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# Study of Different Bracing Systems in RC Structure for Seismic Resilience - A Comparative Performance based Review

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***Abstract*— Reinforced concrete (RC) structures that have been designed without appropriate seismic detailing are extremely prone to seismic hazards. The obvious reason is that RC structures lack lateral strength quantities along with poor ductility and capacity to dissipate seismic energies. The probable outcome could be significant inter-storey drift followed by brittle failure. Steel Bracing Systems have proven to be an efficient method in seismic retrofitting measures that may be adopted in RC structures in order to improve their seismic performance. The current paper emphasizes the extensive comparative performance-based evaluation of regular as well as advanced types of Bracing Systems in RC Structural Systems, like diagonal, X, V, and inverted V Bracing Systems, along with buckling-restrained Bracing Systems, self-centering Bracing Systems, variable stiffness Bracing Systems, hybrid Bracing Systems along with Bracing Systems having damper components. Special attention is given to nonlinear static and dynamic assessment concepts along with resilience-based assessment measures. This assessment also identifies the major gaps for future R&D activities related to unified comparative approaches, mode shape sensitivity, as well as resilience measures. This establishes a technical basis for possible future earthquake assessment and retrofit of R/C structures.**

***Index Terms*— Modal Characteristics; Performance-Based Design; Reinforced Concrete Structures; Steel Bracing; Seismic Resilience.**

## I. INTRODUCTION

This research aims to establish a comprehensive synthesis of various published scholarly researches that measured and assessed various seismic attributes of retrofitted reinforced concrete frame structures with metal brace elements. This study includes experimental, analytical, and computational investigations on conventional and innovative types of metal brace configurations.

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Damage from earthquake excitations for reinforced concrete (RC) buildings has remained a pressing issue in seismically active areas, especially for buildings designed before the implementation of seismic design standards. Significantly, a vast majority of RC structures existing in seismically active regions are of gravity-load designed moment resisting frames, which are inherently deficient in the aspect of seismic resistance especially in terms of seismic stiffness, seismic ductility, and energy dissipation capacity [1], [2]. Studies of earthquake reconnaissance surveys, as well as analytical works, have identified excessive inter-storey drift, soft-storey mechanisms, and brittle column/shear failure of beam-column joints [3], [4]. By adding axial force-dominated members to the structure, the effect of bracing is found to improve the global stiffness of the structure and affects the seismic force distribution in the structure significantly [5], [6]. Steel bracing systems can be effectively utilized in RC structures varying in heights and seismic loading conditions, and the structural efficiency has been verified by various research studies experimentally and numerically [7], [8]. The conventional braces like diagonal braces, X-bracing, V-bracing, and inverted V-bracing have been found efficient in reducing lateral displacement and inter-story drift while changing the dynamic properties of RC structures [9], [10]. Yet, their seismic responses are significantly dependent on brace layout parameters, stiffness ratios, and compression and tensile cyclic responses [11]. Such drawbacks have promoted the design and conceptualization of improved brace systems like buckling-restricted braces, self-centering braces, variable-stiffness braces, and hybrid braces with dampers with regard to improved hysteretic curves, energy dissipation capabilities, and residual displacement control [12], [13], [14].Although a lot of research has been done in this area, most of the available studies on this topic are limited to isolated bracing configurations or individual response components, so that an overall comparison of different bracing configurations from a unified performance aspect cannot be developed [15], [16]. Additionally, the effect of different bracing configurations on modal values, higher-mode aspects, and resilience performance indicators is not appropriately explored in this area [17], [18].

