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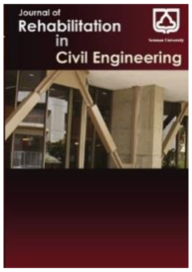

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Seismic Improvement and Rehabilitation of Steel Concentric Braced Frames: A Framework-Based Review

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ABSTRACT

The ability of structures to withstand seismic loads is the most important feature of earthquake engineering. Because of their high stiffness and lateral strength, concentrically braced frames (CBF) are one of the most prevalent resisting methods in engineering structures. Under moderate seismic events, CBFs have limited lateral displacement capability, resulting in structural damage and substantial post-earthquake expenses. However, when these constructions are exposed to moderate to severe seismic events, their compression members start to buckle. Buckling these compression members in CBF also reduces ductility and causes hysteresis curve deterioration. As a result, they become brittle and have a limited capacity to dissipate seismic energy. On the other hand, conventional CBF constructions exposed to seismic hazards may display an unacceptable soft-story mechanism, in which drift and damage are localized in a single-story, while all the other stories are comparatively unscathed. Several research works have improved CBF seismic behavior, and different strategies have resulted in seismic improvement. This paper presented an overview of seismic improvement modifications of CBF, which have been studied in the literature. A review of current studies to better understand and analyze CBF behavior is presented.

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1. Introduction

Steel buildings are, without a doubt, one of the most frequent structures used in the construction of residential buildings across the world. These buildings make use of a variety of bracing techniques. Braced frames are classified into concentric and eccentric categories, each with its own set of features and determines.

CBFs are often used in low- to mid-rise steel structures that can use bracing elements placed in various configurations, such as X-bracing, 2-story X-bracing, and chevron. Typical bracing in CBFs or eccentrically braced frames (EBFs) has several advantages, such as cost, effortlessness, and design accuracy, but it is susceptible to compression buckling when buildings are subjected to substantial seismic loading, which results in nonsymmetric, degrading cyclic force-deformation (hysteretic) behavior of the frame. Concentrically braced frames (CBFs) are cost-effective, and their stiffness and strength aid in achieving serviceability limit states in performance-based seismic design. Brace yielding and buckling start happening during strong, rare seismic events, and this response can provide the deformation and energy absorption capacities to meet life-safety and collapse-prevention performance targets. These goals are addressed by the AISC Seismic Design Provision AISC 2005a's [1] special concentrically braced frame (SCBF) design standards. For these benefits and the uncertainties surrounding the behavior of special moment resisting frames following the 1994 Northridge Earthquake, SCBFs have become more popular recently [2,3].

The CBFs offer excellent elastic stiffness and strength and are thought to decrease structure's drift more successfully than conventional lateral force resisting systems (LFRSs) throughout a seismic event. CBFs built following pre-modern seismic requirements, on the other hand, lack the ductile designing and member capacity design criteria [4] needed for appropriate nonlinear response under seismic stresses. Early fracture or failure of the brace or gusset plate connection is also possible. Furthermore, previous studies have demonstrated that when exposed to maximum considered earthquake (MCE) stresses, even CBFs developed to current seismic requirements may display soft-story performance [5]. As illustrated in Figure 1, a soft-story mechanism entails a concentrated drift and failure in a single level of the frame, while the rest of the stories are generally unaffected.

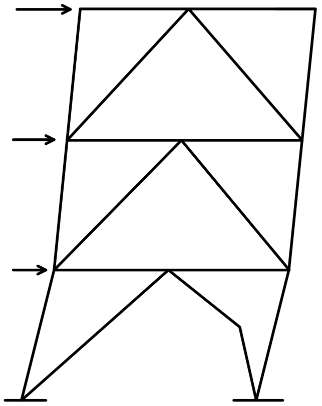


Fig. 1. soft-story failure in a deficient CBF.

CBF inter-story strength irregularities, either inherent in the design or from nonuniform hysteretic deterioration of brace elements, cause disparities in inter-story seismic shear demands and capabilities. Inter-story shear demands on LFRS columns can result in a plastic panel mechanism, which precludes lateral loads redistribution and plastic deformation along with the building's height. Multi-story structures seismic design necessitates capacity design concepts that provide distributed damages (plastic member deformations) across the structure height while eliminating soft-story mechanisms that might collapse [6–8]. Numerous designers have looked for novel seismic-resistant structural technologies to provide stiffness and ductility while preventing damage concentration in the past several years. Previous studies have recommended several rehabilitation or engineering strategies to reduce inter-story drift concentration [9–11].

Current structure design must include seismic resilience. Building resilience is a non-dimensional variable that assesses a structure's ability to operate following an earthquake. Resilience, for instance, is 100% for a non-damaged structure and 0% for a total loss structure [12]. Many investigations have been undertaken to see if the damage concentration in CBFs may be minimized. 1) The employment of dual structural systems for a mix of moment resisting frames (MRFs) and CBFs as a backup system, in which the frame action substitutes for the loss of story shear capacity due to buckling of the brace, is one approach [13–17]; 2) the use of slender braces with a high tension-to-compression capacity causes force to be redistributed from the compression brace to the tension brace [18]; 3) the usage of BRBs with a high deformation hardening factor, that cause yielding in neighboring stories due to substantial plastic strains [19–25]; 4) the employment of a continuous column with sufficient flexural strength and stiffness to avoid soft-story mechanism in inelastic demand, which shifts the load capacity loss to adjacent stories in the structure due to localized brace buckling [9,26,27]. 5) Using a tied column in a zipper-braced frame to spread inelastic demand over the building's height [28–35]; 6) Using a robust back structure with an elastic truss configuration to reduce soft-story behavior [36–38]. Following the 1994 Northridge earthquake, there has been a surge of interest in a seismic design technique that incorporates fuse-like dampening components for energy absorption while the principal structural system is meant to be damage-free [39–41]. Friction dampers [42–44], buckling-restrained braces [45,46], metallic yield dampers [47,48], SMA dampers [22,49,50] and other forms of passive or semiactive dampers are samples of these energy absorption technologies. Beside classic approaches, there are also machine learning based methods in the recent engineering studies which results in accurate and robust outcomes [51–54].

The primary goal of this work is to study the seismic behavior and flaws of steel CBFs in light of the foregoing explanations. This state-of-the-art review gives an overview of the various more important seismic improvement strategies, devices, and technologies presented and studied in the literature.

2. Seismic Improvement and Rehabilitation Strategies of CBFs in Literature

This section discusses the most popular and functional strategies for seismic improvement and rehabilitation of CBFs. The historical development will be investigated firstly. Following that, the results of various numerical and experimental research endeavors will be reported.

