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Steel Bracing Systems for Seismic Performance Enhancement of Reinforced Concrete Frames: A Review

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Abstract — Reinforced concrete (RC) moment-resisting frames are widely used in multi-storey construction but are inherently flexible under lateral seismic loading, which can lead to excessive storey drift, non-structural damage and, in severe cases, structural collapse. Supplementing an RC frame with steel bracing is one of the most widely researched and applied means of improving its seismic performance, and a large and growing body of literature has examined the many forms this strategy can take. This paper presents a review of published research on steel-braced RC frames, covering the classification of bracing systems (concentric diagonal, X, V, inverted-V/chevron and K arrangements; eccentric and off-diagonal bracing; buckling-restrained and self-centering braces), their reported effects on lateral stiffness, storey displacement, inter-storey drift, ductility and energy dissipation, the influence of building height and structural irregularity on bracing effectiveness, retrofit and brace-to-frame connection strategies, and the analytical, numerical and experimental methods used to evaluate them. The review finds broad agreement that steel bracing substantially improves lateral stiffness and reduces storey drift relative to a bare RC frame, that X-type and inverted-V (chevron) configurations are the most frequently reported as most effective for stiffness and drift control though the relative ranking varies between studies, and that eccentric and buckling-restrained systems offer superior ductility and energy dissipation at some cost in stiffness. The review also identifies persistent gaps in the literature, including a shortage of controlled, zone-wise or intensity-wise comparisons of a single bracing configuration across the full range of seismic demand, limited experimental validation of brace-to-RC-frame connection detailing at full scale, and a continuing reliance on linear or pushover-level analysis rather than nonlinear time-history assessment for tall buildings. These gaps are identified as priorities for future research.

Keywords— Steel bracing, reinforced concrete frame, seismic performance, X-bracing, storey drift, ductility, buckling-restrained brace, literature review

I. INTRODUCTION

Reinforced concrete (RC) multi-storey buildings are widely constructed for their structural efficiency, durability and economic advantages, but the moment-resisting RC frame that forms the primary lateral load-resisting system in many such buildings is comparatively flexible under earthquake loading.

Excessive lateral flexibility manifests as large storey displacement and inter-storey drift, which in turn causes damage to non-structural elements, discomfort to occupants and, in extreme cases, loss of stability of the gravity load path. Improving the lateral stiffness and energy-dissipation capacity of RC frames without a complete structural redesign is therefore a long-standing problem in earthquake engineering.

Steel bracing is one of the most extensively studied solutions to this problem. By introducing diagonal steel members into the bays of an RC frame, either as part of the original design or as a later retrofit, a substantial portion of the lateral load is transferred through axial action in the braces rather than through flexure in the beams and columns, increasing stiffness and reducing drift with comparatively little added mass or construction complexity. Because bracing can be arranged in many geometric configurations, connected to the frame in several different ways, and combined with a range of supplementary devices such as buckling-restrained cores or self-centering mechanisms, a large and diverse literature has developed around the topic over the past three decades.

This paper reviews that literature. Rather than presenting new analytical or experimental results, the objective is to synthesise the existing body of published work on steel-braced RC frames — covering bracing classification, reported seismic performance, the influence of configuration and building characteristics, retrofit and connection practice, and the assessment methods used — and to identify where the literature remains thin or inconsistent.

The review is intended to orient researchers and practising engineers to the current state of knowledge and to motivate further controlled comparative studies.

II. CLASSIFICATION OF STEEL BRACING SYSTEMS

Steel bracing systems for RC frames are broadly classified by the geometric arrangement of the diagonal members and by whether the bracing intersects the beam at a single point (concentric) or offset from the beam-column joint (eccentric).
Concentric Bracing:

In concentrically braced frames (CBFs), the centrelines of the diagonal brace, beam and column intersect at a single point, so that lateral load is resisted almost entirely by axial force in the braces. Common concentric arrangements include single diagonal bracing (one brace per bay, most efficient in one direction of loading), X-bracing (two crossing diagonals, engaging one member in tension and the other in compression under either direction of loading), V- and inverted-V (chevron) bracing (paired diagonals meeting at the mid-span of the beam above or below), and K-bracing (paired diagonals meeting at the mid-height of the column, which is generally prohibited in seismic design because brace buckling imposes a net lateral force on the column at mid-height). X-bracing is widely reported as the stiffest of the common concentric arrangements because both diagonals participate under either direction of load, though chevron bracing is also frequently reported as highly effective for drift control.

