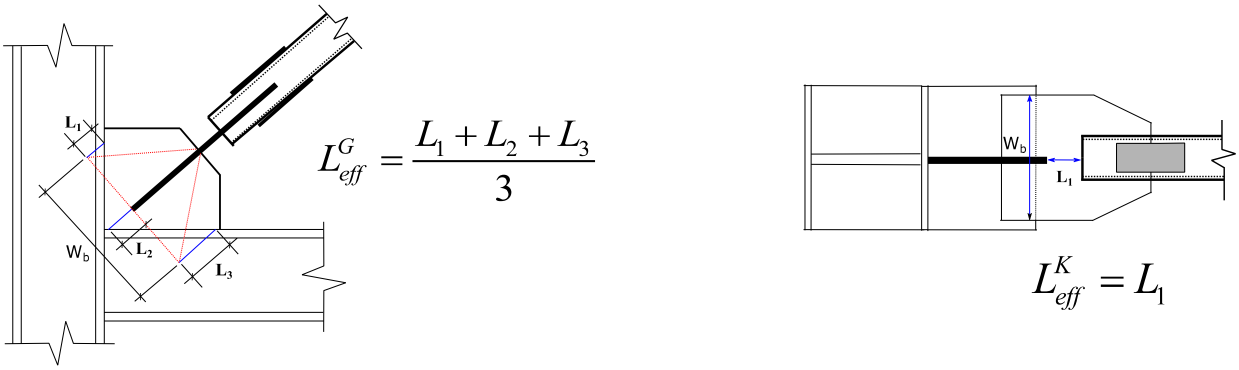


Figure 2. Various limit state criteria for the IPB braced frame system.



(**a**) (**b**)

Figure 3. Illustration of Whitmore effective width and effective buckling length in (**a**) gusset plate and (**b**) knife plate of the IPB braced system.

5. Limitation in the Design Criteria

Figure 4 highlights the undesirable failure modes of IPB braced frames observed in past experimental studies [10,31–33]. These modes include the OOPB brace buckling, yielding of gusset plates, interface weld failure, and fracturing of knife plates. The design limit states for the OOPB braced system are well-established in the literature and are validated through experimental studies. However, the limits state design criteria for the recently developed IPB braced system are not defined as mentioned. The arrangements of gusset plates/knife plates in the end connections require different limit state criteria for design and reliably withstand the load. Though most of the limit state criteria of the IPB braced systems are identical to those of OOPB systems, the force demand at the end connections differs greatly. Due to the unavailability of proper design guidelines, the end-protected zones of the IPB bracing systems may be either over-designed or under-designed, which may lead to premature failure.