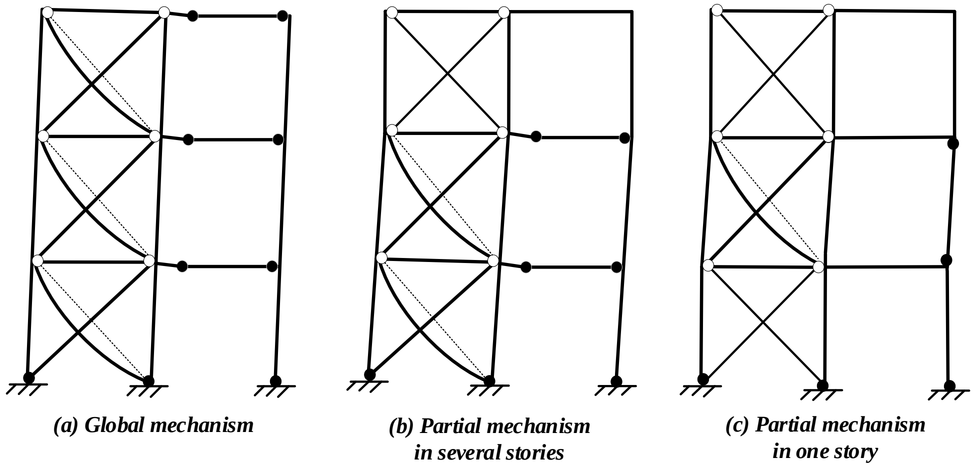
2.1. Dual Structural Systems

Various notable remedies have been discovered to alleviate the soft-storey mechanism. The dual-system idea, for example, is capable of providing steady hysteresis behavior, which is suggestive of stiff braced frames, while the moment frameworks as a backup system to ensure appropriate flexural behavior [55–57]. Designers and engineers commonly use steel dual concentrically braced frames (SDCBFs) in seismically active areas because they are practical and cost-efficient. A basic LFRS with significant lateral stiffness (e.g., SCBFs) is combined with a flexible but still ductile backup LFRS (e.g., special moment frames) to develop a steel dual structural system. This aims to achieve the strict drift standards stated in contemporary building regulations (e.g., ASCE 7 [58]) without significantly affecting the entire buildings' ductility and redundancy, whilst improving the capacity to sustain gravity loads during significant seismic events. SDCBFs are frequently used to address permanent drift demands and the possibility for drift concentrating in a single story due to brace buckling in typical CBFs [15]. Also, the structural redundancy necessity to withstand seismic events and secure load routes is provided by dual structural systems [59]. ASCE/SEI 7-16 also provides the design requirements for dual configurations. The dual system's MRFs have been designed to act as secondary frames to the bracing systems, providing strength and rigidity to keep the structure from collapsing in the case of severe and uncommon seismic activity. "For a dual configuration, the moment frames should be strong enough to resist at least 25 percent of the total of the seismic design loads," states section 12.2.5.1 of the ASCE/SEI 7-16 [60] standard.

Numerous researchers have investigated the seismic performance of steel dual braced systems during the last decades, focusing on various characteristics of these systems [14,16,66–69,55,57,59,61–65]. Khatib et al. [66] examined the factors that may influence inelastic force redistribution in chevron type CBF numerically and proposed optimum proportioning procedures to improve the performance. It was demonstrated that the additional interaction stresses caused by deformation compatibility in a dual arrangement might diminish total strength. Jain et al. [68] investigated the seismic behavior of CBFs either in the presence or absence of a backing strategy to highlight the importance of the backup part of the structure in the inelastic behavior. A novel design method for CBF-MRF dual systems that follow global failure mode was described in Giugliano et al. [69] study. For double chevron CBFs, Bosco et al. [55] assessed the design principles and behavioral parameters recommended by EC8 [70]. Their evaluations revealed that the capacity design technique described in EC8 successfully achieved an acceptable seismic behavior. The theory of plastic mechanism control (TPMC) was applied to CBF-MRF dual systems in Longo et al. [57], and a comparison with EC8 design criteria was made. The use of the suggested design technique was demonstrated with the help of a case study with a 3-bay 8-story dual configuration. The yielding pattern revealed that all tensile diagonals have yielded, all compression diagonals have buckled, and plastic hinges are present at all beam ends and at the base of first-story columns. As seen in Fig 2, collapse processes of dual CBFs against horizontal forces fall into three categories. Global mechanism is shown in Figure 2(a) which is happen in all stories and partial mechanisms in a dual frame is presented in Figure 2(b, c) that happens in one or several stories. As a consequence, according to

Longo et al. [56] the analysis findings demonstrated the correctness of the design approach, proving that it is capable of preventing the formation of undesirable partial mechanisms while ensuring the development of a global mode collapse mechanism.

Costanzo et al. [16] analyzed the effect of adding moment resisting beam-column joints (MRJs) into braced bays of chevron type CBFs. To conduct these analyses, a collection of low, medium and high-rise 2D frames was taken from a reference residential structure and numerically evaluated (using pinned or MRJs). The findings revealed that completely restrained joints could provide an extra reserve of strength, stiffness, and ductility, which can be useful. Bradley et al. [13] suggested design requirements for an SDCBF system in their research. Their suggested SDCBF design method focused on examining the strength and integrity of the post-elastic, deteriorated system. Their work showed that the proposed SDCBF system outperformed the low-ductility CBF systems and ordinary CBF systems in terms of collapse behavior without the need for expensive ductility details or significant revisions to existing seismic design measures.


(a) Global mechanism

(b) Partial mechanism in several stories

(c) Partial mechanism in one story

Fig. 2. Collapse mechanism typologies of a dual system [57].

In addition to all of the benefits of the dual braced system, it has been discovered that when one of the braces fails, the braced frame's beam is more prone to developing a plastic hinge at the place of the connected braces. As a result, a more conservative capacity design method for braced frame beams might be used and examined, considering various brace failure scenarios [59].

2.2. Continuous Seismic and Gravity Columns

Supporting frames are believed to provide the ability to reduce the soft-story mechanism by increasing the capacity to convey inelastic demand across the building height. Supporting systems are necessitated in Japan, and rigid beam-column joints are being used. In the United States, typically low-rise structure support systems are built using pinned beam-column joints, and gravity columns generally continue throughout the height. Whenever adjacent levels have unequal drifts, bending moments might occur in these columns. Due to the added flexural stiffness and resistance, continuous gravity columns are advantageous in minimizing drift accumulation and mitigating the story-collapse process [26].

MacRae and Kimura [27] presented empirical formulae to depict the influence of gravity columns and investigated the relationship between the stiffnesses of the column and drift concentration. The braces were considered comparable yield properties in tension and compression and a linear-elastic perfectly-plastic hysteresis behavior in the formulations. Their investigation reflected the buckling properties of gravity columns in low-rise structures and attempted to produce better-quantified estimations of the strength demands of gravity columns. The influence of gravity columns for CBFs on the control of drift concentration in severe seismic occurrences was discussed by Ji et al. [26]. The stiffness/strength demands of gravity columns were evaluated, utilizing a simplified theory-based framework and nonlinear dynamic analysis. They proved that increasing lateral stiffness and strength to gravity columns could help mitigate drift concentration. Fixed-base gravity columns were much more successful than pinned-base gravity columns in lowering drift concentration in the first storey of their three story CBF model.

2.3. Zipper Braced Frames (ZBFs)

To counteract the soft-story mechanism, Khatib et al. [66] stated that "a structural arrangement provides trilinear hysteresis curves without needing stiff beams and thin braces, and without creating a significant rise in axial column loads" is required. They then recommended adding a new vertical brace, dubbed the zipper, to connect the brace-beam joint locations between consecutive levels. In this regard, the zipper components work in tension or compression to activate the "zipper mechanism," which causes the braces on neighboring levels to buckle concurrently or sequentially. As a result, in the "Zipper" arrangement, the vertical braces distribute the imbalance force created by buckling braces in neighboring levels, forcing the braces on these levels to buckle [32]. This presented technique can develop steady hysteresis behavior while maintaining a more uniform damage distribution along with the height of the building. Moreover, it does not necessitate particularly strong beams and provides a reasonable amount of storey drift and energy absorption during seismic events. ZBF expected behavior is shown in Figure 3.