## II. Seismic Vulnerability of Existing Reinforced Concrete Frame Structures

Specific nonlinear seismic assessments have demonstrated that bare RC moment-resisting frames have longer fundamental periods and limited hysteretic energy dissipation capacity, which tend to increase the displacement demand during strong ground motion [19]. Seismic strengthening thus becomes necessary not only for ensuring life safety but also for post-event functionality. Inter-Storey Drift Ratio (ISDR) For the case of the braced RC frame structure, the Inter-Storey Drift Ratio (ISDR) is defined as the measure of the relative vibration of two adjacent stories to the height of the story [4] and equation (1) is of ISDR.

$$ISDRi= \Delta_i - \Delta_{i-1} / hi \qquad (1)$$

- $\Delta_i$ = lateral displacement at storey *i*
- $\Delta_{i-1}$ = lateral displacement at storey *i–1*
- hi = height of storey *i*

TABLE I: INTER-STOREY DRIFT RATIO (ISDR) LIMITS CORRESPONDING TO PERFORMANCE LEVELS

| Performance Level | Typical ISDR Limit |
|---|---|
| Immediate Occupancy (IO) | ≤ 0.5 % |
| Life Safety (LS) | ≤ 1.5 % |
| Collapse Prevention (CP) | ≤ 2.5 % |

Table 1 shows illustrate that in performance-based seismic assessment of braced RC buildings, ISDR is used to verify compliance with accepted performance limits

## III. Conventional Steel Bracing Systems in Reinforced Concrete Frames

Traditional steel bracing systems are widely used to improve the stiffness and resistance capacity of RC frames against the lateral load by providing an additional load path using the axial force effect in the structure due to the seismic action [13][5]. Research has found the implementation of steel bracing systems can significantly reduce the first period of time and the maximum drift response of RC structures [18][8]. Bracing stiffens the structure sufficiently to resist the softening effect and allow the main structural elements of RC structures to remain in the linear region for a longer time [19].
The figure 1 illustrates the transformation of a bare reinforced concrete frame into a braced system through the introduction of steel X-bracing.

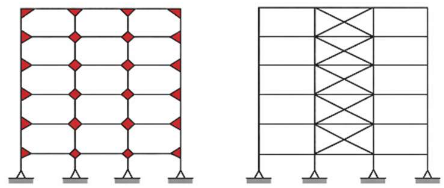


Figure 1. Moment frame and Braced frame

## IV. Comparative Seismic Performance of Shear Wall and Braced RC Systems

Shear walls and steel bracing systems are two different methodologies used to enhance RC buildings against earthquakes. Shear walls exhibit a higher in-plane stiffness and strength, which reduces lateral displacement and storey drift effectively [20], [15]. But during earthquakes, the higher stiffness of shear walls aggravates base shear forces and concentration of forces in walls and foundations [21]. Comparative analyses have demonstrated that braced RC frames have usually longer fundamental periods and smaller force demand during earthquakes than shear wall systems but with greater displacement sensitivity [20], [16].

## V. Seismic Retrofitting Strategies for Existing RC Buildings

RC building seismic retrofitting techniques involve upgrading global performance by enhancing stiffness and strength or local ductility capacity of vulnerable elements of RC structures [22], [23]. The global seismic retrofitting solutions involve supplemental steel bracing systems of RC shear walls and dual systems that reduce seismic deformation and seismic force actions efficiently and effectively [24]. In the case of Eccentrically Braced Frames (EBFs) which have a special joint element designed into them for a stable inelastic response which in turn effectively dissipates seismic energy with minimum impact on the existing RC structure elements [25]. Buckling-Restrained Braces (BRBs) have taken to retrofitting projects due to their which display symmetric yield in tens and compression during cycle loading and also perform well in terms of key markers of seismic performance like residual drift and damage concentration [26][27]. These systems would make it possible to create a well-balanced structure regarding elasticity and ductility. Nonlinear static and dynamic analysis in the evaluation of performance under seismic activity would be a priority [28]. Local approaches of retrofitting via jacketing, diagonal haunches, and upgrading of joints can enhance performance with respect to components; nevertheless, they may not be able to enhance displacement performance satisfactorily [29], [30].Evaluations indicate that response spectrum analysis methods are valid tools for quantifying drift demand, base shear, and modal response in braced RC structures or RC-Steel structures, while concentrically-braced structures verified that configuration and stiffness of bracing systems significantly influence lateral stiffness enhancement/drift reduction of structures in direct relationship to their seismic resilience [31][32][33][34].

