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Seismic Behaviour of Reinforced Concrete Frames with Concentric Steel Bracing: A Review of Research from 1990 to 2023

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Abstract— Reinforced concrete (RC) buildings strengthened with concentric steel bracing systems have been widely investigated as an effective strategy for enhancing seismic resistance in both existing and newly designed structures. However, existing studies are dispersed across various bracing configurations, design methodologies, and performance evaluation approaches, making it difficult to establish a comprehensive understanding of their seismic behavior. This study presents a systematic review of approximately 75 published studies from 1990 to 2023 retrieved from major scientific databases including Scopus, Web of Science, ScienceDirect, and Google Scholar. The reviewed literature was screened based on relevance to concentric steel-braced RC frames, seismic retrofitting, structural design, and seismic performance assessment. The findings indicate that X-bracing, Chevron bracing, and Buckling-Restrained Braces (BRBs) significantly improve lateral stiffness, energy dissipation capacity, ductility, and overall seismic performance. Experimental and numerical studies consistently report substantial reductions in inter-story drift and enhanced structural resilience under seismic loading. Recent developments involving performance-based seismic design, self-centering systems, hysteretic dampers, and computational optimization techniques have further expanded the applicability of braced RC systems. Nevertheless, challenges remain regarding standardized response modification factor evaluation, performance-based design implementation, and high-rise applications. The review highlights current research trends, identifies critical knowledge gaps, and provides recommendations for future investigations involving advanced materials, hybrid systems, and artificial intelligence-based structural optimization.

Keywords: Concentric braced, Reinforced concrete, Retrofitting, Steel bracing.

1. Introduction

Steel bracing applications in steel structures are common and several studies have been conducted on such structures in both concentric and eccentric bracing. Also, it is common to use the shear wall (SW) in the RC structure. The bracing (steel) & shear wall are both used in the structure to increase the seismic resistance of the whole structure. The steel bracing is used in a structure mainly for two purposes such as retrofitting in the existing RC frame and new design of RC frame with steel bracing. The steel bracing in the RC frame is used in a strengthening or retrofitting process to improve the lateral shear and stiffness capacity in the existing structure. Relatively low cost of steel bracing as compared to the other moment-

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resisting structures and concrete shear wall buildings. It reduced the weight of the structure and it is also easy to construct additional ductility as compared to the RC shear wall. The research help to get brief information and an idea about the RC frame with steel braced configuration and seismic effect in the structure.

The earliest building having structural bracing is constructed in 1965, Chicago is known as Dewitt-chestnut building. In 1970, Fazlur designed the braced tube system, the building name is John Hancock center in Chicago. In 1964 Fazlur designed the tower (diagonally braces) in the thesis writing. Ontario Centre in Chicago in 1985, which is constructed with an external brace with concentrically braced RC frame concrete [1].

The review of the research paper mainly focused on the experimental and numerical analysis & design of different types of concentrically braced RC frames in both senses, like retrofit and design of new RC frames with bracing. Further, the study identified the area of future research. The study is focused on the seismic behaviors of RC structures with steel bracings and studies the seismic behaviors parameters such as ductility of the frame, energy dissipation, response modification factor, failure mapping, story drift and displacement, stiffness, etc. described by different researchers.

2. Type of concentric bracing

The concentric bracings are categorized according to their use, material and lateral load transfer. There are two types of bracing, namely, concentrically and eccentrically braced systems. The first type is mainly classified as a diagonally braced frame, inverted chevron braced frame, K bracing, X- & multi X-braced, and inverted V bracing frame as shown in Figure 1. Some other types of concentrically braced frames are BRBs [2], [3], [4], ultra-lightweight BRB, post-tensioning braced [5], [6], etc. are also used in the construction of the building.