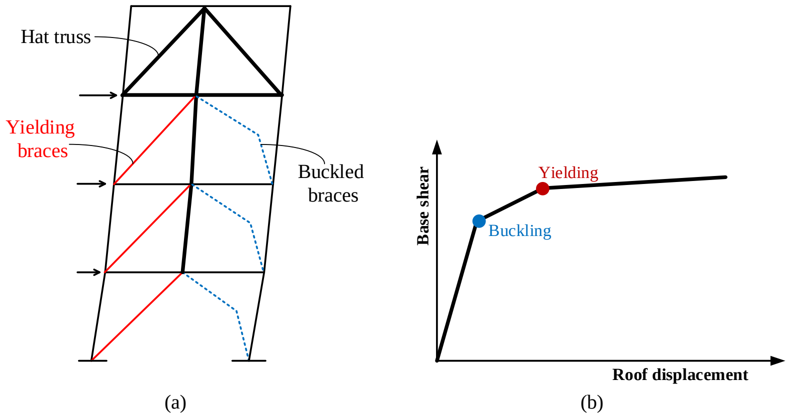


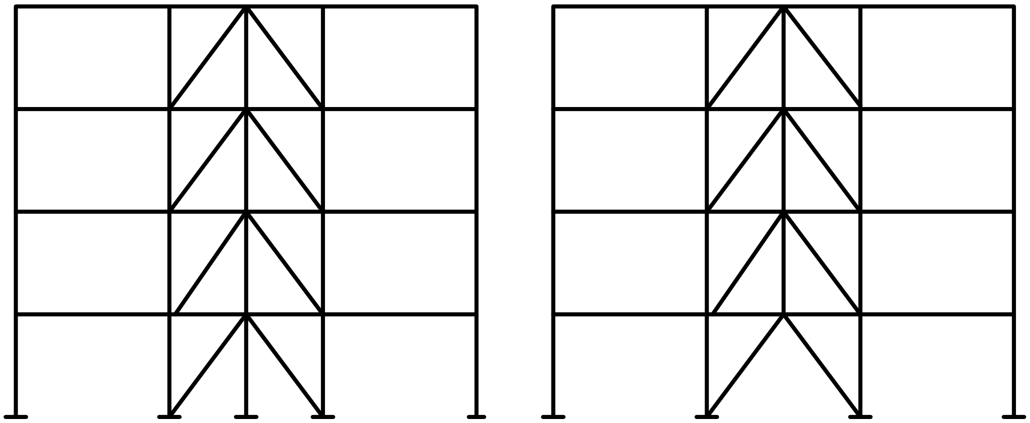
Fig. 3. ZBF: (a) Expected frame behavior, (b) Base shear-Roof displacement response [28].

Sabelli [71] evaluated the uniform distribution of inter-story drifts in ZBFs. Yang et al. [28] suggested a design technique for ZBFs to obtain ductility. They simulated three zipper-braced models spanning from low-rise to high-rise structures and assessed them using either pushover and nonlinear dynamic analyses. In Nouri et al. [31] paper, zipper columns are employed in 3-, 6-, 9-, and 12-story Inverted-V-braced frames for structural rehabilitation. According to the findings of their study, the zipper system was successful in 3-, 6-, and 9-story frames, and it increased the lateral resisting of the building to a life-safety level. However, in the high-rise 12 story frame, it did not function well. To address this issue, the braced bay was divided into smaller "units" along with the height of the frame, and each of them was a zipper-braced bay with several storeys, so the lateral resistance of 12 stories Inverted-V-braced frames was enhanced to the safety life level utilizing this technology.

Chevron braced frames are also vulnerable to storey mechanism development and poor energy absorption capability because of limitations in dispersing internal brace forces after braces buckle. So, zipper columns were employed in Chen et al. [32] thesis to surpass chevron braced frames restrictions. Zippers were designed in his study to stay elastic during the seismic motions while conveying the imbalance brace forces caused by buckling. The author improved Tremblay and Tirca's [72] technique for the design of the zipper. Following their [72] research path, several force redistributing patterns were investigated by Chen [32] to take into account the highest compressive and tensile stresses in zippers. He then tested the suggested design process under a variety of conditions to clarify the behavior of zipper braced frames.

Wijesundara et al. [34] launched a research program to analyze the seismic behavior of suspended zipper concentric braced frames developed based on Eurocode 8 and compare their performance to that of typical CBFs. It's worth noting that their research presents a revolutionary design technique for selecting braces, zippers, beams, and columns sections in this frame type. Two CBFs from suspended zipper and stud-to-ground (STG) configurations were developed and analyzed for seismic forces. To better understand these configurations, STG and suspended zipper samples are presented in Figure 4. Based on their [34] findings, it could be concluded that the performance of suspended zipper frames outperforms that of normal CBFs in medium-rise structures, although not in low-rise ones. Regarding column axial load demand in high-rise structures, Ozcelik et al. (2016) demonstrated that CBFs behave better than modified ZBFs.

Zipper columns were also used in Irani et al. [33] research to upgrade the seismic behavior of rocking CBFs as described in detail in this paper. Using zippers in combination with the rocking system, the frame's seismic performance in terms of uniform story drift distribution improved, resulting in decreased structural failure. Zippers, in other terms, reduce failure concentration by spreading unbalanced stress across the height of the frame.



(a) Strut-To-Ground (STG) braced configuration

(b) Zipper configuration

Fig. 4. STG and suspended zipper configurations.

2.4. Buckling Restrained Braces

BRB is a structural passive damper with lots of energy absorption capacity and consistent hysteretic response. The following are the main components of a conventional BRB: a steel core element that offers axial stiffness, load-carrying potential, and energy absorption; a confining element that restricts the core part from significant local or global buckling deflection under compression; and unbonding content between the above-mentioned two segments. The confining component is usually a concrete-filled steel tube or a stack of metal sheets, while the steel core element is constructed of ductile steel. BRBs have lately been widely chosen as high-performance seismic-resisting devices due to their excellent energy absorption capability [73,74]. Following the seismic event, the BRB frame (BRBF) was widely employed for seismic purposes in Japan, and it is now is popular in the US following the 1994 Northridge earthquake. Because of their outstanding ductile behavior, BRBFs seem to be ideal for the seismic design of structures and rehabilitation [21,75].

BRBs have been shown in studies to be an excellent instrument for controlling damage and dissipating seismic energy [21,74,76,77] and BRBs and BRBFs have acceptable seismic behavior, giving appropriate life safety for design level seismic events [75,78–81]. The seismic behavior of diagrids with buckling restrained braces (BRBs) was studied by [24]. The impacts of BRBs on diagrid seismological performance characteristics such as response modification factor, overstrength factor, ductility ratio, and median collapse capacity, S_{CT}, were examined in this respect. To this goal, six 3D diagrid buildings with varying heights and diagonal angles were developed using the OpenSees software [82] and outfitted with BRBs in a new configuration An examination of the cumulative probability graphs of the 8 and 12 story models of Sadeghi et al. [24] with diagonal angles of 45° demonstrates that upgrading diagrid models using BRBs typically pushes the cumulative distribution functions graphs of the original (without BRB) models to the right. This indicates that the collapse capacity of models upgraded with BRBs became higher than that of basic models.