The efficacy of supplemental lateral load systems in enhancing seismic performance variables impacted by vertical stiffness abnormalities is supported by other studies employing soft storey/float column RC building designs [35].

Shear walls require careful performance-based evaluation during retrofit design work because, despite their deformability, they have been linked to greater internal load effects, according to comparative studies [36]. Additionally, the importance of seismic and combined seismic and wind load calculations in multi-story structures has been made clear by debates and analyses that focus on precast structural systems and seismic response [37][38][39][40].

## VI. Buckling-Restrained and Self-Centering Bracing Systems

By confining the steel core, buckling-restrained bracing (BRBs) prevent global buckling and allow for symmetric and stable hysteretic behavior under cyclic stress [30], [24]. However, because of yielding-dominated behavior, BRBs may cause residual deformations [24]. Self-centering bracing systems using friction or post-tensioning mechanisms have been designed to overcome this constraint [27], [23]. These devices greatly enhance post-earthquake serviceability by restoring force capability while preserving regulated energy dissipation [9][41][42].

Figure 2 shows the structural configuration of the buckling-restrained brace-an energy-dissipating element for enhancing seismic performance of structures-is shown. In order to prevent its global buckling, it is placed within inner and outer restraint tubes, which give continuous lateral confining while permitting axial deformation [43][24][44]. End plates, cross-plates, and force transmission plates at both ends ensure efficient load transfer between the brace and the surrounding structural frame [45][46]. Another positive approach would be to combine damping systems with a brace and shear wall system. This arrangement enables the brace to function as a structural fuse [47][48].

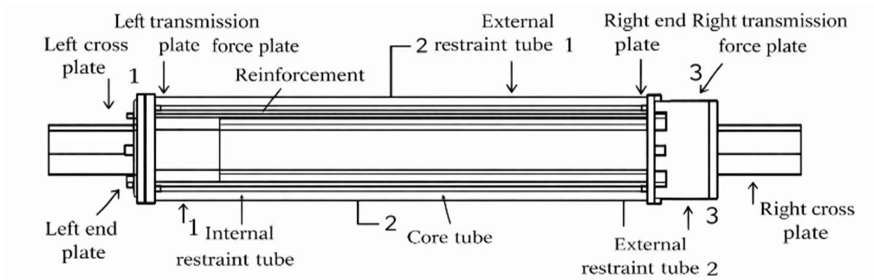


Figure 2. Self-Centering Bracing Systems

## VII. Variable Stiffness and Hybrid Bracing Systems

Flexible performance in mild quakes and better resistance in large scale events is a feature of variable stiffness bracing systems which change their mechanical properties in response to greater degrees of deformation [49]. What we see in these systems is a staged response which has rigid materials play the primary role in control of initial elastic drift, and the ductile bracing system take part in the inelastic deformation process which is related to the dissipation of seismic forces thus0 which in turn limits damage in key RC structures via the redundancy of the system [50][51].The variable stiffness/hybrid braced system's force-displacement hysteresis response exhibits cyclic behavior in response to increasing displacement amplitude values [49].