3. Retrofitting of concentrically steel-braced RC frame.

Retrofitting technique is used in an existing building to improve seismic performance [7], [8], [9], [10]. It is a cheap and effective method of strengthening the RC frame against the lateral loading commonly known as earthquake loading. There are different reasons such as designing only considering gravity load, updating of seismic codes, modifying of building, Change of use of the building and strengthening the building it may necessitate providing a retrofit technique in existing non-ductile buildings. The different experimental and numerical techniques are investigated in RC buildings with various types of bracing, commonly X- bracing, chevron and inverted chevron bracing and diagonal bracing [11], [12], [13], [14]. Several researchers studied the retrofitting, strengthening, and seismic rehabilitation of the RC structure with concentric bracing and the result suggested an improvement of seismic performance and ductility of the existing structure[15], [16], [17], [18], [19]. [20]suggested different criteria about the RC braced frame and it was concluded that use the low slenderness ratio to get none non-buckling bracing system. [21]studied the RC building having steel bracing as a retrofit technique to increase the seismic performance. (Bush et al., 1991)Experimented on two-thirds scale RC frame models of two bays and three levels with X steel bracing for re-strengthening the existing frame under the cyclic and lateral loading.

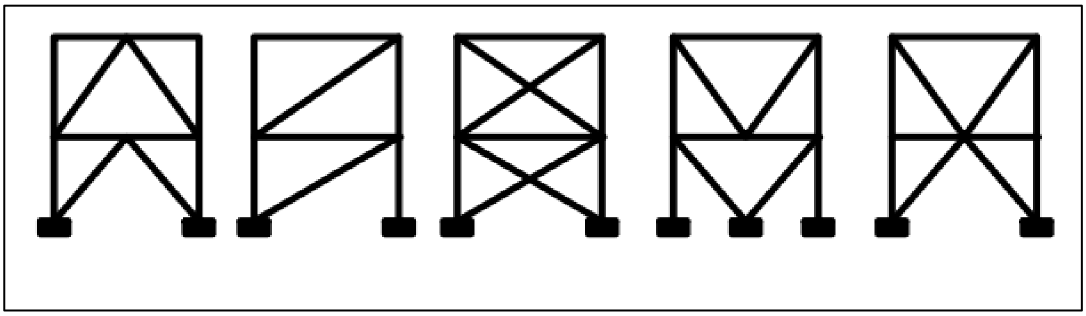

Figure 1. Different concentrically braced frames.

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The result suggested that the X-bracing increased the stiffness and strength of the frame. It was reported that the 60-70% lateral strength was carried by the braces and the remaining to the columns, and suggested that columns were increased at least 50 % lateral capacity. [23] studied retrofitting of the telephone buildings in Mexico. It was concluded thata significant reduction of story displacement was observed after applied the steel bracing. Yamamoto and Umemura (1992) studied the RC with steel braced frame used in retrofitting. [24] studied the K-braced RC model with various irregular columns (T, L, + shaped) and checked experimentally (by using a shaking table) to the failure sequence. The study noticed that the bracings fail first, the secondly beam and then the columns fail, which indicates that the study achieved the basic design philosophy (strong columns, weak beam, and weaker bracings).

The post-tensioned bracing was introduced by some researchers in strengthening the RC structure. In 1992,[5] studied the performance of a post-tensioned bracing system in strengthening low and medium-rise buildings constructed in the 1960s in the U.S. However, the result suggested that post-tension steel bracing was used in a low-rise building in both firm and soft soil conditions.[25]studied the three retrofitting techniques, namely post-tensioned bracing, X bracing, and structural walls in low to medium-rise buildings. The Maximum allowable drift of the original and retrofitted structure depends upon the level of damage.

The lateral strength & stiffness of the structure was affected by the behavior of bracing as shown in figure 2. Figure 2 shows the lateral strength of the post-tensioned braced structures and compared with other types: X bracing, structural wall and original buildings.[6]investigated the low to medium-rise existing structure located in the United States. They used inelastic static and dynamic methods in RC frames with a different type of retrofit technique (steel braced, post-tensioned braced and infill walls). The result suggested that in 7 and 12 story buildings, the bracing system did not always show satisfactorily feasible options. The ductility and response factors also affected with the heights of the structures while using the steel bracings in the RC buildings [26][27].

[28] investigated a building that was originally designed as a five-story structure but later the owners decided to add three more stories. It was observed the seismic retrofitting with X-steel bracing was acceptable for the 8-story RC structure by the owners of the building. [29] studied the existing nine-story building which is located in Mexico City. The building was retrofitted by steel bracing. The studies were focusing on the resonant response and along with pounding potential from the structural point of view. The retrofitted building was survived the 1985's Michoacán earthquake which indicated the effectiveness of the steel bracings in RC buildings.

