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Steel Brace Connection with Reinforced Concrete Frame Structure: A Review

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Abstract— Steel bracing is widely used in reinforced concrete (RC) structures to enhance their lateral load resistance and seismic performance. This review paper compiles and examines various experimental and numerical studies on steel bracing systems and their connection details with RC frames. Three primary types of brace-to-frame connections were analysed, focusing on their effects on structural parameters such as crack patterns, response modification factor (R factor), overstrength, and stiffness. The studies show that while the X-bracing configuration has been extensively examined, other bracing types require further investigation, particularly regarding their connection behaviour and performance. Observations highlight that bracing significantly reduces inter-story drift, displacement, and natural period while increasing base shear capacity. However, the effectiveness of the bracing system largely depends on the type and strength of the connection between the steel braces and RC elements. Issues such as hinge formation near brace connections, shifting of plastic hinges, and localized failures in beams and columns demand further exploration. Additionally, experimental studies reveal that inadequate connections can lead to premature failure, while well-designed connections improve strength, energy dissipation, and ductility. This review emphasizes the urgent need for developing standardized, simple, and effective connection detailing for both new construction and retrofitting purposes. Future research should focus on optimizing the design of brace connections in various configurations, quantifying overstrength factors and stiffness ratios, and extending the study to diverse bracing types beyond the commonly studied X-bracing.

Keywords: Steel bracing, bracing connection, failure pattern and Overstrength.

1. Introduction

RC structures are widely used in modern construction due to their durability and cost-effectiveness. However, in seismically active regions, RC structures are often vulnerable to lateral loads induced by earthquakes, which can lead to excessive displacement, structural damage, or even collapse [1], [2]. To enhance the seismic performance of such structures, lateral load-resisting systems such as steel bracings and shear walls are commonly employed [3]–[5]. Among these systems, steel bracing has emerged as one of the most practical, economical, and efficient solutions for both new construction and retrofitting of existing buildings [6], [7]. Steel bracings increase the lateral stiffness and load-carrying capacity of RC frames without significantly increasing the structural mass. They also improve energy dissipation during seismic events, thereby reducing damage and enhancing overall stability [8]–[12]. There are several types of steel bracings used in RC structures, such as X-bracing, diagonal bracing, K-bracing,

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multi-X bracing, inverted V-bracing, and V-bracing. Numerous studies have demonstrated the effectiveness of these bracing types in improving the seismic behavior of structures [13]–[20]. As a result, steel bracing has become a cost-effective method for enhancing the performance of existing buildings under lateral loads. Both numerical and experimental analyses have been carried out on RC buildings equipped with steel bracings in various configurations [21]–[27]. Ghaffarzadeh and Maheri (2006), for example, conducted scaled experimental and numerical investigations comparing RC frames with and without steel bracings. In these experiments, the researchers used a direct internal steel bracing system and subjected the frames to cyclic loading. Their findings indicated that the use of bracing significantly increased the strength of the frames and effectively reduced drift levels [28].

When steel bracings are implemented in RC structures, they are shown to reduce inter-story drift, displacements, and natural periods, while also increasing the base shear capacity of the structure [29]–[32]. A study by Bohara et al. (2021) investigated the effectiveness of bracing in L-shaped RC buildings, observing the torsional behavior and seismic performance of such irregular structures with and without steel bracings [33]. Furthermore, Rahimi and Maheri studied the influence of X-bracings in two-dimensional RC structures with varying story heights, using time-history analysis to evaluate both the positive and negative impacts of steel bracings [34], [35]. This study focuses on the connection design between RC frames and steel bracings and how these connections affect the structural integrity of RC members. It provides a review of several research efforts examining the performance of steel bracings as a lateral load-resisting system in RC structures. Additionally, it explores various connection types used in practice and the failure mechanisms observed during loading conditions. Special attention is given to the behavior of diagonal bracing elements under both tension and compression.