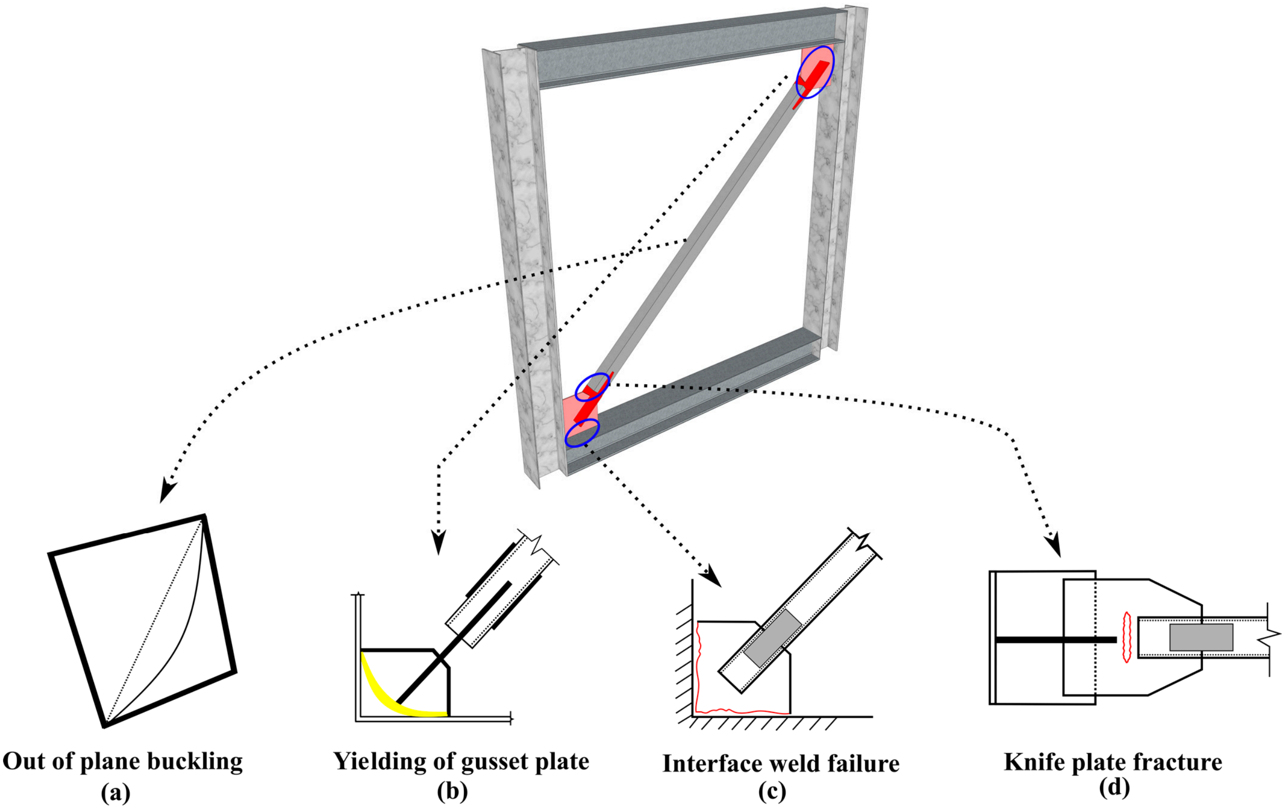


Figure 4. Failure modes observed in past experimental studies [10,31,32].

6. Summary of Experimental Investigation

As discussed earlier, most studies in the past were focused on the OOPB end connection brace frame, and very limited studies were conducted on the newly developed IPB end connections braced frame. As traced by the authors, the first full-scale test of the IPB braced system was conducted by Lumpkin [31] on the reusable three-story frame with a composite concrete slab at each story. The design limit state criteria to prevent out-of-plane buckling were not considered, and undesirable failure mode, including out-of-plane buckling of braces, was observed in the third story of the braced frame at a drift of 0.52%. Some tests were also conducted at the component level without considering the actual end connection and biased moment of inertia along the two perpendicular buckling axes [32]. However, these tests did not depict the actual end connection arrangement. Recently, Sen et al. [10,27] conducted four tests on the IPB braced system, out of which three failed through out-of-buckling of the brace member. One specimen did not fail through the aforementioned mode because the rectangular brace member was used to prevent out-of-plane buckling by orienting the lower moment of inertia of the brace member along the in-plane direction. Out of the four tests, three were conducted on the one-story frame and one was conducted on the two-story frame with an IPB connection at the ground story only. The authors [24] also conducted three tests on IPB connection with sub-assemblage test configuration on the hollow circular section as the brace member. Table 1 shows the details of the experimental program along with modes of buckling and failure modes observed in the studies.

Table 1. Summary and modes of buckling observed in the past experimental studies on IPB braced frame.

Reference Study	Specimen	Section	Description	Observed Mode of Buckling	Failure Mode
Lumpkin [31]	L-3S	HSS 125 × 25 × 9	Third story of 3-story single bay frame #	Out-of-plane	Brace fracture
Sen et al. [27]	S-2S	HSS 127 × 127 × 9.5	First story of 2-story single bay frame #	In-plane	GP weld fracture
Sen et al. [10]	S-1A S-1B S-1C	HRS 52.4 × 101.6 × 9.5 HRS 152.4 × 101.6 × 9.5 HSS 127 × 127 × 9.5	1-story single bay frame %	In-plane Out-of-plane Out-of-plane	GP weld fracture GP weld fracture GP weld fracture
Patra and Sahoo [24]	P-1A P-1B P-1C	HCS 76.1 × 2.9 HCS 76.1 × 2.9 HCS 88.9 × 3.2	1-story sub-assemblage system %	In-plane In-plane In-plane	Brace fracture Brace fracture Brace fracture

Chevron configuration; % single-story diagonal configuration; GP—Gusset Plate.

The brace member used in the studies has a uniform moment of inertia about both the buckling axes except the hollow rectangular section that was used for specimen S-1A and S-1B in the experimental studies of Sen et al. [10] (Table 1). It is worth noting that despite the lower radius of gyration along the in-plane direction, the S-1B specimen which shows in-plane buckling at a lower drift range of 0.6% but fails due to out-of-plane buckling at 1.5% drift range. The undesirable buckling mode also attracts premature failure at the interface of the gusset plate and reduces the seismic performance of the braced frame system.

7. Review of Current Design Practices

Current design practices of the connections for the CBFs system vary across the globe. Different types of connections with diverse design methodologies are recommended through various codes. AIJ [34] (Japanese code) provides guidelines for DC and OOPB braced frame systems. It recommends only the brace axial force for the design of the interface weld, termed the AIJ method. EN 1998–1-1 [35] (Eurocode), AS 1170.4 [36] (Australian code), and CSA-S16 [37] (Canadian code) recommend semirigid and partial-strength connections for the braced frame systems without any guidelines on the design and detailing of end connections. NZS 3404:1997 [38] (New Zealand code) implicitly discusses all three types of connections (e.g., DC, OOPB, and IPB). It incorporates the frame action by accommodating the opening and closing of beam– column joints. However, the design method to evaluate the interface stress and rotational rigidity of the minor axis bending of the gusset is absent. The recent version of ANSI/AISC 341 [26] implicitly includes all three types of brace connections. However, the design check to prevent out-of-plane buckling is lacking.