[30] studied the low/rise RC structure which was re-strengthen by using X bracing. The three-story building was observed its seismic performance by using different ground motions. It was suggested that the number of the braced bay be increased then the load on RC columns was reduced.

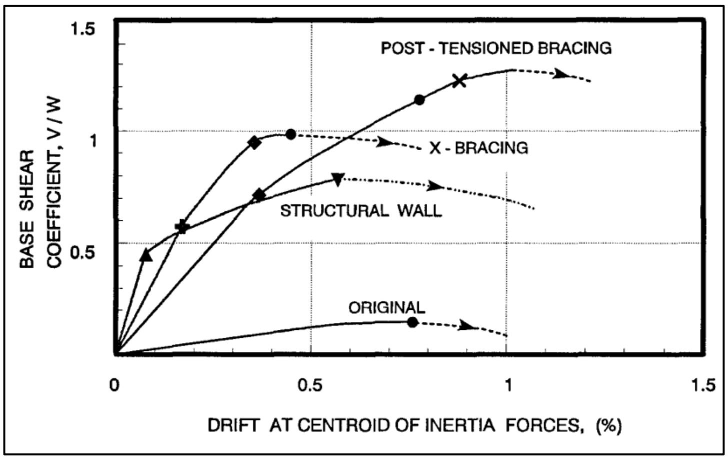
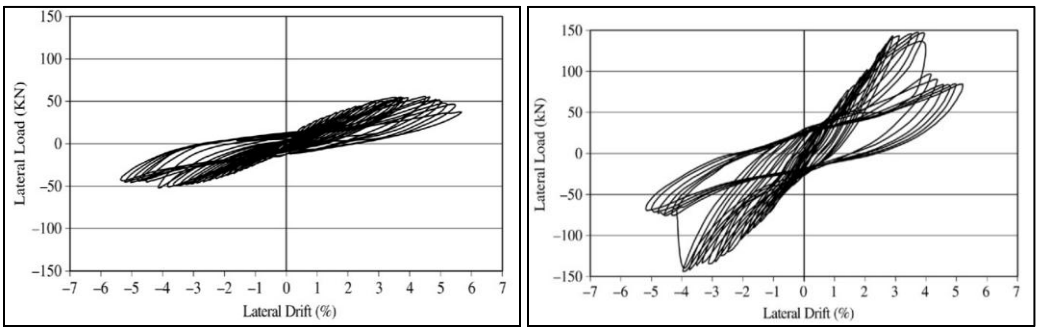


Figure 2. Comparison between original and retrofitted RC buildings [25].

A new device is known as a compression release device (have no compressive stress) in steel bracing was also used in retrofitting the RC structure. In 2006 [31]used compression release device (CAD) for steel bracing in the RC frame. It was observed that buckling failure of the compressive brace was highly reduced the ductility of the RC frame. [32]performed both experimental and numerical investigation in a 2/5 scale RC frame with and without steel bracing. In this experiment, they used the directly connected concentric internal steel bracing. The researchers applied the cyclic loading to the experiment and the results show that adding steel bracings reduced the lateral drift easily. Energy dissipation at high drift level of the structure having bracing found higher than without a bracing. [33]experimented with a reinforced concrete frames models with and without steel bracing. The braced and unbraced frames were tested under the cycling load and the main objective of this research to compare the conventional moment-resisting RC frame & RC frame with steel braced (see figure 3). Figure 3 indicated the hysteretic behavior of the moment and braced frames and this shows that the braced frames have more energy dissipation capacity than the moment frame. The study observed that the failure drifts for braced frame and moment frame were 4.00% and 5.00% respectively.