2. Design of Connection in Concentric Steel Braced and RC Members

Connections between steel bracing and reinforced concrete (RC) frames can be established through various methods, depending on whether the system is implemented in new construction or as part of a retrofitting process for existing buildings [36], [37]. In retrofitting applications, one common approach involves drilling holes into existing concrete elements and anchoring steel plates using bolts to secure the bracing system [38]. The selection of connection technique plays a crucial role in ensuring effective load transfer and overall structural performance, especially under lateral forces induced by seismic events. Significant research has been conducted in this area, notably by Maheri, who has extensively studied the behavior and design of steel bracing systems in RC structures. His work provides valuable insights into connection detailing, performance under cyclic loading, and practical implementation strategies for enhancing the seismic resistance of RC frames using steel bracings [39], [40]. These studies emphasize that the connection design should not only facilitate force transmission but also account for ductility, constructability, and potential differential stiffness between steel and concrete elements.

Steel bracings are primarily designed to resist axial loads, including both compression and tension forces. It has been observed that a direct connection between the brace and RC frame is easier to construct and can significantly reduce construction cost and time. However, such connections must be engineered to safely transfer the loads without introducing weak points in the structural system. Research conducted by Maheri and Sahebi (1997) [41] investigated an experimental RC frame with X-shaped steel bracing. Their findings revealed that the X-braced frame possessed four times the strength of an unbraced frame. Additionally, their study evaluated different steel-to-concrete connection types. Figure 1 shows a basic connection concept between RC members and steel bracings, while Figure 2 illustrates four specific connection types. Two types (Fig. 2a and 2b) represent connections made during construction, and the other two (Fig. 2c and 2d) represent retrofitted connections after construction. Among these, connection type (d) exhibited the least load-carrying capacity during tests. The failure mechanism typically begins with tensile bracing failure, followed by compressive member buckling. Therefore, the researchers strongly recommended avoiding weak or poorly detailed connections to ensure optimal seismic performance and safety.

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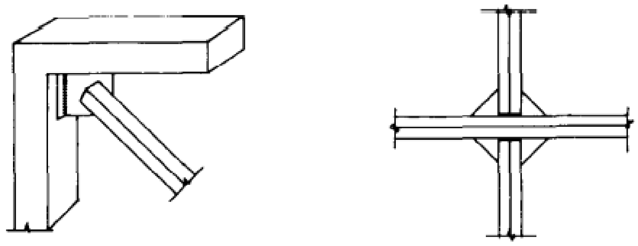
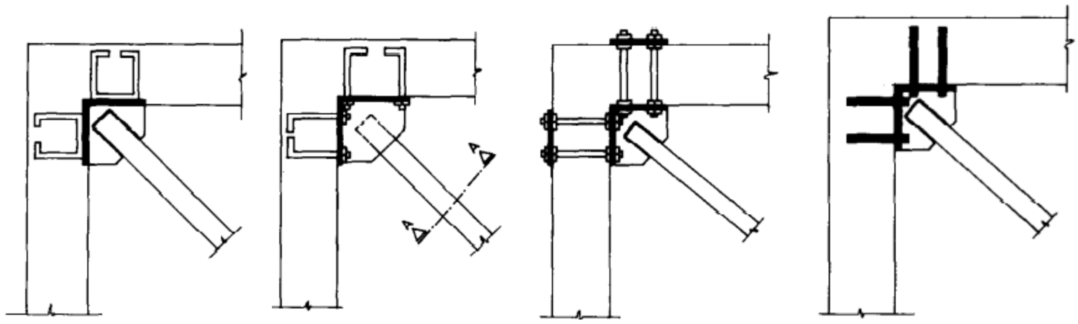


Figure 1 Connection detailing in both concrete steel bracings connection and steel cross-bracing connection [41].



a) b) c) d)

Figure 2 Connection used in the frame and bracing, a and b are used during construction and c and d are used after the construction of the frame [41].