In the absence of a design guideline, the designer either neglects the possible mode of failure, compares the buckling load of the IPB braced system for the two different planes based on the effective length of the respective plane, or minimizes the radius of gyration along the in-plane buckling direction of the brace frame system [10]. However, it is observed that both methods do not provide efficient design criteria, and premature failures have been observed.

8. Recent Advances in the Design of IPB Braced Frame

This section highlights some of the recent developments in the design and detailing of the end connection of the IPB braced frame system. Most of these discussed design improvements were developed after the 2016 AISC 341-16 [26] seismic provision.

8.1. Discussion of Modes of Buckling

Braces in IPB systems are expected to buckle in-plane when the compressive force demand exceeds their buckling capacity. This is ensured by introducing knife plates in the end connections. However, past studies (e.g., [10,31]) have shown that IPB braces may undergo out-of-plane buckling (Figure 2a). Traditionally, the detailing of end connections of OOPB braced systems involves the provision of linear or elliptical clearance in the gusset plates. This facilitates the out-of-plane buckling of braces with low stress demand on the interface connection. However, there is no clarity on how a brace performs when the end clearance is not provided in the gusset plate. It is shown in Figure 4a that despite no or low clearance, out-of-plane buckling of braces has been observed in the IPB braced system due to bending and subsequent yielding of gusset plates [31] (Figure 4b). The undesired out-of-plane brace buckling would impose additional flexural demand on the interface weld of the gusset plates. Since these welds are often not designed to take into account this additional demand, this may lead to their failure prior to the in-plane buckling of the brace.

Out-of-plane buckling was found to be one of the major problems that prevent the use of the IPB connection. The gusset and knife plate's inherent orientation facilitates two different buckling modes. These modes are observed to be closely spaced modes and highly sensitive to geometry and mass/stiffness distribution present along the length of the member. The OOPB mode is formed when the plastic hinges are formed in the gusset plates and in the middle of the brace. In contrast, the IPB mode is formed when the plastic hinges are formed in the knife plates and the middle of the brace. It can also be interpreted that the minor-axis bending of the gusset plate and knife plate facilitate OOPB and IPB modes, respectively. The illustration of the plane of buckling and the orientation of the plate to facilitate the modes is shown in Figure 5. Based on the deformed configuration, associated hinge zones are formed in the respective plates. In both cases, the hinge at the brace member is formed at the center. In general, it can be concluded that the modes of buckling primarily depend on the effective buckling length and characteristics of the end connections. Here, the tendency of the brace member to buckle is unbiased for both directions (sections including Hollow Square Section (HSS) and Hollow Circular Section (HCS)).

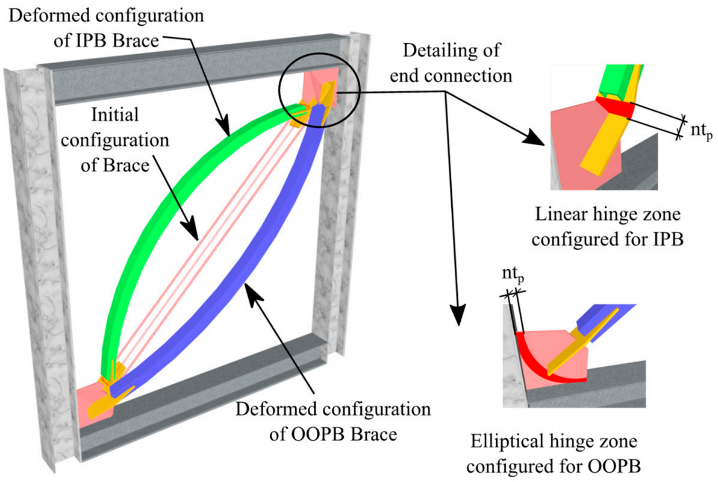


Figure 5. Illustration of plane of buckling and detailing of end connection including hinge zone. (t_{kp}—thickness of knife plate, t_{gp}—thickness of gusset plate, n—any rational number).

The clearance of the gusset plate is denoted based on the design philosophy considered while detailing the end connection. To ensure uniform nomenclature for the gusset plate, the area on the gusset plate is broadly classified into three regions: no clearance zone (NCZ), elliptical clearance zone (ECZ), and linear clearance zone (LCZ), as shown in Figure 6. Based on the insertion of the knife plate, the clearance zone and its associated value in terms of thickness can be expressed. The clearance in each zone is quantified based on the associated partition line. For the ECZ and NCZ, the clearance is measured along the centreline of the brace member toward the center of the brace. For the NCZ, it is measured along the centreline of the brace and away from the center of the brace. The nomenclature is used to quantify the extent of the insertion and clearance of the gusset plate.