The findings of a numerical study of the seismic behavior of BRBF systems were given by Naghavi et al. [23]. Conventional CBF designs were compared with the results of BRBF systems. Four CBF (X, V, inverted V, and two-story X) and four BRBF (diagonal, V, inverted V, and two-story X) designs were investigated. To capture BRB components, frames were simulated in ABAQUS. Compared to similar CBF simulations, BRBF systems showed significant increases in energy absorption and ductility. The CBF results of Naghavi et al. [23] indicate very narrow hysteresis loops, reflecting lesser power absorption and ductility. The BRBF results, however, indicate comparably broader hysteresis loops, implying significantly increased energy absorption and ductility in the frames.

The steel frame with DYBs was proposed as a feasible replacement to the traditional steel concentric braced frame in Barbagallo et al. [25] research. In reality, the frame with DYBs corrects the common flaws of the concentrically braced frame, namely the impact of poor structural redundancy and the dissipative member's low energy absorption capability. Figure 5 depicts the schematics of the two main components of the DYB investigated by Pan and colleagues [83], as well as their assemblage. The dissipative core (Figure 5(a)) is composed of a steel plate with two reduced cross-section elements and three complete cross-section elements (Figure 5(b)). Barbagallo et al. [25] employed DYBs in an 8-story inverted V CBF in all floors. The DYB's fat-shaped and robust hysteresis loops assure the structural system's substantial and efficient energy dissipation capability at the member level.

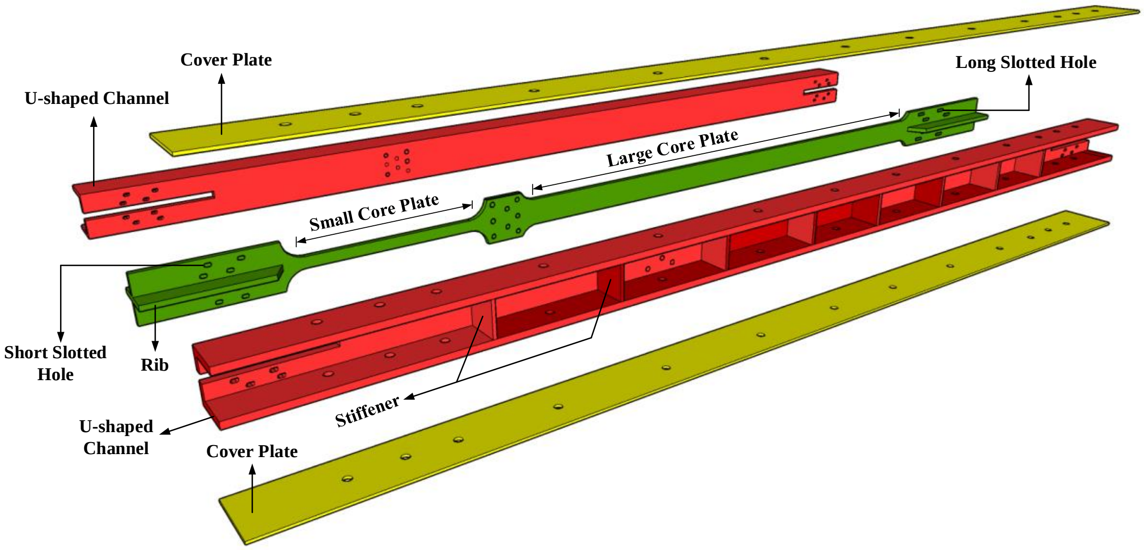


Fig. 5. The geometry of the double-stage yield BRB used in Barbagallo et al. [25] .

Buckling Restrained Environmental Braces (BRB) in high-rise structures were investigated and compared to ordinary CBFs using nonlinear time-history dynamics analysis by Razzaghi et al. [77]. The structures evaluated were 20, 40, and 60 stories tall, with perimeter bracing. The results reveal that employing BRB instead of typical brace frames in high-rise steel structures improves the hysteresis behavior of the braces, reduces lateral displacements, and enhances the base shear capacity. Also, several studies [20,21] were conducted that described and asses a new Composite Buckling Restrained Fuse (CBRF) that can be employed as a bracing part in CBFs as illustrated in Figure 6. CBRFs are a shortened version of BRB with varying tension and compression characteristics. Using tensile-only components in this fuse with a novel arrangement enhances energy-absorbing effectiveness and overcomes tensile strength limits of bracing elements that comprise typical BRB fuses.

As studies show, while BRBFs have the benefits listed above over conventional steel buildings, they are nonetheless prone to considerable post-seismic residual drift in the event of a significant seismic event, owing to CBRBs' poor secondary stiffness [74].

2.5. Stiff Rocking Core (SRC) Techniques

The strategy of using a rocking core employs one or more stiff elastic "spines" that is appended in conjunction with the existing seismic LFRS to support redistributing of lateral forces among all stories, preventing the soft-story occurrence and early collapse of buildings. The SRC has a base connection that restricts it from getting involved in seismic performance throughout uniform building drift; nevertheless, the SRC's high inter-story stiffness offers appropriate remedial resistive forces at the initiation of soft-story forming, potentially blocking much more accumulation of failure on that story [10,84–88]. The SRC could also be connected to the current frame using steel yielding energy-absorbing devices, which can have a significant role in SRC rehabilitation configuration to further strengthen existing sub-standard structures to provide adequate seismic behavior. The SRC rehabilitation technology is shown in Figure 7. In Figure 7(a), a CBF mechanism is shown, which is identified as a soft-story mechanism. In figure 7(b, c) SRC technology is presented using an elastic truss or a stiff wall, respectively. According to Wiebe et al. [89], greater mode influences can be significantly decreased by allowing rocking to occur at several sites across the height of a rocking system.

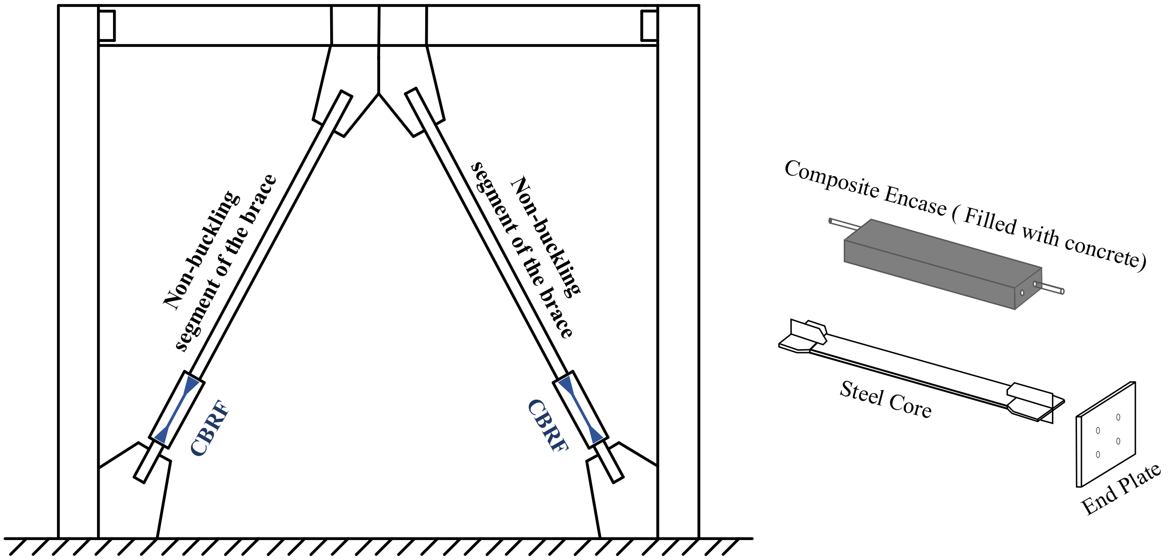


Fig. 6. CBRF assemblage and placement in a chevron CBF [20].

