

Seismic Performance of Reinforced Concrete Buildings with Different Lateral Load-Resisting Systems: A Critical Review

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Abstract - The lateral load-resisting system largely decides how a multi-storey reinforced concrete building responds to earthquake ground motion, yet published comparisons of alternative systems are hard to combine because they differ in building height, plan, design code, seismic input and method of analysis. This paper presents a narrative critical review of thirty-three published sources, from foundational analytical work to studies published in 2026, together with the relevant Indian standards. It covers four systems that are commonly considered for mid-rise buildings in regions of high seismicity: special moment-resisting frames, frames combined with reinforced concrete shear walls, frames stiffened with concentric steel bracing, and central cores connected to perimeter columns by outriggers and belt trusses. The studies are grouped by system and compared in terms of modelling assumptions, ground-motion representation, analysis procedure and the response measures they report, namely fundamental period, displacement, inter-storey drift, base shear, storey stiffness and the response reduction factor. The literature agrees that each stiffening system shortens the period and reduces displacement and drift relative to a bare frame. It disagrees on the most effective location of walls and of outriggers, and the reported magnitudes depend strongly on the building, the baseline, the response measure and the method. Bracing studies are concentrated in low-rise and retrofit cases and outrigger studies in buildings of more than twenty storeys, and few studies hold the frame, mass, response reduction factor and base-shear scaling constant while changing the lateral system. These gaps point to the need for controlled comparisons of all four systems in buildings of about twelve to twenty storeys designed to Indian provisions, followed by nonlinear verification.

Keywords - Reinforced concrete buildings; lateral load-resisting systems; shear walls; steel bracing; outrigger and belt truss; response spectrum analysis; inter-storey drift; response reduction factor

I. INTRODUCTION

An earthquake loads a building indirectly. The ground moves, and the floors, because of their inertia, lag behind; the structure then has to generate restoring forces large enough to drag its mass along with the ground. How large those forces are, and how they are shared among the members, depends on the mass and stiffness of the building and on where its natural periods fall within the frequency content of the shaking. For a multi-storey reinforced concrete (RC) building, the element of

the design that controls most of these properties is the lateral load-resisting system. It sets the lateral stiffness, the shape of the deflected profile, the distribution of storey shear and overturning moment, and the path by which these actions reach the foundation.

In India the choice of system is framed by IS 1893 (Part 1):2016 [1], which defines the design spectrum, the response reduction factor R for each structural type, the empirical period expressions and a storey drift limit of 0.004 times the storey height. Ductile detailing follows IS 13920:2016 [2], and RC buildings taller than 50 m fall under IS 16700:2023 [3], which limits the height up to which each structural system may be used. Buildings of roughly twelve to twenty storeys occupy an awkward position in this framework. A bare moment frame of that height in a high seismic zone tends to be governed by drift rather than strength, whereas the systems developed for tall buildings, such as cores with outriggers, have mostly been studied at much greater heights. Designers of mid-rise buildings therefore choose among four practical options, shown schematically in Fig. 1: a special moment-resisting frame (SMRF), an SMRF with RC shear walls (a dual system), an SMRF stiffened with concentric steel bracing, and a central RC core linked to the perimeter columns by outrigger and belt trusses.

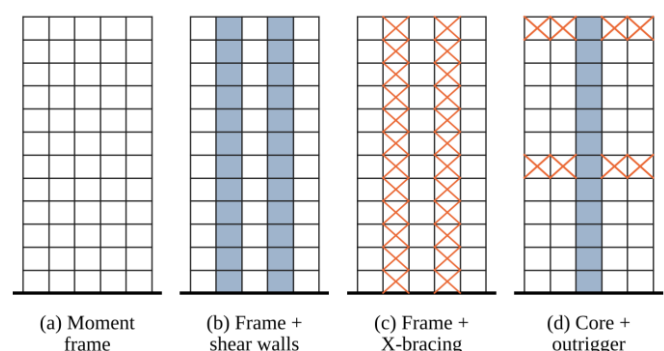


Fig. 1. Lateral load-resisting systems considered in this review (schematic elevations, not to scale).