Eccentric and Off-Diagonal Bracing
Eccentrically braced frames (EBFs) intentionally offset the brace-to-beam connection from the column, creating a short "link" segment in the beam that is designed to yield in shear or flexure before the brace itself buckles. This link acts as a ductile fuse, giving EBFs a combination of the high elastic stiffness associated with concentric bracing and the ductility and energy-dissipation capacity associated with moment frames. Off-Diagonal Bracing Systems (ODBS) and similar hybrid arrangements have also been proposed as concentric-type systems that avoid some of the drawbacks of conventional X- and V-bracing while retaining comparable stiffness.

Buckling-Restrained and Self-Centering Braces
Buckling-restrained braces (BRBs) confine a yielding steel core within an outer sleeve, preventing compressive buckling and allowing the brace to yield in both tension and compression, which produces stable, symmetric hysteretic behaviour and substantially greater energy dissipation than a conventional brace of similar size. Self-centering bracing systems, a more recent development, incorporate pre-tensioned tendons or other restoring mechanisms so that the structure returns towards its original position after an earthquake, reducing residual drift. Both systems are typically reviewed alongside conventional concentric bracing because they are installed in the same bay locations and compared using the same drift- and stiffness-based performance metrics.

III. LITERATURE REVIEW

1. Effect of Bracing on Lateral Stiffness and Displacement
A consistent finding across the reviewed literature is that adding steel bracing to an RC frame produces a substantial increase in lateral stiffness and a corresponding reduction in storey displacement relative to the unbraced (bare) frame, regardless of the specific configuration adopted. Comparative studies using X-type and inverted-V bracing in RC buildings have reported maximum storey-displacement reductions on the order of 45% relative to the bare frame, with the improvement most pronounced at the upper storeys where lateral displacement accumulates. Parametric studies comparing braced and unbraced multi-storey frames have similarly reported large reductions in roof-level drift, in some cases exceeding 60% at the top storey, when X-bracing is introduced. The displacement-control benefit of bracing has also been reported to depend on where in the building height the bracing is placed and how many spans or storeys it covers. Studies examining bracing placed at different spans and storey ranges have found that continuous bracing over the full height generally outperforms bracing concentrated in a limited zone, though partial-height bracing schemes have been proposed as a more economical compromise where full-height bracing is impractical.

2. Influence of Bracing Configuration
Because bracing configuration governs how lateral force is transferred through the frame, a substantial share of the literature is devoted to comparing configurations against one another under otherwise identical conditions. The overall picture that emerges is one of broad but not universal agreement that X-type bracing provides the greatest stiffness and drift control among conventional concentric arrangements.

Comparative studies of X-type against V-type bracing in multi-storey buildings have reported that X-bracing produces lower bending moment and shear force in frame members than V-bracing, along with measurably lower storey drift, while V-bracing produced a higher peak axial force at certain levels. Parametric studies comparing X-bracing against a bare (unbraced) frame have reported drift reductions of roughly 66% at the roof and upper storeys, and around 36% at the first storey, indicating that the relative benefit of X-bracing is not uniform over building height. Comparisons of X-bracing, inverted-V bracing and an unbraced frame using nonlinear static (pushover) analysis have likewise concluded that X-braced frames achieve the best overall combination of storey-drift control and lateral stiffness among the arrangements tested.

Not every study reaches the same ranking, however. At least one comparative study of eccentric bracing configurations found inverted-V bracing to be more effective than X-bracing at reducing storey drift for the particular building and loading case examined, and a separate comparison of buckling-restrained braces against conventional X, diagonal, V and inverted-V steel braces found that buckling-restrained bracing outperformed all of the conventional steel configurations for storey displacement and drift, while conventional steel bracing retained an advantage in controlling overturning moment and base shear. Similarly, a study comparing moment frames, X-bracing and inverted-V bracing across buildings of different heights found that the best-performing configuration for displacement control changed with the number of storeys — X-bracing performing best for shorter buildings and inverted-V performing best at an intermediate height in that study — which suggests that the relative ranking of bracing configurations is sensitive to building height, span, storey height and the specific demand parameter being optimised, and should not be assumed to transfer automatically from one building geometry to another.

Research on brace-to-frame force transfer has also identified configuration-specific failure modes that influence the practical choice of bracing. Out-of-plane instability of the brace in multistorey X-braced steel frames has been shown to induce large unbalanced vertical force and displacement in the beam at the point where the diagonals cross, motivating the development of improved X-brace details intended to mitigate this effect. K-bracing, in which paired diagonals meet at column mid-height, is generally excluded from seismic applications for a related reason: brace buckling produces a net lateral force on the column at an unbraced mid-height location, which the column is not typically designed to resist.