## VIII. Experimental and Numerical Investigations on Braced RC Frames

The efficiency of bracing systems in shifting seismic load from RC members to axial brace elements has been confirmed by experimental studies employing cyclic and pseudo-dynamic testing [52] [53]. Stable hysteresis, delayed stiffness loss, and better damage distribution are characteristics of advanced bracing systems [12], [54].
When predicting drift, base shear, and modal features, numerical simulations using nonlinear static and dynamic analysis exhibit good agreement with actual data [6], [55]. Time-history analysis aids in understanding residual deformation and cumulative damage, thereby improving applied methodologies in damage assessment [52]. The unique approach in Kotnake et al. [56] corresponds with most contemporary performance-based assessment techniques, in which parametric modelling and comparison are critical to structural decision-making. M Bhorkar and K Dabhekar put forth an in-depth study of the analysis and design of multi storey reinforced concrete buildings which include floating columns in different seismic zones in India. [56]. For the performance-based seismic evaluation of RC frames with various seismic bracing systems, SAP 2000 is used as the primary analysis tool in this study [58]. To ascertain the structural periods, mode shapes, base shear, inter-story drift, and residual displacement, respectively, modal analysis, response spectrum analysis, pushover analysis, and non-linear time history analysis have been employed [59][60]. ETABS, as a building-oriented analysis platform, is utilized in this study for the seismic performance evaluation of several reinforced concrete frames with varying bracing systems [61]. Previous studies have established that ETABS is reliable for performance-based seismic assessment of braced reinforced concrete buildings [62]. These models utilize MIDAS Civil and MIDAS Gen as finite element analysis tools for advanced seismic assessment of R/C, steel, and hybrid braced structures. These models are capable of analyzing R/C and steel structure behavior using frame, shell, and composite types of elements to effectively model interaction and load transfer [63]. Static and dynamic linear and nonlinear, modal, and response spectrum analysis is carried out for assessing seismic demand parameters like period, base shear, and inter-storey drift [64]. Optimization and design capabilities are provided for repeated assessments of structural performance. Relevance of MIDAS software to advanced seismic and performance-based assessments has already been confirmed in previous research works [65]. Tekla Structural Designer is utilized as an integrated analysis tool for reinforced concrete and steel structural systems involving bracing layout schemes [66][67]. Existing research work shows that Tekla Structural Designer is beneficial for code-oriented seismic analysis and comparative analyses of structural schemes of buildings [68].

TABLE II: PERFORMANCE-BASED COMPARISON OF CONVENTIONAL AND ADVANCED BRACING SYSTEMS FOR ENHANCING SEISMIC RESILIENCE OF REINFORCED CONCRETE STRUCTURES

| Bracing System | Drift Reduction | Energy Dissipation | Residual Displacement | Primary Advantage | Key Limitation |
|---|---|---|---|---|---|
| Diagonal / X | High | Moderate | Moderate | Simple, cost-effective | Buckling under compression |
| V / Inverted V | Moderate | Moderate | Moderate–High | Architectural compatibility | Beam force imbalance |
| Buckling-Restrained Brace | Very High | Very High | Moderate | Stable hysteresis | Residual drift |
| Self-Centering Bracing | High | Moderate | Very Low | Rapid post-earthquake | Lower dissipation |
| Variable Stiffness Bracing | High | High | Low | Adaptive response | Analysis complexity |
| Hybrid Bracing–Damper | Very High | Very High | Very Low | Balanced resilience | Higher initial cost |

Table 2 presents a summary of the relative effectiveness of regular as well as advanced types of bracing systems in relation to drift reduction capacity, energy dissipation ability, residual displacement, as well as the practical implications for the application of such systems in the retrofitting of R.C structures [12][54].

## IX. INFLUENCE OF BRACING CONFIGURATION AND GEOMETRY

Bracing system configuration impacts stiffness distribution, torsion behavior, and mode characteristics of RC frames considerably [16], [7]. Symmetric and continuous bracing systems have less torsion irregularities and promote equal force distribution [69].

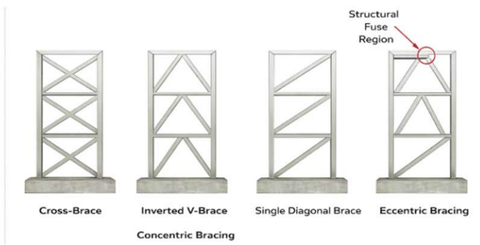


Figure 3. Influence of bracing configuration and geometry on seismic response of RC frames.