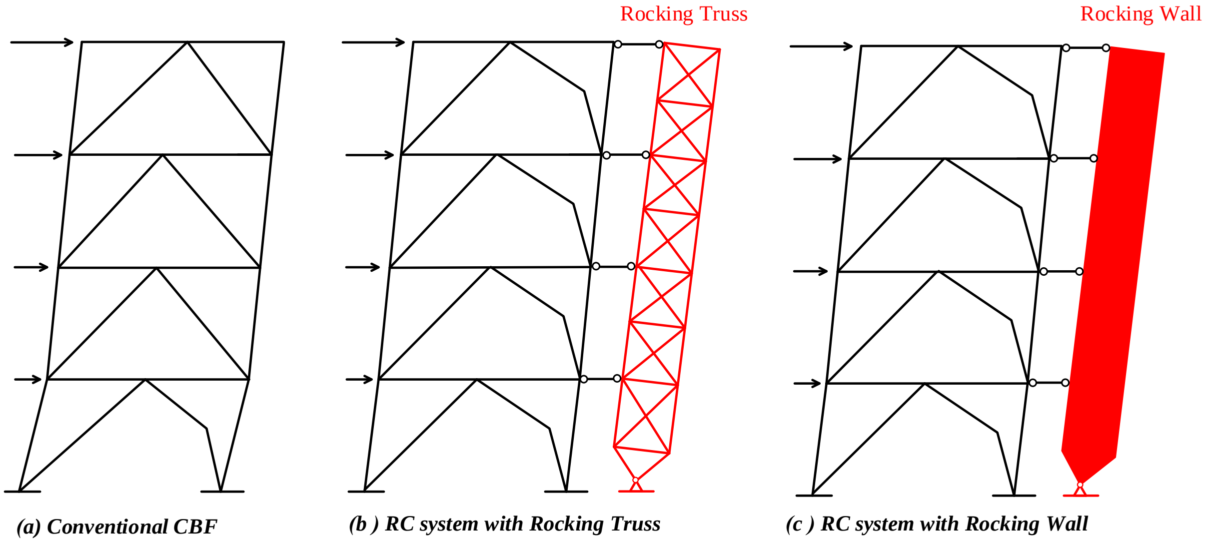


Fig. 7. Illustration of the RC seismic rehabilitation technology [90].

Compared to conventional rehabilitation techniques, the SRC approach has significant benefits:

- During development, there will be minimal disruption to routine business activities;
- Extra stresses on the existing structure were kept under control;
- Following an earthquake, this approach makes it possible to employ self- or re-centering using post-tensioning (PT) or hydraulic jacks to minimize residual building drift [91].

Whenever exposed to seismic events, previous studies have demonstrated that this sort of lateral load resisting rehabilitation technique in low- to mid-rise buildings could limit soft-story mechanisms [5,90,92–95]. Qu et al. [90] also recommended SRCs as a novel seismic rehabilitation technique for low-rise and mid-rise CBFs subject to inter-story drift concentration and soft-story collapses. The SRC stiffness varied in the nonlinear static pushover analysis, and the Monte-Carlo simulation approach was used to randomly produce lateral force distributions. When both benchmark structures meet the inter-story drift limitations related (collapse prevention, lift safety, and immediate occupancy as defined by FEMA 356), the SRC was demonstrated to minimize inter-story drift concentration successfully. They [96] also assessed the efficacy of the SRC rehabilitation method in SCBFs in near-fault zones. Slovenec et al. [97] SRC rehabilitation study included an experimental testing program on two 3-story, 1/3-scale prototypes representing both modern and premodern existing CBF structures. The premodern 3-story frame (3NCBF) was coupled to the SRC at all floors by yielding flexural links, but the modern 6-story frame (6SCBF; upper four stories were simulated analytically) was linked to the SRC at just the 1st and 2nd floors by nonyielding pin-ended link elements as illustrated in Figure 8. According to their findings, SRC introduced beneficial in controlling large concentrations of drift across the height of its deployment. Yet, even in the absence of yield components, total construction drift might surpass the intended behaviour target for certain current frames.

In comparison with the existing rehabilitative techniques, Pollino et al. [3] described the SRC methodology as a comparatively nonintrusive strategy that may fulfil a maximum stated storey drift for a certain risk level. The objective of their report was to provide a primary mechanical and dynamic performance of SRC-rehabilitated structures that were required to support the suggested design technique and analytically validate its effectiveness. Also, the article by Hu et al. [98] investigated how SRC technology could be used in beam-through CBFs with tension-only bracing (BTFs) to improve their seismic behavior.