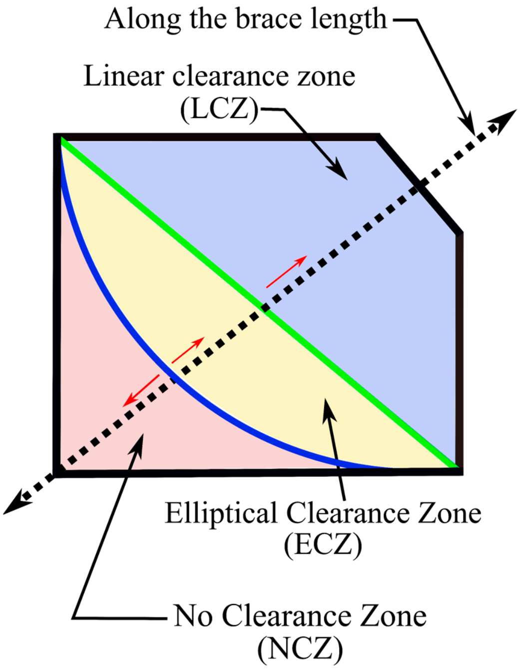


Figure 6. Different clearance zones associated with the gusset plate.

Uncertainties Involved in Predicting Buckling Direction

In structural design, stability calculations are critical because of the uncertain behavior of its components that arises from the fabrication and manufacturing process. Figure 7 shows the list of uncertainties that may be involved in predicting the direction of buckling. These uncertainties can be broadly divided into two types, i.e., local-level uncertainties and global-level uncertainties. Local-level uncertainties are (a) uncertainties involved in predicting rigidity of the end connection toward the bending in the presence of the different support conditions, (b) imperfection of the brace, gusset plate, and knife plate due to the manufacturing process, welding distortion, or mishandling during transportation, (c) residual stress of the gusset plate and knife plate (due to the welding and manufacturing process), (d) residual stress of the brace member, and (e) additional force on the gusset plate due to the frame action at the beam to column junction. Similarly, the global-level uncertainties are (a) different levels of imperfection in the brace member along the different planes, (b) the influence of the axial force on the bending capacity of the gusset plate and knife plate, (c) the influence of the load reversely on the buckling direction, (d) uncertainties involved in predicting buckling of closely spaced modes, and (e) the effect on the partial yielding of the gusset plate and knife plate on the stability of the brace member. The variability involved in the sensitivity of these parameters is also one of the major concerns for the stability assessment of the frame.

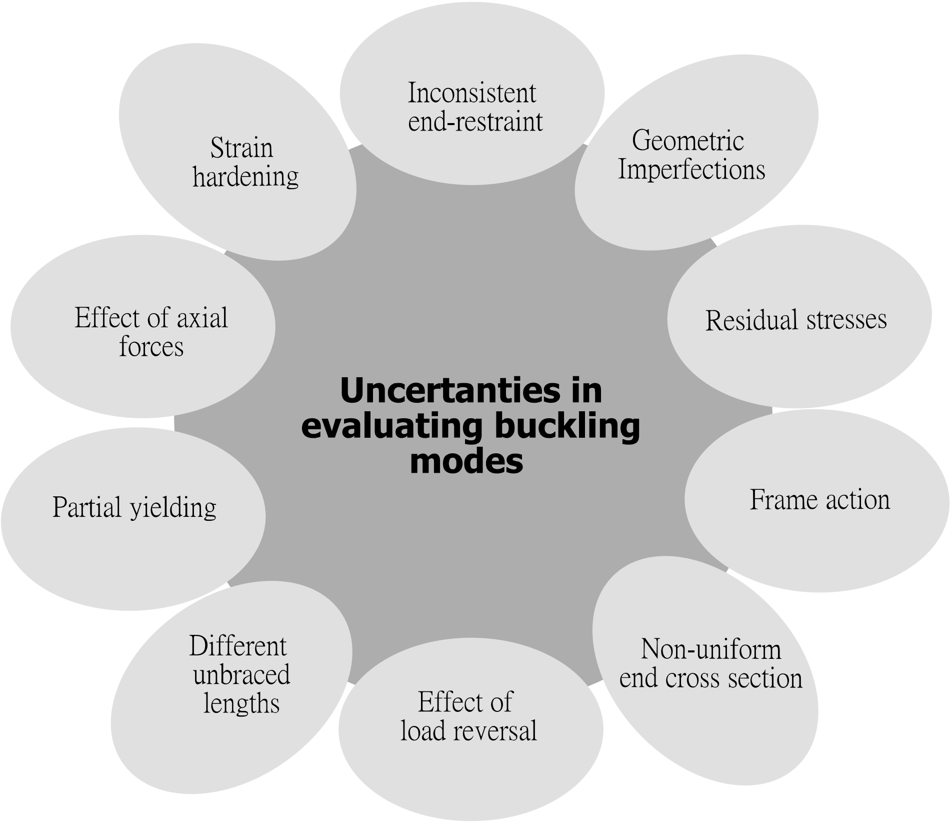
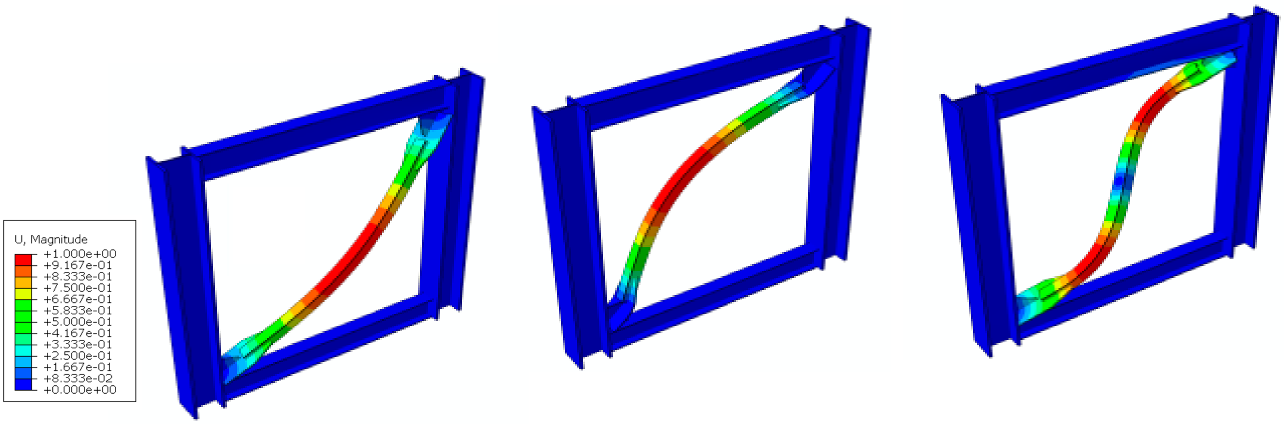