The influence of symmetric and asymmetric bracing layouts on seismic response is conceptually shown in Figure 3[70]. Equation (2) [70] illustrates how the participation factor, also known as the modal mass participation factor, estimates the effective amount of the entire structural mass engaging in a certain vibration mode under seismic excitation:

$$\Gamma_n = \frac{\phi_n^T M\, r}{\phi_n^T M\, \phi_n} \qquad (2)$$

where

- $\phi_n^T$ = mode shape vector of the $n$-th mode
- $M$ = global mass matrix
- $r$ = influence vector (usually unity in the excitation direction)

TABLE III: MODAL MASS PARTICIPATION FOR A BRACED RC FRAME

| Mode No. | Dominant Mode Type | Modal Mass Participation (%) | Cumulative Mass Participation (%) |
|---|---|---|---|
| 1 | Translational (X) | 52.4 | 52.4 |
| 2 | Translational (Y) | 18.7 | 71.1 |
| 3 | Torsional | 9.6 | 80.7 |
| 4 | Translational (X) | 5.8 | 86.5 |
| 5 | Translational (Y) | 3.2 | 89.7 |
| 6 | Torsional | 1.5 | 91.2 |
| 7 | Translational (X) | 0.9 | 92.1 |
| 8 | Translational (Y) | 0.6 | 92.7 |

Table 3 which presents results from modal analysis we see that first mode does not dominate as much because of the stiffness improvement which is a result of bracing, instead we see large play of higher translational and torsional modes. We achieve 90% cumulative mass participation at the sixth mode which in turn addresses the characteristic stiffness share redistribution in braced RC structures [70].

## X. Seismic Resilience and Performance-based Assessment

Currently, resilience-based indices, like residual drift, energy dissipation efficiency, or functional recovery, have attracted widespread research attention [71], [14]. In the case of braced RC buildings, [72] performance assessment is done using nonlinear analyses, which include pushover analyses and nonlinear time history analyses. Performance parameters include storey drift ratios, the formation of plastic hinges, the drift ratio, and the energy dissipation capacity of the structure. In bracing systems, the performance is checked to see whether there is deformation demand on the RC structure, while the nonlinear response is concentrated on the designated components, such as braces [74][73][74][75].

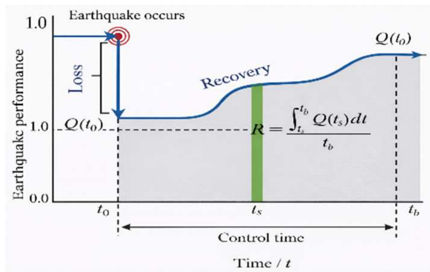


Figure 4. Conceptual framework linking performance-based assessment and seismic resilience.

The relationship between conventional performance measures and resilience objectives is illustrated in Figure 4[76] Equivalent Viscous Damping Ratio (ξeq) equation (3) in Braced RC Structures [76].

$$\xi_{eq} = \left(\frac{1}{4\pi}\right)\left(\frac{E_h}{0.5\, F_{max}\Delta_{max}}\right) \quad (3)$$

- $E_h$ = hysteretic energy dissipated per loading cycle (area enclosed by force–deformation loop)
- $F_{max}$ = maximum resisting force
- $\Delta_{max}$ = maximum deformation

## XI. Research Gaps Identified from Literature

Combined studies of SAP2000 simulations related to regional seismic designs are also minimal.[77] Recent research related to braced RC buildings provides insight into seismic response, though limitations remain from a performance-based resilience perspective. Sundar et al., 2023 showed, for example, the effect of different steel bracing systems on displacement, storey drift, and base shear [78]. According to Vishwakarma et al. (2018), shear walls supported with steel elements significantly increase the rigidity of RC structures. Wang et al., 2021 compared shear wall and braced RC systems utilizing advanced numerical analysis. [77][25][61].

## XII. Conclusion

In view of performance-based design, the use of a steel bracing system has shown good promise in meeting specific performance objectives by controlling drift and enhancing stiffness. The performance of buckling-restrained and self-centering bracing systems has shown considerable promise in meeting specific performance objectives in stability as well as stability-derived demand components like the prevention of collapse, but it lags behind in meeting residual drift. The variable stiffness and hybrid damper design show a good promise in meeting specific performance objectives during earthquake-resistant design by enhancing maximum balance, effectiveness, drift control, and energy dissipating capacity along with the restriction of residual deformation, and hence it can be considered as suitable in meeting performance objectives like rapid functionality recovery.

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