To get further information and design methodology, researchers Maheri and A. Hadjipour studied the steel brace connection with RC frames. Maheri and A. Hadjipour (2003) [42] investigated the full scale of RC and steel braced connection models (fig. 3 to 5). The model was tested experimentally with applied direct tensile force to determine the ultimate failure of the braced member. For the design of steel connection in the RC member, the load transferred through the different elements are considered. These elements are bracing, a connection between the brace and gusset plate, gusset, gusset and connecting plate, connecting plate, anchor bolts and last connection between bolts and concrete members. Three types of connection were observed, (i) bracing was welded with gusset and connecting plates were connected with the frame members with the help of hooked anchor bolts inserted in RC frame (see fig 3), (ii) same as (i), but the plates were linked to the RC frame by the help of bolts, anchored at another face with a backplate & nuts (see fig 4) and type (iii) the corner of the frame was made up with RC so that one connecting plate was used and neglecting the opposite corner plate (fig 5). The researchers successfully made the connection between steel and RC frames. The researcher observed that type (i) and (ii) more stronger connections. However, type (iii) may use increased ductility in the connection. Figure 6 shows the relationship of between the load applied and the corresponding displacement observed in each three types of connection.

Maheri, S. Yazdani (2016) [43] studied the RC with Steel bracing connection by using the Uniform Force Method (UFM) (see fig 7). The experimentally and numerically modeled were studied and the types of connection were the same as M.R. Maheri, A. Hadjipour (2003) [42]. Researchers have taken the same connection type (i) and Type (ii), where one is a new connection and the one is used in retrofitting existing buildings. Both connections were corner connections that joined the X bracing. The authors observed the use of the uniform force method was correspondingly applicable in the designed RC frame with steel bracing connection. It is found that this method accurately predicted the components of the forces acting in plate connections. It was also observed that this method gives true value if the angle of bracing ranges from 30° to 60°. Suggested that this method provided a safe design solution. Maheri, A. Hadjipour (2003) [42] suggested that the yielding of the brace occurred nearly close to the design yield strength and somewhat less than the theoretical yield strength. Same as to further clarification in the design of connection, Mahmoud R. Maheri and S. Yazdani (2016) [44] Conducted the experimental and numerical analysis to get the performance of three connection types (same type of connection used in the previous study [43]. The study points out that type A connection shows better performance in term of energy dissipation and ductility as compared to type B. It can be seen that types (a) and (b) connections are relatively similar behaviors in terms of stiffness, capacity and energy dissipation. However, type 'c ' has more energy dissipation capacity as shown in fig 8.

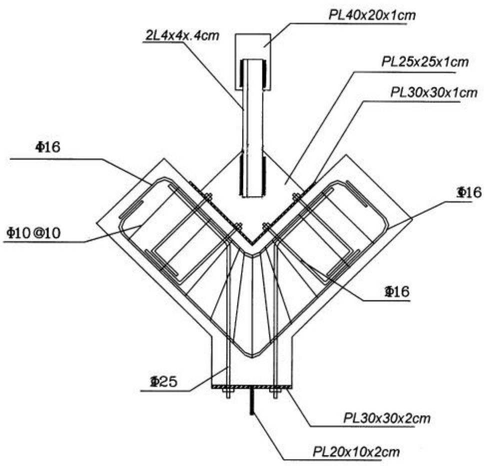


Figure 3 Connection Type (i) or (a) [42].

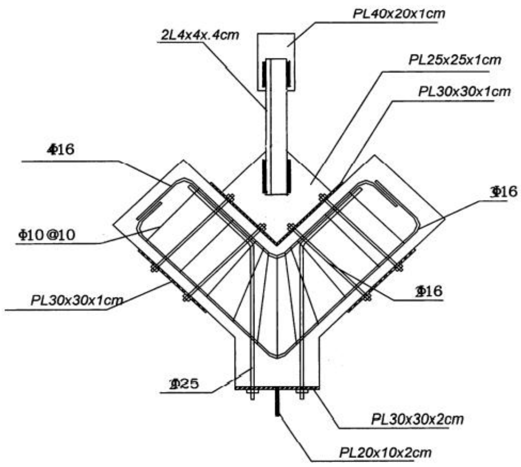


Figure 4 Connection Type (ii) or (b) [42].