Figure 7. List of uncertainties involved in predicting buckling directions.

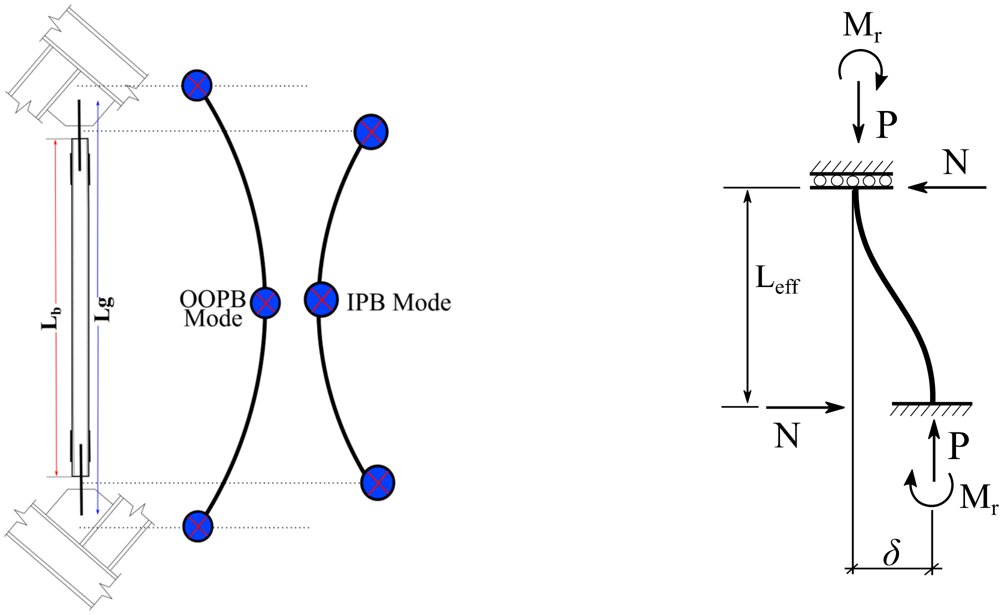
The first three modes of buckling of the IPB braced system obtained from the linear buckling analysis of the FEM model are shown in Figure 8. Some of the parameters destabilize the members and reduce their buckling loads, whereas some other parameters delay their buckling. The first two buckling modes for the IPB brace system are very closely spaced, which requires consideration of these uncertainties in evaluating the buckling mode such that the most destabilizing effect can be generated for the undesirable failure mode.



(**a**) 1st mode of buckling (**b**) 2nd mode of buckling (**c**) 3rd mode of buckling

Figure 8. Modes of buckling.

It can be seen that the primary hinge, i.e., at the mid of the brace member, is common for both modes of buckling. As stated earlier, the bending capacity of the hinge plate is primarily responsible for the direction of buckling. The modes of buckling and the stability of the hinge plate are shown in Figure 9. Because both modes are in different planes, the interaction of the hinges does not occur. The imperfection associated with the brace and the hinge plate introduces additional bending moments on the plate.



(**a**) (**b**)

Figure 9. Illustration of (**a**) the modes of buckling and (**b**) the gusset plate stability model.