Progressive-collapse studies provide an additional and largely independent line of evidence favouring X-bracing. A recent comparative study of X- and inverted-V bracing for controlling progressive collapse in RC buildings concluded that X-bracing provided superior resistance to collapse propagation compared with inverted-V bracing, and offered placement recommendations for maximising this benefit, reinforcing the case for X-bracing as a robust general-purpose configuration even though inverted-V and other arrangements may be preferable for specific objectives such as drift control in a particular building.

3. Influence of Building Height and Structural Irregularity

Beyond the choice of bracing configuration, several studies have examined how bracing effectiveness varies with building height, plan geometry and irregularity. Investigations of steel-braced RC frames with varying numbers of storeys and varying brace cross-sections have found that both the height of the building and the size of the bracing member have a marked influence on load-carrying capacity, inter-storey drift, ductility, column force demand and energy-absorption capacity, indicating that a bracing scheme validated on a low-rise building cannot automatically be assumed to perform equivalently when applied to a high-rise structure.

Studies of high-rise buildings specifically have reported that the benefit of X-bracing can vary considerably with storey level, with the largest relative reduction in lateral displacement typically observed towards the upper portion of the building, consistent with the general pattern that displacement-control benefits of bracing accumulate with height. Plan irregularity introduces a further complication: several studies analysing irregular RC buildings with different bracing configurations have used response-spectrum or nonlinear analysis specifically to capture torsional and other irregularity-driven effects that are not present in regular, doubly symmetric buildings, underscoring that bracing performance reported for regular plan geometries should be extended cautiously to irregular buildings.

4. Ductility, Energy Dissipation and Modern Bracing Systems

Lateral stiffness and drift control are only part of the seismic-performance picture; ductility and energy-dissipation capacity govern how a structure behaves once inelastic response begins, and are particularly important for bracing systems intended to survive a design-level or larger earthquake without collapse. Conventional concentric bracing, including X-bracing, is generally reported to increase stiffness at some cost to ductility relative to a moment frame, because compression braces are prone to buckling and subsequent strength degradation under cyclic loading. This trade-off has motivated substantial research into bracing systems that retain the stiffness benefits of concentric bracing while improving cyclic behaviour.

A comprehensive review of concentrically braced steel frames, synthesising 27 experimental programmes comprising 189 individual tests conducted between 2002 and 2023, catalogued the section sizes, geometries and cyclic-loading results of conventional, modern and self-centering bracing systems, and concluded that a range of recently developed brace mechanisms — including buckling-restrained cores and self-centering tendon systems — substantially improve energy dissipation and reduce residual damage compared with conventional bracing, while requiring more complex detailing and, in the case of self-centering systems, additional post-tensioning hardware.

Eccentrically braced frames occupy an intermediate position, using a designed shear or flexural link to dissipate energy while retaining much of the stiffness benefit of concentric bracing. A study comparing several EBF configurations in steel buildings found that peak inter-storey drift demand concentrated in the lower storeys where the links were engaged in inelastic behaviour, with drift decreasing at greater height, and noted that the relative seismic performance of different EBF link arrangements had not been conclusively established in the prior literature, motivating further comparative work in that area.

Buckling-restrained braces have received particular research attention as a retrofit measure for existing RC frames subjected to sequential or repeated seismic events. A study of RC frames with BRBs subjected to a real sequential mainshock-aftershock earthquake sequence found that BRBs significantly increased lateral load capacity and reduced deformation demand relative to the unretrofitted frame, though the added stiffness was also found to increase floor accelerations, illustrating that a bracing retrofit that improves drift performance can simultaneously introduce a different design consideration — acceleration-sensitive non-structural damage — that must be checked separately. A related study of an external steel frame with slit dampers, evaluated under mainshock-aftershock sequences using nonlinear dynamic analysis, similarly found that supplementary bracing-type retrofit systems could substantially improve seismic resilience under repeated shaking, an increasingly important consideration given the observed frequency of aftershock sequences in recent major earthquakes.

5. Retrofit Strategies and Brace-to-Frame Connections

A large share of the steel-bracing literature is motivated by retrofit of existing RC buildings rather than the design of new construction, since bracing can often be added to an existing frame with comparatively little disruption relative to alternatives such as full shear-wall construction. Early experimental work established that steel bracing can be connected directly to an existing RC frame without requiring an intermediate steel sub-frame, provided the connection between the brace and the RC beam-column joint is adequately detailed to transfer the concentrated brace force into the concrete elements; this finding underpins much of the subsequent literature on direct steel-to-RC brace connections. Related experimental investigations of internally X-braced RC frames further examined how the connection detailing affects the overall seismic behaviour of the retrofitted frame, including the distribution of force between the bracing and the surrounding RC members.