[34]performed an incremental dynamic analysis in low to medium-rise non-ductile RC frame using four rehabilitated techniques, these were reinforced concrete shear wall, steel bracing, diagonal FRP strips and wrapping. Seismic performance parameters were studied in the term of maximum inter-story drift (ISD) ratio, maximum story base shear/seismic weight ratio and energy dissipater capacity. The study observed that adding the RC wall increased the story shear and when the FRP wrapping used the PGA, and energy dissipation capacity increased.[35] also studied the steel bracing and FRP technique in 9 and 18 story buildings. The study concluded that adding the FRP reduced the ductile failure modes and steel bracings effectively play the main role in stiffness and decreased the ISD of frames. (2011) [36]presented the retrofitting technique in 3- and 6- story RC buildings. Different types of concentric steel braced that was used such that X-, chevron braced, Z/X-, and Z (Zipper) braced. It was concluded that adding the bracing and increasing the dimensions of the section enhanced the building strength capacity.

The study also suggested that using tube sections performs better than other sections. (Liu et al., 2012) The experimental analysis of 1/2 scale RC frame of bare, steel braced& FRP retrofitting techniques was considered. The seismic performance in these three models has been studied and concluded that the FRP technique improves global performance, ductility, and energy dissipation capacity. However, the experiment shows that steel-braced frames have more stiffness value than others (see Figure 4). [38]studied the experimental and numerical analysis of the RC frame having steel bracing to observe the performance of the building. The result shows that for a dual system, the ultimate strength of the frame increased by 18.34%. [39]observed the seismic behavior of RC with steel bracing. Three methods are used to study the performance of the models namely NSPDCM (“Nonlinear Static Pushover Displacement Coefficient method”), FEMA-440, and dynamic analysis with the Indonesian code. It was concluded that the size of bracing used in the RC frame improves the lateral force performances of the structures. [40]studied steel bracing as a commonly used retrofitting technique to increase seismic performance. The concentric X-bracings were used and also compared with different alternative bracing patterns.



a) Moment resisting frame b) braced frame

Figure 3. Curves between lateral load and drift (%) for braced and unbraced frames [33].

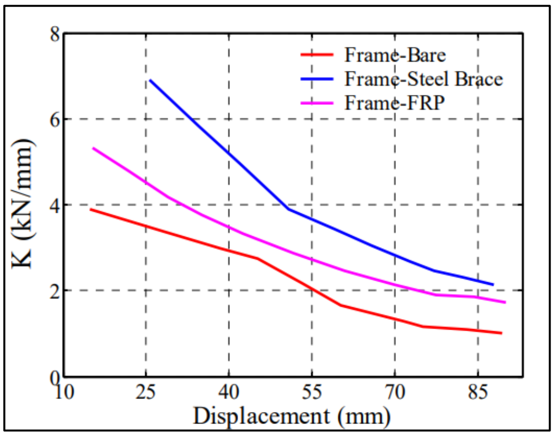


Figure 4.Comparative study of stiffness of Bare, steel brace and FRP frame [37]

[41] used a new non-compression carbon fiber X-bracing (zero compression force in bracings with carbon fiber) system to restrict the brittle and buckling failures. In this study, an experimental observation was done in the CF (Carbon Fiber) X-braced system as a retrofitting process & tested under the cyclic load. It is observed that there were no buckling and brittle failures reported in non-compression carbon fiber X bracing, which is better than the conventional steel X bracing system.

[42] studied three concrete braced, steel braced and infilled frames for resisting the lateral shear force. The experimental of these models were tested under cyclic loading. The result revealed that the lateral load resisting capacity increases by using any type of bracing as compared to the without braced frame. It was noticed that using steel and concrete bracing was the lateral strength increased 142%, 200%, and the stiffness increased 290%, 280% respectively by the comparison with nonstrengthened frames.

[43]studied the strengthening of the RC frame with steel bracing in low to medium-rise buildings. The 3, 5, 8, and 10 story RC frame building having chevron-A braced and X-bracing provided in the mid-bay were considered. The results suggested that chevron A-type bracing showed better behavior than using X-type bracing. Chevron 'A' shaped was stiffer as compared to X-braced frames with ratios 1.07 and 1.05 for 8 and 10-story buildings respectively.) [44]studied the topology optimization used to derive the bracing configuration. The results indicated that the stiffness and strength of the structures improved when the steel bracings were used but it may reduce the ductility when excessive brace volume was applied.[45]studied the effectiveness of the two retrofitting methods, namely a new type of cylindrical friction damper (CFD) and concentric chevron bracing (CCB). Two types of 6-story moment resisting buildings, one is steel and the one is RC building with various ground motions were considered. The seismic behaviors were observed by using the nonlinear software known as OpenSees. The result revealed that the use of CFD performed better than the CCB method in terms of mean annual frequency, annual losses and collapse probability. However, the use of CFD increased the overall cost of the structure.