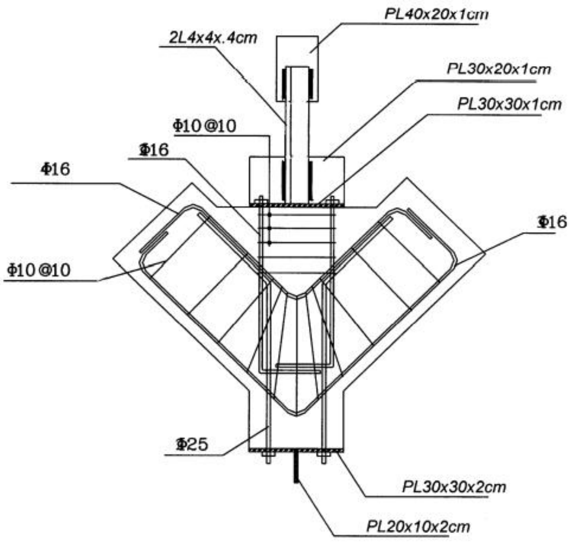


Figure 5 Connection Type (iii) or (c) [42].

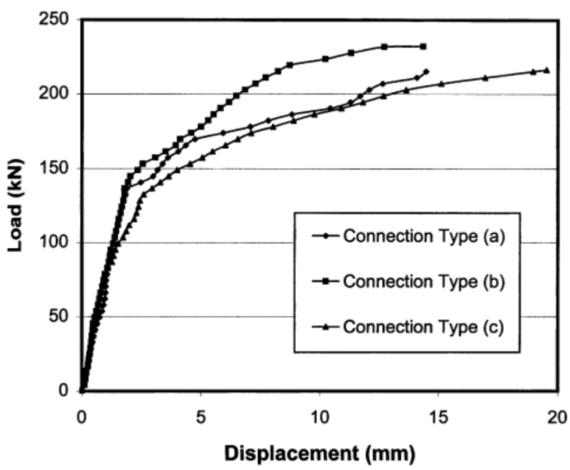


Figure 6. Relationship between load and displacements for three type of connection [42]

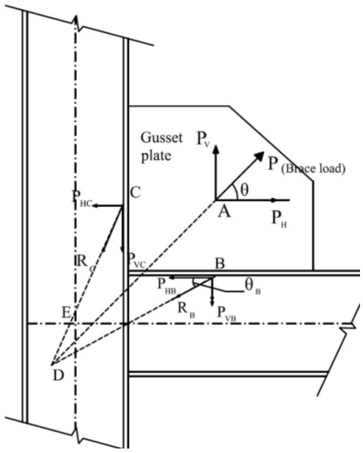


Figure 7. The uniform force method used in connection design [44].

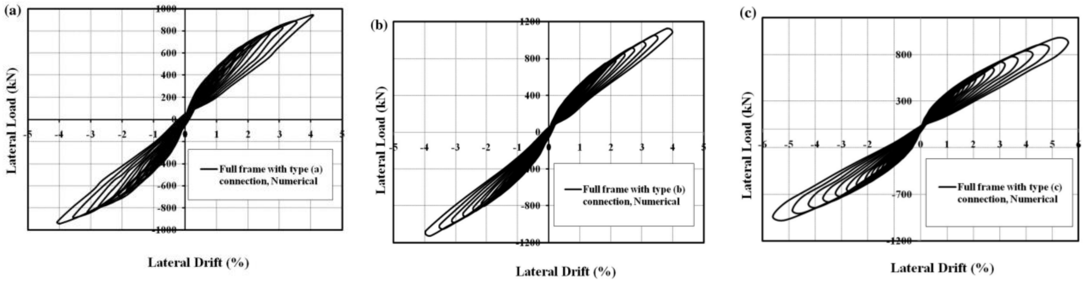


Figure 8: The different hysteresis loops for brace and frame connection systems with connection types (a), (b) and (c) [44].

M.A. Youssef et al. (2007) [45] studied the models with steel bracings and observed the performance of frames with steel bracings. In this study, UFM is used for connection design. Figure 9 shows the detailing of the connection provided by this study. The results show that the acceptable seismic behaviors of braced RC frames and have higher lateral load resisting capacity as compared to moment frames. Figure 10 shows the crack formation pattern near the brace frame connection portions. Figure 10 also shows that less number of cracks were formed as compared to the moment-resisting frames.