It is very difficult to developed analytical formula to evaluate the plan of buckling due to the uncertainties involved in the IPB braced frame system. Patra and Sahoo [39–41] proposed a simplified analytical equation incorporating the uncertainties empirically using the multivariate regression analysis, as shown in Equation (1).

$$\text{Mode of Buckling} = \left.\frac{M_c^k \times \left[\left(\frac{L_b}{L_k}\right)^{1.73} \times \left(\frac{L_{eff,k}}{t_k}\right)^{0.09} \times \left(\frac{L_{eff,g}}{t_g}\right)^{0.55} \times \lambda^{-1.63}\right]}{M_c^g}\right\} \begin{array}{l} < 1 \rightarrow \text{IPB mode} \\ \geq 1 \rightarrow \text{OOPB mode} \end{array} \tag{1}$$

where M_c^k and M_c^g are the reduced flexural capacities of knife plate and gusset plate, respectively, (L_b/L_k) is the ratio of the effective length of the plane of mode, $(L_{eff,k}/t_k)$ is the knife plate effective slenderness ratio, $(L_{eff,g}/t_g)$ is the gusset plate effective slenderness ratio, and λ is the normalized brace global slenderness ratio. Table 2 shows the comparison of the predicted and observed mode of buckling from past experimental studies. It is observed that the recently developed limit state criterion reliably evaluates the mode of buckling and prevents premature failure of the braced frame system.

Table 2. Comparison of the predicted and observed mode of buckling from past experimental studies.

Study	Specimen	Brace Slenderness	Effective Knife Plate Slenderness	Effective Gusset Plate Slenderness	Effective Buckling Length		Observed Mode of Buckling	Predicting the Mode of Buckling
					In-Plane	Out-of-Plane		
Lumpkin (2009) [31]	HSS 125 × 125 × 9	70	2	6	3725	4320	Out-of-plane	Out-of-plane
Sen et al. (2016) [27]	HSS 127 × 127 × 9.5	75	3	8	3562	4120	In-plane	In-plane
Sen et al. (2017) [10]	HSS 127 × 127 × 9.5	77	3	7.5	3734	4548	Out-of-plane	Out-of-plane
	HSS 152.4 × 101.6 × 9.5	94	3	8.2	3710	4421	Out-of-plane	Out-of-plane
	HSS 152.4 × 101.6 × 9.5	94	3	8.5	3680	4345	In-plane	In-plane
Patra and Sahoo (2021) [24]	HCS 76.1 × 2.9	83	3	6	2160	2850	In-plane	In-plane
	HCS 76.1 × 2.9	87	6	6	2264	2941	In-plane	In-plane
	HCS 88.9 × 3.2	75	6	7.2	2264	2941	In-plane	In-plane

8.2. Connection Influence on the Ductility of the Braced System

Past research on the OOPB braced system has established that allowing the secondary hinges to form at the connection enhances the structure's ductility. The hinges in the connection are introduce by providing clearance at the gusset plate, as discussed earlier. The effectiveness of the IPB braced system as compared to its counterpart, the OOPB braced system, is shown in Figure 10. The backbone curves of the respective connections were generated from past experimental investigations [24]. From Figure 10, it can be seen that the IPB connection performs better than the OOPB connection. It is observed that the rotational fixity of the connection has influenced the ductility of the braced system. Less rotational restrain delays the fracture of the brace member, provided other limit states are satisfied.