The effect of steel bracings in RC buildings under the seismic effect was considered by [46]however detailed information was obtained in Rahimi and Maheri's study in the 2018 paper.[47] investigated the effect of steel bracing in RC structures. The study highlighted some positive effects such as shear capacity, reduction in displacement, improvement of structural seismic performances, and decreased drift. The seismic effects in the columns were considered when the x bracing was used in the RC structures. It was concluded that when columns were directly connected with bracing, the shear value was increased adversely. Also in the columns attached with bracing, the axial compression forced increased as the height. It was concluded, a low-rise RC frame with steel x bracing showed good results during seismic loading. [48]studied the effect of bracing in RC structures. The researchers examined four, eight, & twelve-story high two-dimensional structures by using the time history analysis. It was concluded that the X bracing improved the overall seismic behavior by decreasing the ISD, maximum top-story displacement, and demand base shear. Adding the steel as bracing in already exist RC structures, increased global stiffness and shear resisting capacity. However, it also increased the demand base shear which demands some members in the structure. It was also noted that the base shear increased as an average of 20% because of retrofitting in a four-story frame, 52% in 8-storey, and 63% base shear in frame twelve-story frame as shown in Figure 5. It was studied that adding the steel bracing in the RC frame it decreasing the beam's ductility demands which is good. In the connection of steel and RC beam-column joint, the location of the plastic hinge is shifted to the location where less shear reinforcement present. Also, the shifting of the hinge formation reduced the effective length of the beam and in the columns, it reduces the effective length of the column and there may be a short column effect.

[49]discussed the seismic vulnerability of RC structures designed for the gravity load only. The models (bare frame, full infilled, and pilot is frame) were retrofitted with using of external steel bracing systems. It was concluded that the use of the X bracing system was more effective and also increased the safety factor of the building.

To improve the seismic behaviors of RC buildings with steel bracings, Mazza and Vulcano introduced the design of hysteretic damped braces (HYDBs) in their study [50]. F. Mazza and A. Vulcano studied the damped braces and designed them by using the direct displacement-based design with the theoretical formulation in part 1[51]and numerical results in part 2[52].[53] presented the observation in steel braced equipped hysteretic dissipative devices (HYDBs) and carbon fiber reinforced polymer (CFRPs) as a retrofitting the RC building and results was suggested that HYDBs effectively reduced the seismic demand. Mazza focused on HYDBs as retrofitting in unsymmetrical plan structure and used DBD(displacement-based design)[54], [55], [56].Metallic yielding dampers and bracing introduced in the RC frame as a retrofitting process[57]. Hysteric energy dissipation bracing(EDB) [58]and design procedure was presented by Di Cesare et al. (2017) in the existing RC frame by using EDB with the help of a case study[59]and also in a hospital building as a retrofitting[60]. [61]observed the open ground story (soft story) RC buildings and noticed that steel bracings and shear wall effectively decreased the peak ISD response. For strengthen buildings, the peak floor acceleration of the building also amplified more than 205 times un-strengthen frame. overall results suggested that the concentrically braced frames are used in the existing RC building effectively improve the lateral capacity, stiffness and strength.

4. Analysis and design of concentrically braced RC frame

Newly designed RC structure either SW frame, coupled wall (CW), or moment-resisting. Bracing in the RC frame has many advantages such as it reduces the weight of the structure so that it also reduces lateral loads and increases the ductility of the building. There are many studies focused on concentric internally braced for new design and constructions, which was studied as experimentally or numerically [62], [22], [20],[63],[64]). After a successful design of steel braced frame in the existing RC building, there are several newly constructed buildings having different types of steel bracing. [65]considered the behaviors of the RC frame with X and K bracing in the 6-story 2-bay interior structure of the symmetrical structure. The slenderness ratio of the bracing was considered between 60 and 120. The strength of bracing was considered as strong, intermediate & weak to observe the failure behaviors during lateral loadings.