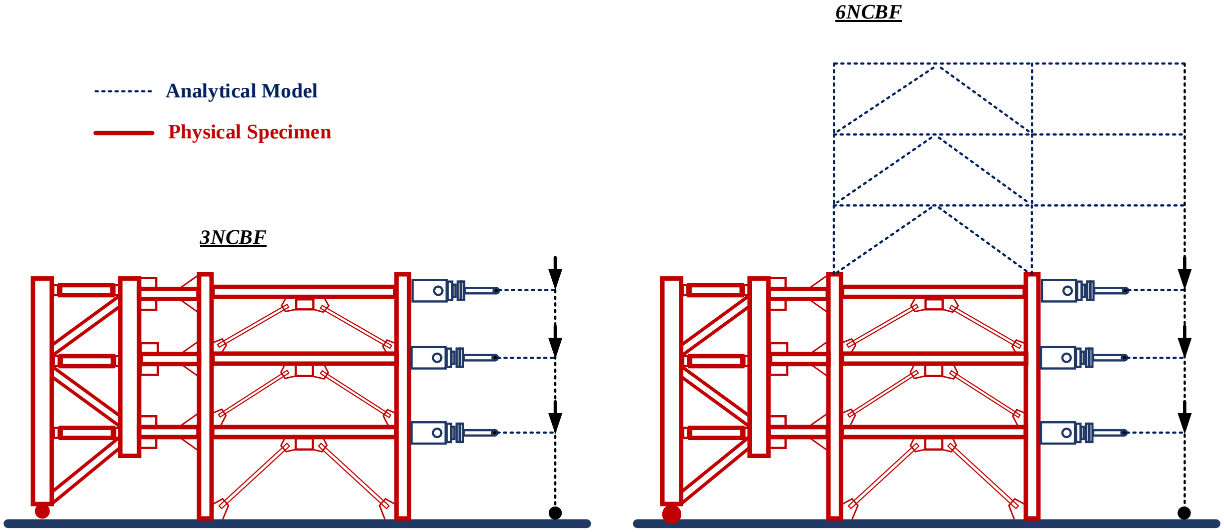


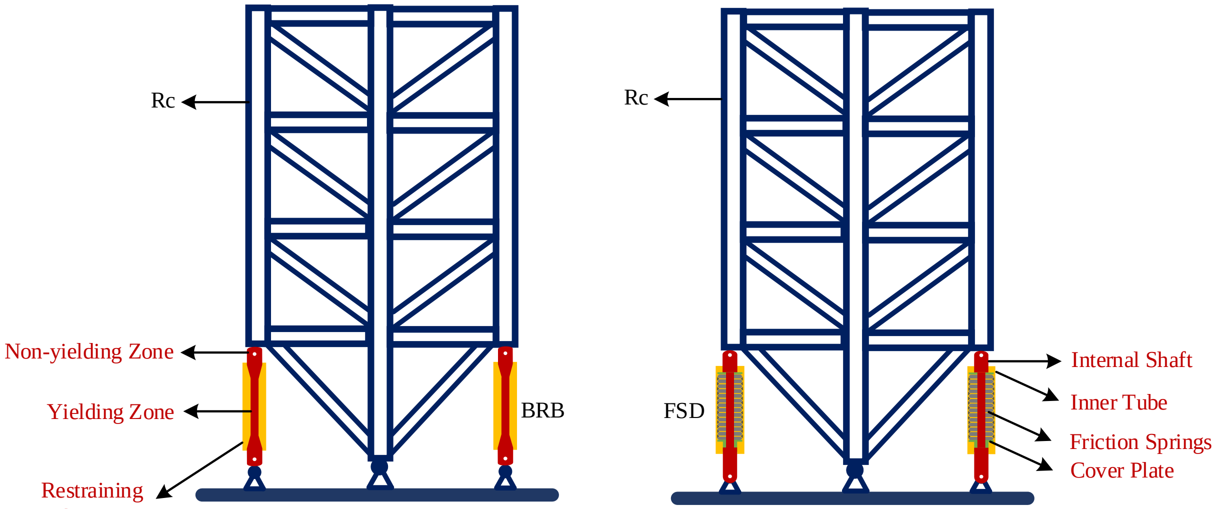
Fig. 8. subassemblies for each hybrid test of Slovenec et al. study [97].

2.5. Self-Centering Systems and Materials

Currently, there has been a significant interest in seismic-resistant mechanisms with self-centring hysteretic behavior. Such self-centering devices with energy absorption capacity often include a flag-shaped hysteresis loop. Damage can be controlled, and residual structural drift can be reduced (or perhaps eliminated) with self-centering devices [99]. This is significant because residual structural drift is highlighted as a vital complementary criterion in the assessment process of structural (and non-structural) loss in the performance-based seismic design and assessment method. Self-centring seismically-resilient buildings, including energy dissipation and self-centring capacities during seismic events, are viable alternatives for structural design in seismically vulnerable areas. There are different kinds of self-centering strategies: (1) using PT steel strands [94,100–102]; (2) Self-centring hysteretic behavior, which is exhibited by specific metals such as superelastic shape memory alloys (SMA). However, without pre-tensioning, superelastic SMA would most likely stay linear, resulting in little energy absorption during seismic events. (3) special systems or dampers.

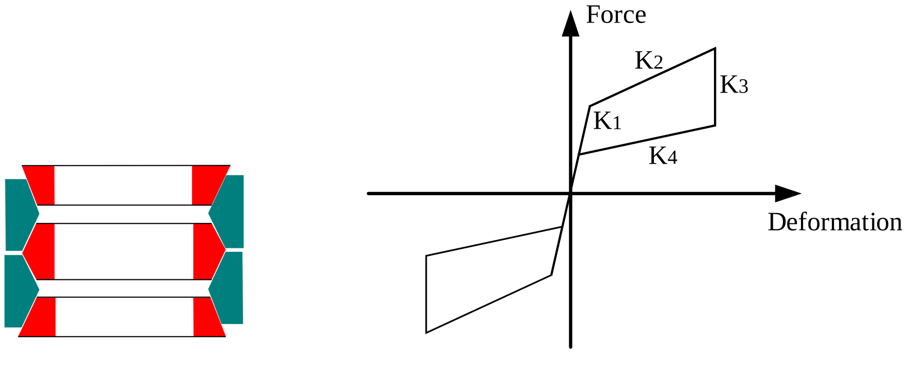
Eatherton et al. [103] were one of the investigating groups which presented and examined the principles of developing self-centering steel braced frames for controlled rocking. They [104] also reported seven semi-static cycle tests of 1/2-scale SRC frames that were performed to investigate the reaction of the structure and its elements, verify the modeling, identify the limit states of seismological behavior, and evaluate details of construction. Hu et al. [105–108] suggested an Energy-absorbing Rocking Core (ERC) that comprised of a pin-supported SRC with either two friction spring dampers (FSDs) or two buckling-restrained braces (BRBs) to mitigate soft-story collapse and increase the energy absorption capacity of BTF. These two types of ERC are presented in Figure 9.

Furthermore, because of FSDs' greater self-centering capability, they can help eliminate residual structural system drift. The ERC greatly improved the seismic behavior of BTFs and kept the maximum residual inter-story drift to less than 0.5 percent, according to the observations. Another study [109] investigated the seismological design and behavior of low-rise steel structures using self-centering energy-absorbing dual rocking core systems (SEDRC) in far-field and near-fault ground motions. Two SRCs and shear friction spring dampers were suggested as part of the SEDRC system (SFSDs).