More recent retrofit-design methodologies have sought to formalise the process of selecting and sizing a bracing retrofit. A displacement-based retrofit procedure built on the Simple Lateral Mechanism Analysis (SLaMA) framework has been proposed specifically for RC frame buildings retrofitted with alternative bracing systems, allowing engineers to estimate the retrofitted building's global capacity curve without requiring a full nonlinear model at the preliminary design stage. At the assessment end of the same problem, seismic fragility analysis has been used to quantify the probability of reaching defined damage or collapse states for RC moment frames retrofitted with a strongback braced system, providing a probabilistic rather than deterministic measure of retrofit effectiveness that complements the deterministic drift- and stiffness-based comparisons more commonly reported elsewhere in the literature.

Comparative retrofit studies have also examined bracing alongside entirely different strengthening techniques. A comparative experimental study of RC-frame strengthening approaches — including RC jacketing, steel jacketing and base isolation — found that jacketing techniques produced greater stiffness and energy-dissipation gain per unit of added material, while base isolation was more effective at reducing the force transmitted into the superstructure, indicating that the choice between bracing, jacketing and isolation should be guided by which performance objective (stiffness, energy dissipation, or force reduction) is prioritised for a given retrofit project, rather than assuming bracing is uniformly superior or inferior to these alternatives.

6. Analytical, Numerical and Experimental Assessment Methods

The methods used to evaluate steel-braced RC frames in the literature range from simplified linear analysis to full nonlinear time-history and shake-table testing, and the choice of method strongly influences what can be concluded from a given study. Linear equivalent-static and response-spectrum analyses remain widely used for comparative studies of bracing configuration because they are computationally inexpensive and allow a large number of configurations, storey counts or seismic zones to be compared systematically; the majority of the configuration-comparison studies discussed in Section III-B rely on this class of method.

Nonlinear static (pushover) analysis is used considerably more often where ductility, hinge formation sequence or post-yield capacity is of direct interest, since linear analysis cannot

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capture these effects. Several of the configuration and connection studies discussed above rely on pushover analysis specifically to compare stiffness, drift and energy-related metrics between bracing arrangements at the point of significant inelastic response, rather than only in the initial elastic range.

Nonlinear dynamic time-history analysis, though more computationally demanding, is increasingly used where the sequence and timing of seismic demand matters, such as evaluating structural response to sequential mainshock-aftershock earthquake records, or where the specific hysteretic behaviour of a bracing device (for example, a buckling-restrained or self-centering brace) is central to the research question. Physical experimental methods, ranging from cyclic loading of isolated brace-to-frame subassemblies to full shake-table testing of scaled multi-storey frames, remain comparatively scarce relative to the volume of analytical and numerical work, but provide the validation data against which analytical models are ultimately checked; the 189-test survey noted in Section III-D represents one of the more extensive compilations of this experimental evidence currently available.

IV. SYNTHESIS AND RESEARCH GAPS

Drawing the reviewed literature together, three broad conclusions can be stated with reasonable confidence. First, steel bracing of essentially any conventional configuration substantially increases the lateral stiffness of an RC frame and reduces storey displacement and inter-storey drift relative to the bare frame, and this benefit is reported consistently across a wide range of building heights, seismic intensities and analysis methods. Second, X-type and chevron (inverted-V) bracing are the configurations most frequently reported as providing the best stiffness and drift control among conventional concentric arrangements, though the literature also contains credible exceptions in which another configuration outperformed X-bracing for a specific building, height range or response parameter, indicating that configuration ranking is sensitive to case-specific geometry rather than fixed. Third, ductility and energy-dissipation performance follow a largely separate hierarchy from stiffness performance: eccentric, buckling-restrained and self-centering systems generally outperform conventional concentric bracing on these measures, at the cost of more complex detailing and, in some cases, increased floor acceleration.