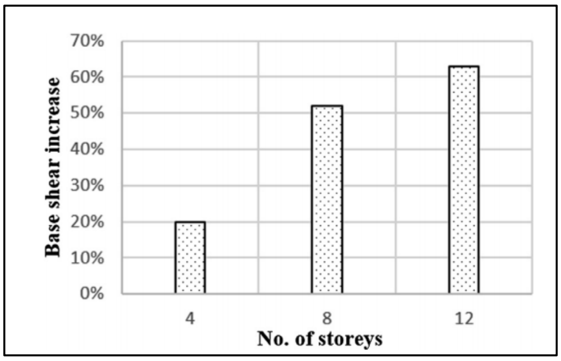


Figure 5. Increases the average base shear for 4, 8 and 12-story buildings [48].

The study concluded that (i) the 80 % slenderness ratio seems to be good in RC frames and (ii) avoid the strong and weaker bracing members because they caused excessive inelastic behavior in the frame. [66] conducted the static pushover analysis experiments on the ductile reinforced concrete frame, which were used steel (Knee and X) braces. One of the conclusions indicated that the ultimate capacity and strength capacity of reinforced concrete models have improved and the story displacements have reduced when X- and knee bracing were introduced. A study noticed that when retrofitting or designing for damaged leveled earthquakes, X- and knee-braced systems may be used and however, for collapse-level earthquakes, knee-braced braced were more effective.

[67] performed the parametric study of the RC frame with a different arrangement of concentric bracing with different cross-sectional areas and slenderness ratio of bracing. They observed the maximum story displacement, maximum beams, and columns rotation demand at each floor, maximum column axial compression at each story, maximum story shear, and uplift induced at the foundation.

[68] studied the non-linear analysis of ductile RC-MRCBFs using chevron shape steel bracing. The analysis was based on the Mexican building code. The study observed 4 to 16 story buildings. the story and drift curves, global lateral shear, yielding mechanism, and overstrength (R) were considered. The authors successfully designed RC-MRCBFs when columns frame resist at least 50% of the overall shear forces. [69]studied 4 to 24 stories ductile RC-MRCBFs using steel-chevron bracing by using nonlinear static analysis on the model and developed a new idea and guideline of designing bracing in RC buildings. Researchers consider the general steel and reinforced concrete guidelines of Mexican Codes. The comparative study for each building having up to 25%, up to 50%, and nearly 75% lateral shear strength provided in columns and analyzed the models. They obtained in this research that they successfully designed the low and medium-rise ductile RC-MRCBFs when columns resist a minimum 50% of the total seismic shear forces.

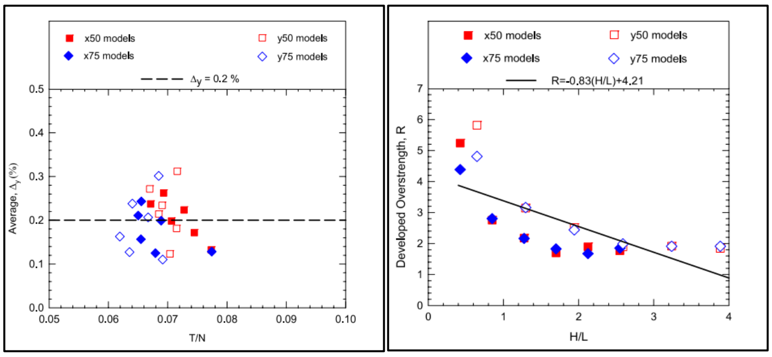
Also in this research, design parameters such as story drift, ultimate capacity, over strength reduction factors were calculated. Figure 5 shows that the study achieved the story drift limit as 0.2% at the yield limit and as the slenderness ratio of the structures increases, the overstrength factors of the buildings decrease.[70]studied the nonlinear dynamic analysis of six, RC-MRCBFs by using the latest Mexico Code (MFDC-04). The building has three different heights 8, 15, and 24 stories expected to be in 3 various soil conditions in Mexico. The research concluded that failure mechanisms for medium-rise models (8 to 15 story) were expected weaker brace/weak beam/ strong column failure mechanism and the height of the building increases the failure pattern was not expected to be weaker brace /weak beam/ strong column.