Each of these systems has been studied extensively, but the results are difficult to combine. The studies differ in building height, plan, design code, seismic input, baseline model and

analysis method, so a drift reduction of 96% reported for walls at an open ground storey [4] and one of 77% reported for bracing in an eight-storey frame [5] describe different quantities measured against different references. Existing reviews concentrate on one system or one method, for example outrigger optimisation [6], nonlinear static procedures [7] or the effect of the seismic incidence angle [8], rather than on how the systems compare with one another.

This paper addresses that gap through a critical comparison of the literature. Its contributions are: (i) a classification of the reviewed studies by structural system, building height and analysis method; (ii) a comparison of their findings on common response parameters that separates results that hold across studies from those that depend on particular assumptions; (iii) a set of research gaps specific to mid-rise RC buildings in high seismic zones designed to Indian provisions; and (iv) the implications of these findings for the design of comparative studies. Section II describes how the review was conducted, Section III summarises the governing mechanics, Section IV reviews the literature by theme, Sections V and VI compare and synthesise the findings, and Sections VII to IX present the gaps, the engineering implications and the conclusions.

II. SCOPE AND METHOD OF THE REVIEW

The review is narrative and critical; it is not a systematic review, and no protocol of the PRISMA type was followed. It was guided by three questions. RQ1: on which effects of each lateral system on period, displacement, drift, base shear and stiffness do the studies agree? RQ2: where do the findings diverge, and which differences in buildings, assumptions or methods explain the divergence? RQ3: what evidence is still missing for mid-rise RC buildings in high seismic zones designed to Indian provisions?

The starting point was the literature assembled for the first author's M.Tech dissertation. It was supplemented by targeted searches of publisher websites, the Directory of Open Access Journals and Crossref metadata, using combinations of the terms reinforced concrete, shear wall, steel bracing, outrigger, belt truss, response spectrum, pushover, storey drift, fundamental period and response reduction factor. Most of the sources date from 2019 to 2026; earlier works from 1964 to 2007 were retained where they established the mechanics or the methods on which later studies rely. A source was included if it was a journal article or conference paper with a verifiable bibliographic record, dealt with RC buildings or with mechanics or methods directly applicable to them, and reported at least one seismic response measure or an analysis procedure. Sources whose bibliographic details could not be confirmed were excluded. The search was not exhaustive and favours open-access and ETABS-based studies, and this selection effect should be borne in mind when reading the comparisons.

Each study was coded by lateral system, number of storeys, plan regularity, design code, analysis method and software, ground-motion input and the response measures reported. Numerical values are quoted as stated by their authors. They apply only to the buildings, loads and codes of the original studies and are not transferable to other buildings.

III. MECHANICS OF LATERAL LOAD RESISTANCE

A. Deformation Modes and System Interaction

A moment-resisting frame resists lateral load by bending of its beams and columns and by the rotational restraint of its joints. Its deflected shape is of the shear type: storey drift is greatest in the lower storeys, where storey shear is largest, and decreases with height. A slender shear wall behaves as a vertical cantilever and deforms in flexure, with small drift near the base and increasing drift towards the top (Fig. 2a). When walls and frames are tied together by rigid floor diaphragms, the two modes are incompatible and the members interact: the wall restrains the frame in the lower storeys, and the frame restrains the wall in the upper storeys. Khan and Sbarounis [9] showed that the resulting distribution of lateral force between the two depends on their relative stiffness and on the number of storeys, which is why the frame share in a dual system changes over the height.

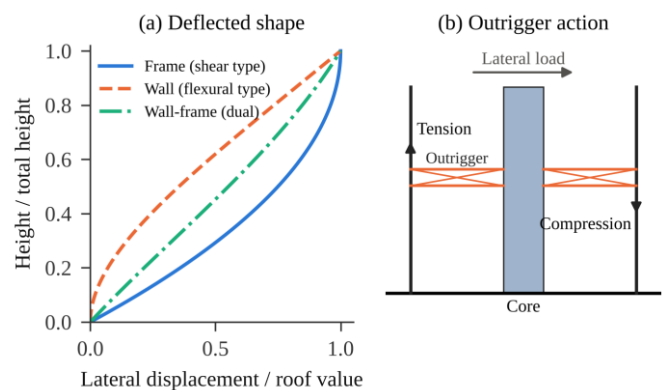


Fig. 2. Mechanics of the systems: (a) normalised deflected shapes of frame, wall and wall-frame systems; (b) outrigger action, in which core rotation is resisted by a tension-compression couple in the perimeter columns (schematic).