A. Said and M. Nehdi (2008) [46] in this study researcher used the concentric steel bracing system in the existing frame, which is a non-ductile RC frame model as shown in Figure 11. The experimental analysis was performed in beam-column joint with bracings. In the experiments, it was observed that the proposed bracing system enhanced the drift at test termination by a factor of 3.0 and 5.5, load-carrying capacity by a factor of 2.6 and 1.7 [46]. A. Massumi and A.A. Tasnimi (2008) [47] presented the X – X-steel bracing in RC frame models (one bay story, 1/2.5 scale). In the experiment, they used various details of the bracing connection with the RC frame. The detail was using bolts and nuts, using steel jackets around the columns, using embedded plates as shown in fig 12.

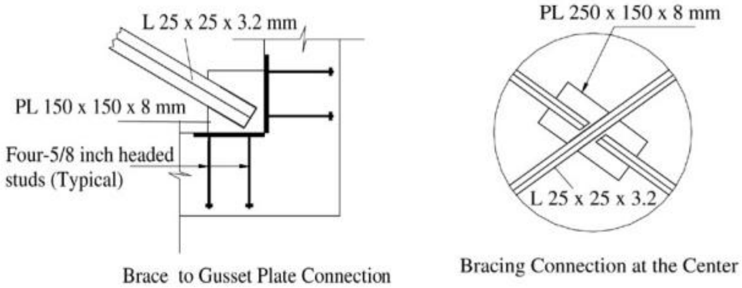


Figure 9 Connection detailing used by [45].

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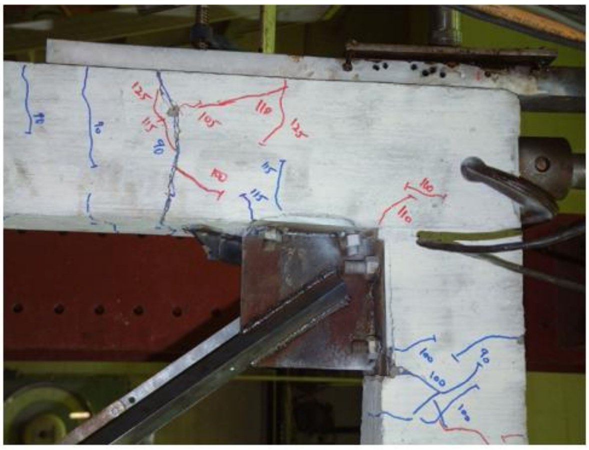

Figure 10: Failure observed in braced RC frame [45].

The models were tested under both cyclic and vertical loads. The result suggested that RC frames having X- X-bracing with different connections increase the stiffness and also change structural behaviors. The association of steel bracing and RC outline in the retrofitting system is discovered that include brittle failure. Ju M et al. (2014) [48] utilized a non-compression carbon fiber X-supporting framework to eliminate buckling failure. In this review, an exploratory perception was done in the Carbon Fiber, X-supported framework as a retrofitting interaction in the RC frame and tried under the cyclic burden. It is seen that there was no buckling failure was accounted for. The numerical modeling was done by Sadeghinezhad et al. (2020) in which retrofitted with X braced four proposed models were observed. The direct internal connection was used, and the study observed that the bearing capacity, absorbed energy capacity, and stiffness was increased up to 2.3, 1.5 and 4 times, respectively [49].

Figure 11 Steel braced column beam joint specimen with cracking formation [46].

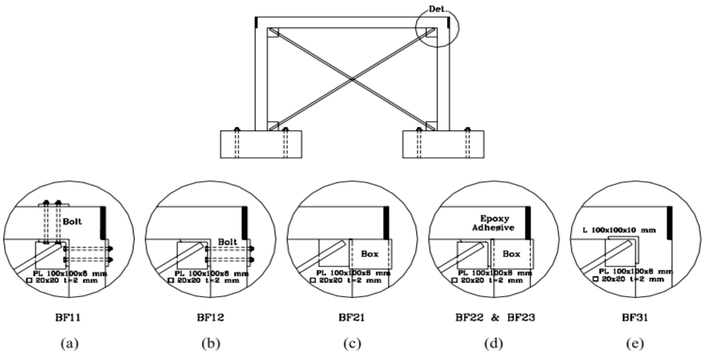

Figure 12 Cross bracing and their connection details [47]