The study also noticed that when the columns resist at least 50% of the total seismic shear forces, they show good seismic behavior, as shown in Figure 7. Figure 7 shows that the formation of the plastic hinge in columns, beams and bracings when columns are designed to resist 50% base shear. [71]studied the seismic performance of six RC-MRCBFs by using nonlinear dynamic analyses. The two different guidelines (MOC-2008, 2009 & MFDC-04, 2004) were used in 15- and 24- stories in height and supposed as an office buildings. The result was based on overall over strength demands & ductility capacities. The paper concluded that the building has a serviceability limit state that becomes acceptable when the anticipated story drift limit $\Delta ser = 0.2\%$ and slender building between $0.4 \leq$ height/length ≤ 4 for the construction of novel design RC-MRCBFs structures as shown in Figure 6. It was also established that the failure mechanisms for medium-rise building only get adequate failure behavior such as weaker brace /weak beam/strong columns mechanism.

[72] considered the series of structures from 5 to 25 stories used nonlinear static analysis, overall seismic design performance parameters were observed in regularly spaced RC-MRBFs with HED equipment attached on steel bracing with inverted V configuration. The observation was made by various elastic stiffness ratios (RC frame and whole building). The study was focused on Mexican Codes and Mexican practices. Also, the study focused on the V/W was observed for all models was 1/10 and inclined of the

inverted V braces (40° to 45°). It was observed that the slenderness ratio (height/Length) increases the response modification factor Q was decreased. The various observation was made based on the several parametric studied and developed in maximum local displacement with ductile property, Story drifts, etc. in this paper. This paper also suggested that further studies were needed such as nonlinear dynamic analysis for typical soil, the effect of a broader range for V/W to assess, additional structural detailing, and its impact on seismic performance.

[3]studied the BRBs frames system in an RC frame system. The zigzag arrangement of BRBs and RC frame connection was studied by applying the nonlinear dynamic analysis in experimental test models. The experimental test was conducted in post-tensioned bolts and concrete corbels connection. The result suggested that the ISD of the whole structure increased when it leads to the flexibility of the concrete corbels connection. Post-tensioned bolts have a slight influence on elastic deformation. It is also concluded that higher mode effects may lead to unsafe connection design. [73]observed frames have four, eight, twelve, and sixteen stories, have 1,2,3 or 4 bay of RC-MRCBFs (Invert V bracing) where the structure was situated in soft soil in Mexico City. The researchers used the earthquake design, RC, and steel procedures of the Mexican Codes. They observed static pushover analysis and the effect of increasing the structural redundancy in the ductility of RC-MRCBFs. When the number of bay increases, then overstrength redundancy factors also increase.



a) Story drift at yield level for inverted V bracingsb) Relationship between the R and slenderness ratio
Figure 6. Drift level and overstrength factors of the RC-MRCBFs [69].

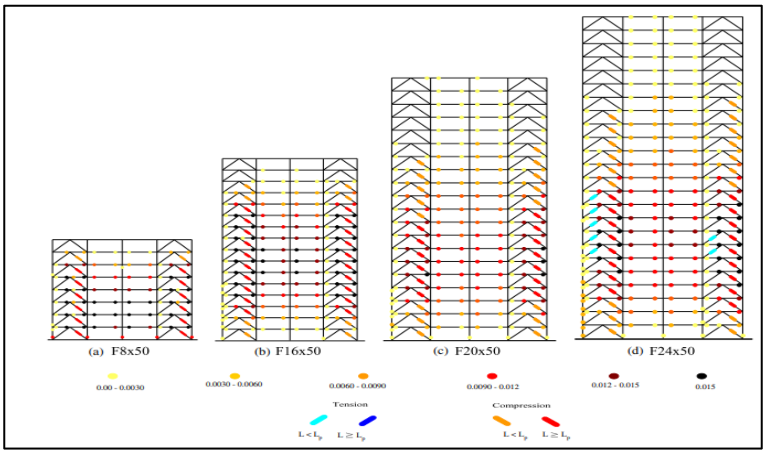


Figure 7. Failure mechanism for structures when the columns resist 50% base shear [69].