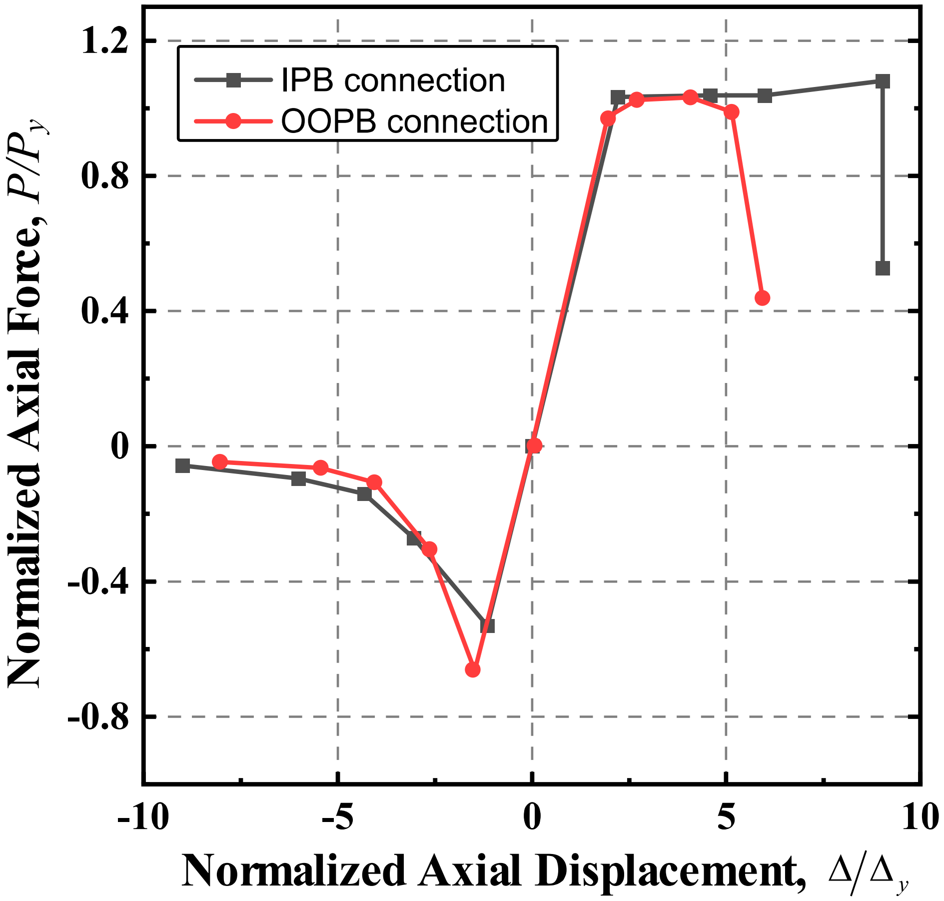


Figure 10. Comparison of the backbone curve of the IPB and OOPB connection braced system.

Various studies in the past have been conducted to evaluate the fracture ductility of the components of the brace frame. These studies are based on the database generated from experimental investigations conducted in the last four decades. The parameters observed mostly govern the fracture ductility found as slenderness ratio and compactness ratio [42–45]. Parameters, such as grade of steel, also profoundly impact predictions of fracture ductility [46,47]. It has been observed that the analytical formula used to calculate the fracture ductility shows a lower coefficient of determination value (R^2). This may be due to other factors, such as hinge plate thickness, out-of-plane stiffness of the hinge plate, and effective brace length, which may affect the fracture ductility of the brace component. However, past studies neglected these effects due to sparse experimental results that explicitly include these effects. Table 3 highlights the various damage stages of the IPB braced system observed in the test conducted by Patra and Sahoo [24].

Table 3. Observation of various damage states of the IPB Braced system.

Drift (%)	Cycle Drift (%) (Cycle no.)	Position and Direction of Loading	Damage States
Specimen IPB-1			
0.36	0.375(1st)	Comp. and peak	Global buckling
0.54	1(1st)	Comp. and loading	Flake of whitewash at mid location of brace
0.75	1(1st)	Comp. and loading	Flake of whitewash at top and bottom of knife plate
1	1(1st)	Comp. and peak	Local cupping at the middle of brace section
1.26	2(1st)	Tension and loading	Tearing across the section of brace
1.80	2(1st)	Tension and loading	Fracture at middle of brace
Specimen IPB-2			
0.34	0.375(1st)	Comp. and peak	Global buckling
2	2(1st)	Comp. and peak	Local cupping at mid of brace; flake of whitewash at middle of brace and top and bottom of knife plate
2.52	3(2nd)	Tension and loading	Initiation of crack on bottom face near middle of brace
2.87	3(2nd)	Tension and loading	Fracture at the middle of brace
Specimen IPB-3			
0.41	0.5(1st)	Comp. and peak	Global buckling
2	2(1st)	Comp. and peak	Local bulging at middle of brace; flake of whitewash at middle of brace and top and bottom of knife plate
2.40	3(2nd)	Tension and loading	Initiation of crack on top face near middle of brace
2.80	3(2nd)	Tension and loading	Tearing across the section of brace
3.08	4(1st)	Tension and loading	Fracture at the middle of brace

The knife pate clearance that facilitates the in-plane buckling in the IPB braced system has evolved in the last decade. The first set of experiments on the IPB braced system conducted by Lumpkin [31] used the 2tp clearance on the detailing of the knife plate. Tsai [32] further changed the clearance to 3tp to enhance the performance and remove the problems of the earlier study. Patra and Sahoo [24] observed that the knife plate's flexibility is retrained due to the insertion of the gusset plate in the middle. This led to the IPB braced system's lower ductility compared to the OOPB braced system. This also led to the initiation of the crack at the knife plate, as observed in the past experimental study. Hence, a clearance of $4t_p$-$6t_p$ (based on the rotational flexibility of the knife; t_p = thickness of the knife plate) is proposed for the IPB braced system to enhance the seismic performance of the braced system.

9. Future Challenges

In-plane buckling arrangement of the brace member in the braced frame system is a relatively new connection detailing. Hence, a comprehensive study is absent in the literature. The limit states that are responsible for the design of the end connection are also not well studied. The experimental study conducted by Sen et al. [10] highlighted some of the deficiencies in the design of the connection. Recent studies cover some of the crucial design criteria and propose design guidelines to achieve the desired performance, as discussed earlier. Here, in this section, some of the challenges that need to be studied to achieve desired performance and prevent premature failure of the IPB braced frame system are discussed.