3. Connection over strength and R factor in steel-braced RC frame.

Maheri and Sahebi [41] presented that using the straightforward connections between the RC member and steel bracing, an intermediary steel frame is needed. Some experimental studies showed the steel bracing frame was used to improve the strength capacity of the concrete building. It is important to study the interaction level between the strength of the RC frame, which is directly connected to steel braces (internal bracing). The friction-based connection was also introduced in [50] which is a clamp-shaped connection. Maheri, H. Ghaffarzadeh (2008) [51] studied the RC with steel braced frame by using the numerical and experimental investigation method with cyclic and lateral loading. This paper studied the connection of the RC frame with an internally braced frame in the strength capacities, with the level of interaction [41] between steel and RC. Stiffening effects of connections cause an overstrength in RC frames with X steel bracing. And also studied that overstrength factors, R, depend upon the number of bays and stories, and are concentrically braced [51]. L. Di Sarno and Manfredi. (2012) [52] also suggested some numerical values of overstrength and R factor. M.R. Maheri, R. Akbari (2003) observed the seismic behavior of the RC frame with X- & knee-braced structure with inelastic pushover analysis method was applied. The study was based on an experimental and analytical investigation. The behavior factor, also called the response reduction factor, was estimated with the help of, ductility reduction factor, the overstrength factor, and the allowable stress factor. The R factor depends upon various factors like the story's number, the shear force of bracing, and the type of bracing configuration. In this study, the researcher has chosen the four-story, eight-story, and twelve-story frames with different base shear values (0, 50, 100%) in steel bracing were investigated. It was observed that the ductility of the building varies with the height of the building and when steel bracing is used, it has been magnified. Also in this paper, it is found that the knee-braced frame has a greater R factor and ductility value [53]. Where R factor is the response modification factor (UBC code), which is the ratio between the shear forces required to keep the building elastic to the inelastic design shear forces of the building [53]. In simple words, to get the design lateral force, there is a factor R that is reduced from the actual base shear force.

4. Conclusion

Several papers are reviewed and observe the different types of steel braces and RC connections. The steel bracings in RC frames improved the seismic performance as well as reduced the cost as compared to the shear wall. The different paper also shows that adding the bracing reduced the inter-story drift and displacements of the structure effectively. Experimental and numerical analysis of the braced and unbraced frame models shows that it is important to design braces and frame connections to get effective and well-designed braced frame structures. Both types of connection, one used after construction (normally for retrofitting process) and the second one is during construction periods (for new constructions) are observed by using different research papers. The study also observed the R factors, ductility, and overstrength factors of the braced RC frames and the effect on them due to the connection. The overall finding is that Steel bracing in RC frames improves the seismic performance, strength, ductility and stiffness of the structures when the steel bracing is used concentrically. The following findings are observed after studying the different papers related to the connection of steel bracing to the RC frame:

a) A lot of improvements are observed in the connection design of the RC buildings with steel bracings. However, there is still a need for additional study to develop the detailing of the connection and also needed codified design.
b) The research on the effect of retrofitting and in the new construction of the RC frame by different bracing on the behavior of the columns, slabs, and beams is very limited. It is also a limited study focused on the effect of bracing in the RC frame, with the connection of bracing to different frame elements. A future study is needed to identify the effect of bracing in connection design with RC frames.
c) The crack formations around the braced connection portions, the hinge formation pattern and the chance to shift the hinge location in the frame structures due to the bracings, failure pattern of beam, column and bracing connection, etc., are needed to further study.

d) Further study is needed in connection with overstrength, stiffness ratio, and R factor for a different type of concentric bracing system. Researchers have been presented with the connection overstrength factor, R factor, & stiffness, and their formulation for only X-bracing and it is needed to further verify for other bracing types.
e) There is only a few studies on the connection or joint of the RC frame and bracing. Thus, an additional study is needed to analyze and design connections in both new constructions as well as retrofitting of the existing structure. There is needed to develop a simple design method for connection.
f) The experimental and numerical results suggested that retrofitting or strengthening of RC buildings with steel bracing has weak connections. If properly connected, it should increase stiffness, strength, and energy dissipation potential. So, further study on the behavior of connection in RC frame and steel braced is required.

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