[2] performed 5- and 10- the story of BRBs (chevron steel) RC-MRBFs was designed. Both static pushover analysis and time history analysis have been used. The result was based on a capacity curve, permanent deformation, yield mechanism, ISD, cumulative ductility demand, & maximum ductility. Also, the paper suggested that the developed design methodology were used other bracing (V-, diagonal, and X) configurations, to get the desired seismic performance. [74]investigated the RC steel braced frame near the fault area where static pushover analysis and time history analysis have been used for seismic

analysis. 4-, 8-, 12- and 16-story reinforced concrete with diagonal steel bracing were designed and code-based design near the high-risk areas. The researcher used the Iranian Seismic Design Code (4rth Edition (2014)) and concluded that in mid-rise and high-rise structures the far-fault motion imposed lesser demands than near-fault. For this study, the maximum IDR is considered and has been found that IDR more than 1% of the shear force is distributed almost evenly in columns and bracing frames. Also in the research, plastic hinges in beam, columns, and bracing were observed.

Research [75] have performed the RC-MRCBFs by considering MFDC-04, 2004. In the research, paper buildings range from 4 to 20 stories RC with X steel bracing and were considered the static pushover analysis and time history analysis. By applying the pushover analyses researcher observed the whole building ductility capacities, overstrength R factor, story displacement, and also other design parameters like dissipating capacity, failure mappings. In the same way in [69]researchers have used 25%, 50%, and 75% of the story lateral force provided in the columns to get a strong columns/weak beam/ weaker columns mechanism. However, the researcher observed that in the ductile model, when the R factor was increased lateral force provided in RC columns also increased. This was the opposite in chevron braced building considered by [69]where when shear strength RC columns increased the R factors decreased. Where the R is the overstrength factor. the study concluded that the R factor depends on the bracing type and plan so that it may need various pre-defined equations to evaluate the R values, also they concluded that to obtain well structural performance for design the RC with steel braced frame could be to consider higher (incremental) of lateral force involvement in columns.

The research papers describe several properties of the braced frame, especially when the steel bracings are used in the RC frames. Different methodologies are used in this field to optimize the result and process. Overall, it is observed that steel bracings are a good option to use in the RC frame to resist both earthquake load as well as wind load.

5. Conclusion

This review consolidates thirty years (1990–2023) of studies focusing on reinforced concrete (RC) frames retrofitted with concentric steel bracing, highlighting their effectiveness in improving seismic performance. Significant results indicate that X-type, V-type, and buckling-restrained braces (BRBs) can greatly enhance lateral stiffness (by as much as 290%), lower inter-story drifts (by 60–70%), and boost energy dissipation, although they may increase base shear demands (by 20–63%) in taller buildings. Retrofitting non-ductile RC frames with steel bracing leads to a strong-column/weak-beam/weaker-brace mechanism, provided that columns handle at least 50% of the seismic shear, as supported by guidelines from Mexican and Iranian regulations. Nonetheless, slenderness ratios (ranging from 80 to 120) and bracing arrangements (such as chevron compared to X-type) play a crucial role in determining ductility and overstrength factors (R). New methods like self-centering systems, hysteretic dampers (HYDBs), and CFRP bracing tackle issues of buckling and brittleness, but there is a need for financial optimization. There are still significant gaps in the standardization of R-factor assessment, guidelines for performance-based design, and investigations into dynamic soil-structure interactions. Future studies should focus on AI-driven topology optimization, hybrid bracing-shear wall solutions for high-rise buildings (more than 12 stories), and extensive testing of asymmetric layouts to connect theoretical insights with practical applications. By incorporating advanced materials (like ultra-lightweight BRBs) and data-informed modeling, concentric steel-braced RC frames can reach next-generation seismic resilience, maintaining a balance among safety, cost-effectiveness, and adaptability to new regulations.

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