(a) ERC-BRB

(b) ERC-FSD



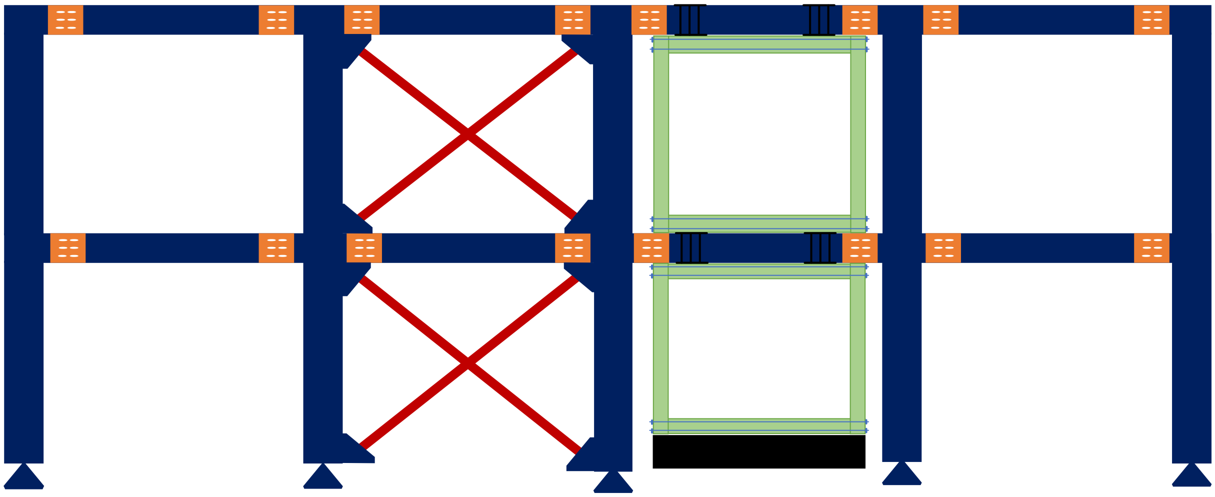
(c) Ring Spring Group

(d) Hysteretic Behavior of FSD

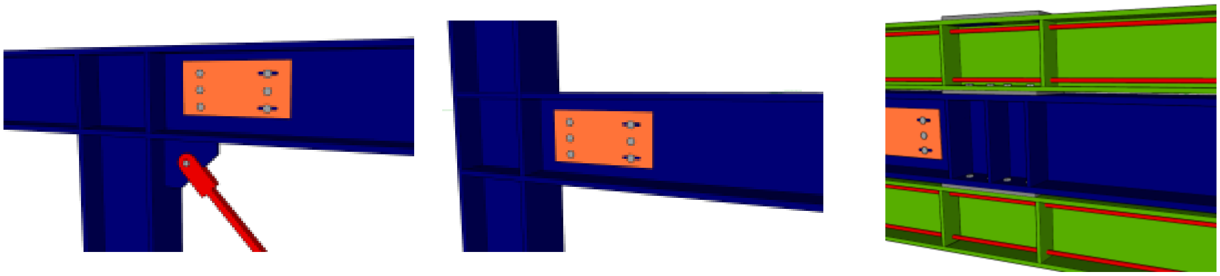
Fig. 9. The considered two types of ERC systems in Hu et al. study [105].

Li et al. [110] concentrated on a novel form of steel LFRS that was developed to address the constraints of traditional self-centering systems with PT beam-column joints.

Their method included a multi-bay perimeter frame with self-centering panels and steel strip bracing, as seen in Figure 10. The self-centering panel was a single-story, single-bay frame with typical PT beam-column joints. Steel strip bracing was attached to the proposed system beyond the self-centering panel to disperse energy and offer extra lateral strength and rigidity.



(a) Elevation of Considered System



(b) Brace-Frame Connection

(c) Beam-Column Connection in Boundary Frame

(d) Panel Beam-Boundary Beam Connection

Fig. 10. Illustration of the Li et al. [110] considered system.

Controlled rocking steel braced frames (CRSBF) was a self-centring LFRS suggested by Steele and Wiebe [111,112] to minimize structural damages during seismic events higher than the design level. The nonlinearity function was uplift of the frame (not pivoting), using PT cables and structure self-weight providing the restoring force to self-centre the structure after a seismic event, and energy absorption was used to decrease deformation demands; these mechanisms result in a flag-shaped hysteresis as can be seen in Figure 11. Steele and Wiebe [112] also evaluated the risk of collapse for three, 6, and 12-story structures using five different CRSBF designs.

Due to buckling of braces in compression, designers can rarely change the stiffness and ductility as required when using typical buckling braces. Mohamed Omar [98] research studied using SMA bracing (SMAB) in steel frames. The usefulness of this technique in the rehabilitation of a mid-rise eight-story steel frame was investigated using SeismoStruct software and time-history nonlinear analysis. Furthermore, Qiu et al. [113] showed that a CBF with SMABs may provide a more uniform temporary inter-story drift profile in the structure than a building with typical BRBs. Their frame is presented in Figure 12. As the time history response shows, using SMA material instead of BRB enabled the system to eliminate frame's permanent inter-story drift.

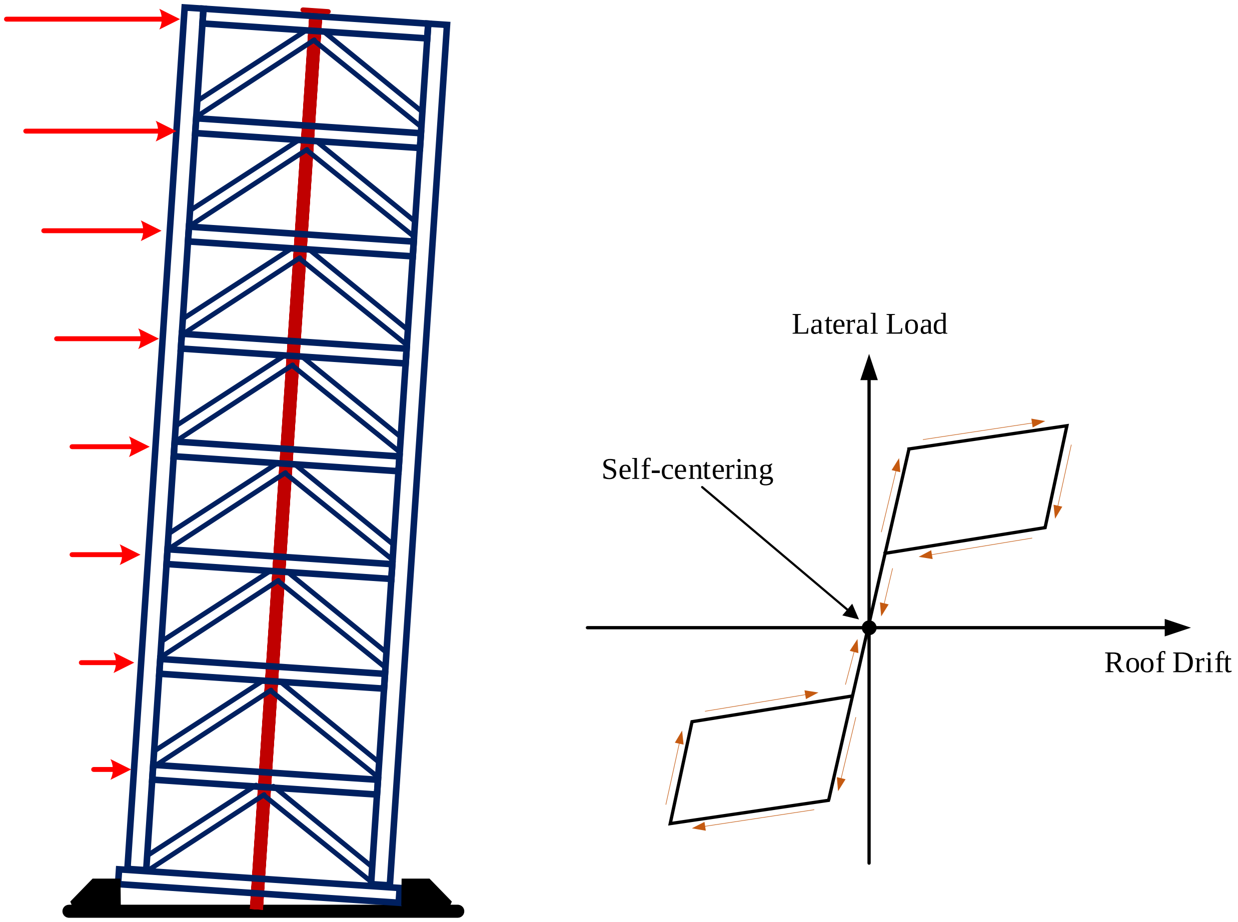


Fig. 11. self-centring flag-shaped hysteresis response of controlled rocking steel braced frames during design-level earthquakes [112].