1. Identified Gaps

Despite the volume of published work, several gaps recur across the reviewed studies. Few papers report a controlled comparison of a single bracing configuration across the full range of seismic zones or intensities for one building, with most studies instead comparing multiple configurations within a single zone or comparing one configuration across a small number of building heights; this makes it difficult to isolate how the benefit of a specific, fixed bracing arrangement scales with seismic demand alone. Experimental validation of brace-to-RC-frame connection detailing, while established in principle, remains comparatively limited in scale and diversity relative to the much larger body of purely analytical configuration-comparison work, leaving open questions about how connection detailing choices affect the numerical predictions on which most of the comparative literature is based. Finally, linear and pushover-level analysis continue to dominate the comparative literature on bracing configuration, while nonlinear time-history assessment — particularly under repeated or sequential seismic demand — is concentrated in a smaller number of studies focused on specific retrofit devices such as buckling-restrained braces, rather than being applied broadly across bracing configurations and building heights.

Addressing these gaps through controlled, zone-wise or intensity-wise comparative studies of a single, well-defined bracing configuration — evaluated consistently across seismic demand levels, validated where possible against connection-level experimental data, and assessed using nonlinear as well as linear methods — represents a clear and achievable direction for future research building on the literature synthesised in this review.

Future Scope

Building on the gaps identified in Section IV, several specific directions are recommended for future research on steel-braced RC frames.

Zone-Wise and Intensity-Wise Comparative Studies

Future work should evaluate a single, well-defined bracing configuration across the full range of seismic zones or intensity levels for one building, rather than comparing multiple configurations within a single zone as most existing studies do. This would allow the benefit of a fixed bracing arrangement to be isolated from the effect of seismic demand itself, and would produce design guidance that is more directly transferable between regions of differing seismicity.

Nonlinear and Shake-Table Validation

Given the current concentration of linear and pushover-level analysis in the comparative literature, future studies should extend zone-wise and configuration comparisons to nonlinear time-history analysis, and where feasible to shake-table testing, so that higher-mode effects, cumulative damage under repeated shaking, and the true hysteretic behaviour of the bracing system are captured rather than approximated.

Connection Detailing and Full-Scale Testing
Because brace-to-RC-frame connection detailing is known to influence overall seismic behaviour but remains comparatively under-tested at full scale, future experimental programmes should prioritise a wider range of connection types, materials and RC member sizes, so that the numerical assumptions used in the much larger body of analytical comparative work can be validated more broadly.

Hybrid and Self-Centering Systems in RC Applications
Self-centering and buckling-restrained bracing has been studied extensively in steel structures but comparatively less in RC-frame applications specifically. Extending these systems, and hybrid combinations of conventional bracing with supplementary dampers, to RC frames represents a promising area where the residual-drift and energy-dissipation benefits already demonstrated in steel construction could be transferred to RC retrofit and new-build practice.

Cost, Constructability and Life-Cycle Assessment
Much of the existing literature evaluates bracing purely in structural-performance terms (stiffness, drift, ductility) without a corresponding assessment of material cost, construction time or life-cycle environmental impact. Future studies that combine seismic performance metrics with cost and constructability data would allow engineers to make a more complete comparison between bracing and competing retrofit or design strategies such as shear walls, jacketing or base isolation.

Optimisation-Based and Code-Oriented Studies
Finally, the growing availability of optimisation and machine-learning-assisted structural design tools suggests an opportunity to move beyond manual comparison of a small number of bracing configurations towards systematic optimisation of brace placement, size and configuration for a given building and seismic environment. Parallel work translating these research findings into explicit code provisions for bracing-based seismic retrofit of existing RC buildings would also help close the gap between the research literature reviewed here and everyday design practice.

V. CONCLUSION

This paper has reviewed the published literature on steel bracing systems for improving the seismic performance of reinforced concrete frames, covering bracing classification, reported effects on stiffness, displacement, drift, ductility and energy dissipation, the influence of bracing configuration and building characteristics, retrofit and connection practice, and the analytical, numerical and experimental methods used to study these systems. The literature is consistent in finding that steel bracing meaningfully improves the lateral performance of RC frames relative to a bare frame, and X-type and chevron bracing are the most frequently favoured conventional configurations, though the relative ranking of configurations is not fixed and depends on building height, geometry and the specific response parameter of interest. Eccentric, buckling-restrained and self-centering systems extend this picture by offering superior ductility and energy dissipation where cyclic performance under strong or repeated shaking is the governing concern.

The review also identifies clear directions for future research: controlled zone-wise or intensity-wise comparison of a single bracing configuration, expanded experimental validation of brace-to-RC-frame connection detailing, and wider use of nonlinear time-history assessment across bracing configurations rather than only for specific retrofit devices. Addressing these gaps would strengthen the evidence base available to engineers selecting a bracing strategy for a specific building and seismic environment.

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