9.1. Failure at the Interface of the Gusset Plate

The limit state for the design of the interface weld of the OOPB braced system evolved with time to prevent premature fracture. Past studies show that weld design using the tensile capacity of the brace and uniform force method leads to premature failure [31]. To prevent such failure, Roeder et al. [48] proposed to calculate the interface weld based on the tensile capacity of the gusset plate and verified the performance with large-scale experiments for the OOPB braced system. The latest 2016 AISC seismic provision [26] proposed two new analytical weld design criteria based on the OOPB braced system, i.e., weld strength evaluated based on the shear capacity of the gusset plate and weak-axis flexure strength of the gusset plate. It is observed that the latter consumes a smaller percentage of weld material. Due to the absence of any experimental studies, these analytical equations need to be validated with test data. Similarly, there is also a need for validation in the case of the IPB braced system, as the design criteria for the interface weld are absent in the literature and mainly follow the design principle for the OOPB braced system.

The stress distribution at the interface of the gusset plate is quite complex and difficult to predict. Approximate and simplified design methods considering only the brace axial force, termed brace action, are often used to design the interface weld [26]. Due to braced frame deformation, the demand from the opening and closing of the beam–column joints, termed the frame action, and out-of-plane bending of the gusset plate, termed the bending action, were mostly neglected in the design of the connection. Recent studies conducted by Cui et al. [49] and Carter et al. [50] separately include the frame action (where the moment release is not provided) and bending action of the gusset plate in the design of the interface weld for the OOPB braced system. However, the combined effect of the brace action, frame action, and bending action of the gusset plate and its stress distribution at higher drift still remain an unsolved problem. In the absence of a reasonable method, the premature or undesirable failure of the interface weld (Figure 4c) is encountered and the mechanism of the energy dissipation of the braced frame system is lost [10,13].

9.2. Knife Plate Fracture

The inelastic zone (clearance distance) of the knife plate is expected to undergo large rotation to facilitate IPB buckling. High rotational demand was observed to initiate fracture at the middle of the knife plate near the gusset–knife plate connection, as shown in Figure 4d. The failure mode was observed because the design did not consider the seismic quantification of the knife plate to the fracture under the fatigue loading [51] and the high stress concentration at the tip-slotted knife plate. A detailed, reliable design guideline is needed to prevent fracture under actual seismic excitation, which may initiate rapid fracture initiation and propagation.

9.3. Buckling of the Hinge Plate

The boundary condition of the knife plate and gusset plate is quite peculiar due to the detailing of the arrangement of the IPB braced frame system. Simplified empirical equations based on the Whitmore effective and Thornton effective length were considered for the design of the gusset plate in the OOP braced system. Doswell [52] studied the past experimental data and finite element model and proposed the effective length factor based on the gusset plate configuration. However, these data did not consider the present detailing of the gusset plate to evaluate the buckling code. It is observed that the design using the above method provides a conservative estimation of the buckling length, which may not be beneficial for the overall ductility of the brace frame system. In the case of the IPB system, the same method was considered to evaluate the buckling load despite the two sets having different boundary conditions. The method for the IPB system was also not supported by the experimental evidence. Thus, future study is required to provide a reliable estimation of the buckling strength hinge plate in the braced frame system.

9.4. Other Limits States Criteria

In the case of the IPB braced system, the gusset plates were designed compact because there is no requirement for any shot of clearance on the gusset plate. Due to this, the Whitmore effective length extended inside the flange and web of the connection. This added difficulty in reliably evaluating its behavior. Thus, the complexity and confusion associated while Whitmore width extended inside the flange and web, as described by Thornton and Lini [53], Sabelli et al. [54], and Elliott and Teh [55], may be explored in future studies.

10. Conclusions

The connection design of the SCBF system evolved in the last decade to improve the seismic performance of the braced frame structure. In that process, a new connection that helps the brace member to buckle in the in-plane direction was proposed. This new connection provides solutions to some of the demerits associated with the OOPB braced system and helps in improving the performance of the structure. The work presented in this paper highlights recent advances in the design of the connection and some of the shortcomings that need further evaluation to have the desired seismic performance for the IPB braced system. The recent advances and challenges in connection design and detailing that have been highlighted in this text are as follows:

- The mode of buckling of the IPB braced system is very closely spaced and highly dependent on the uncertainties of the brace member and the braced frame system.
- To prevent out-of-plane buckling of the braced frame system, a design criterion was developed considering the worst load case scenario along the out-of-plane buckling direction.
- The quantification of the ductility of the OOPB and IPB braced system shows that the IPB braced system has higher ductility as compared to that of the OOPB system, provided the undesirable failure mode does not govern. The rotational rigidity of the end connection influences the ductility of the system.
- In order to have optimum ductility, the clearance of the knife plate was proposed to lie between 4 tp to 6 tp.
- The absence of efficient design guidelines to prevent the failure of the interface weld is one of the major shortcomings of the newly developed connection, which requires further study.
- Quantification of the knife plate fracture should be incorporated to optimize the flexure rigidity and performance of the braced frame system.
- The critical buckling load of the knife plate also needs to be explored as the boundary condition of the knife plate is different than that of the OOPB braced frame system and expected for different effective length factors. The optimization of the shape of the knife plate can also be studied for minimization of cost.
- The associated complexity and confusion because of the Whitmore width extended inside the flange and web may be explored in future studies.

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