BRBs whose their ductility was enhanced using SMA were also evaluated by Nazarimofrad and Shokrgozar [114]. The NTH and IDA analysis of 4 and 8 stories under several records indicated that using BRB constructed of hybrid steel and SMA increased the building's ductility while diminishing residual displacements. Ghowsi and Shahoo [115] SMA based BRB components and assembly are presented in Figure 13. They investigated the behaviour of 4 and 8 storeys frames under varied ground motion recordings using NTH, and IDA approaches.

SMA braced frames (SMABFs), which are not formalized in existing seismic requirements, must have their deformation demand evaluated with certainty during the seismic designing or retrofitting. Qiu et al. [101] investigate the inelastic displacement ratio to solve this problem. In other words, they presented a displacement-based seismic design method for frames using SMA braces.

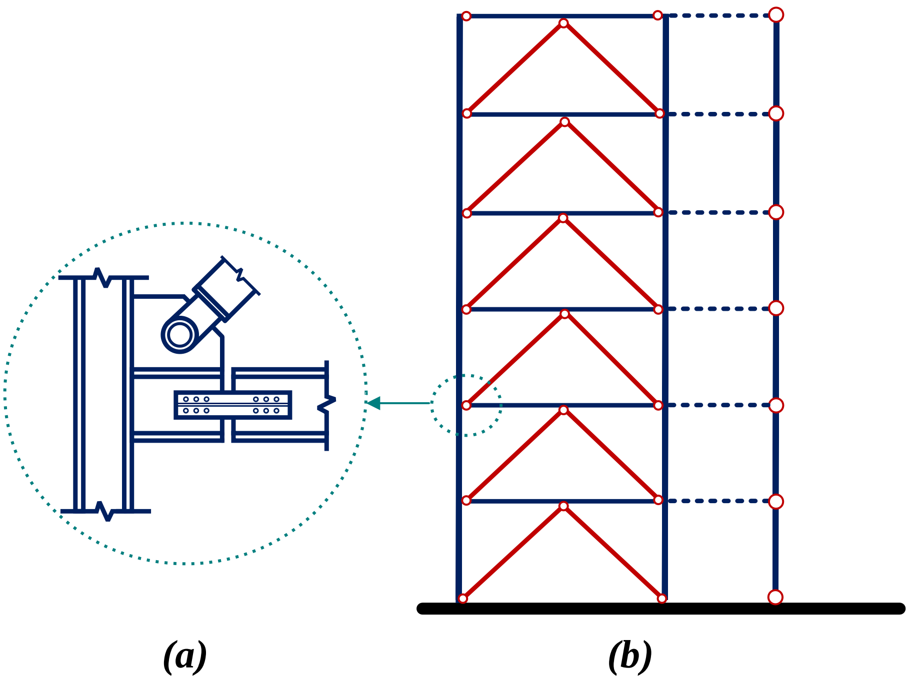


Fig 12. The 6-story demonstration building: (a) brace-frame and beam-column joints; (b) computer model elevation [113].

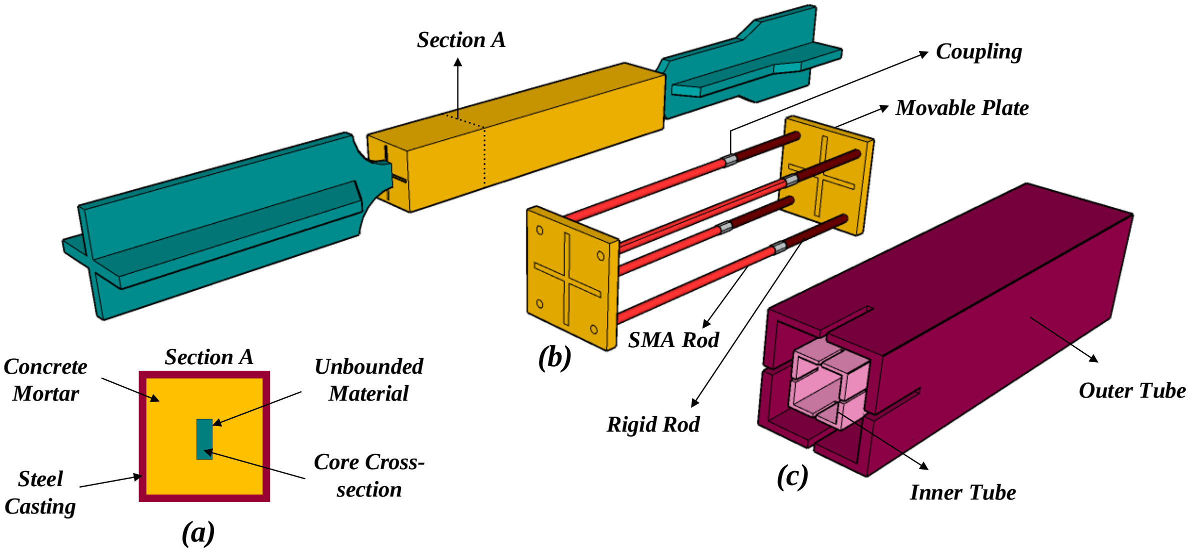


Fig. 13. Components of SC-BRB: (a) BRB, (b) SMA bars and movable plates, (c) Telescopic tube [115].

3. Concluding Remarks

The latest developments in predicting the seismic behavior of concentrically braced frames were reviewed. Recent studies were presented, highlighting the importance of seismic improvement of new structures as well as rehabilitation of old ones. A historical context was presented to demonstrate the progress of CBF seismic performance, with an emphasis on the advancement of methodologies and instruments. The following significant findings may be derived from the comprehensive literature review done in this study:

- Using dual systems instead of braced bays somewhat enhances the ductility and energy dissipation capacity of concentrically braced frames, according to the behaviour factors derived from dynamic analysis. This method is also shown to have an excellent capacity to form plastic excursions, involving all floor levels in a global collapse mechanism.
- When seismic events hit multi-story CBFs with pinned beam-column joints, the drift tends to concentrate on the first floor. Gravity columns can aid in minimizing drift concentration by providing lateral stiffness and strength. Fixed-base gravity columns outperform pinned-base ones in terms of controlling drift concentration in the first storey.
- Based on the inter-story drift distribution profiles over the building's height, the seismic behavior of suspended zipper frames is superior to that of typical CBFs for medium-rise structures. Low-rise typical CBFs, on the other hand, perform better, resulting in a more uniform inter-storey drift distribution over the height of the building in comparison to suspended zipper frames.
- Many of the possible difficulties identified with special CBFs can be avoided by using BRBs. In the investigated high-rise structures with tubular systems, either CBF or BRB braces could not adequately fulfil the lateral displacement constraint, necessitating the use of an extra system, such as a shear wall or a truss belt system.
- The proposed SRC-rehabilitation design method prevents soft-story mechanisms and improves seismic drift behaviour. Even yet, eliminating soft-story advancement may not be adequate to meet seismic performance targets, particularly in older CBFs. Yielding connections added into the SRC-rehabilitation technology improve seismic behavior even more.
- Even after extremely large earthquakes, correctly designed SMA braced frames show low structural failure and permanent deformation, demonstrating the better seismic behavior of this developing class of self-centring seismic-resisting structural systems. The application of SMABs is believed to be in an indoor circumstance with a generally constant room temperature. Future research should focus on discovering SMA materials that really are acceptable for outdoor applications with high temperature variation, as well as establishing a design strategy to account for the temperature effect.

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