Concentric steel bracing converts part of the frame action into axial force in diagonal members, a much stiffer mechanism, so that a braced bay acts as a vertical truss whose flexural component comes from the axial strain of the columns. Bracing adds little mass, but brace buckling in compression, the forces delivered to the RC beams and columns, and the connection between steel and concrete govern its behaviour [10]. A central core alone is again a slender cantilever. Outriggers connect it to the perimeter columns at one or more levels; as the core rotates, the outriggers force the columns on one side into tension and on the other into compression, and the resulting couple reduces the core moment below the outrigger and the lateral deflection (Fig. 2b). In their parametric study Stafford Smith and Salim [11] framed outrigger effectiveness in terms of the relative flexibilities of the core, the columns and the outrigger, a framing that later optimisation studies have retained [6].

B. Period, Design Spectrum and Design Force

In IS 1893 (Part 1):2016 the design horizontal seismic coefficient is

$$A_h = (Z/2)(I/R)(S_a/g) \quad (1)$$

where Z is the zone factor, I the importance factor, R the response reduction factor and S_a/g the spectral acceleration coefficient at the fundamental period [1]. The design base shear is A_h multiplied by the seismic weight. Two consequences

follow for any comparison of systems. First, a stiffer system has a shorter period and, on the descending branch of the spectrum, a larger S_a/g , while walls and cores also add weight; stiffening therefore tends to increase the design base shear even as it reduces displacement. Second, because R divides the elastic demand, systems assigned different R values differ in design force partly because of their code classification rather than their structural behaviour.

The period used in design is itself uncertain. Goel and Chopra found that the code formulas of the time generally gave periods shorter than those measured in instrumented moment-frame buildings during California earthquakes [12] and were "grossly inadequate" for concrete shear wall buildings [13], and they proposed improved formulas calibrated on the measured data. More recently, Emad et al. [14] compared the period formulas of several codes with finite element modal analysis of 93 RC building models and found that most formulas underestimate the period of low- and mid-rise buildings, often by more than 40% when cracked sections are assumed. Because IS 1893 (Part 1):2016 requires response spectrum results to be scaled up to the base shear obtained from the empirical period when they fall below it [1], the design forces of stiff systems may be controlled by the empirical formula rather than by the dynamic properties of the model. This point is seldom discussed in the comparative studies reviewed below.

Modal responses are usually combined by the complete quadratic combination (CQC) rule, which accounts for the correlation of closely spaced modes and reduces to the square-root-of-sum-of-squares rule when the modes are well separated [15]; IS 1893 (Part 1):2016 specifies CQC [1]. For the combination of the two horizontal directions, Cantagallo et al. [8] reviewed more than 80 publications and reported that codes rely on either the square-root-of-sum-of-squares rule or the 30% rule and that no consensus has yet been reached on how incidence-angle effects should be evaluated. Damage to partitions, cladding and joints is commonly judged by the inter-storey drift ratio

$$\theta_i = (\delta_i - \delta_{i-1})/h_i \quad (2)$$

where δ_i is the lateral displacement of floor i and h_i the height of storey i . IS 1893 (Part 1):2016 limits this ratio to 0.004 under the design lateral force [1].

IV. THEMATIC REVIEW OF EXISTING RESEARCH

A. Moment-Resisting Frames and the Response Reduction Factor

The bare SMRF is the reference model in almost every comparative study, but its own design depends on the value of R . Prasanth and Ghosh [16] designed a symmetric G+10 RC frame to IS 13920:2016 with $R = 3, 4, 5$ and 6 and assessed it by nonlinear time-history analysis within a fragility and resilience framework. A higher R produced a higher ductility demand and lower resilience, although $R = 6$ remained acceptable under the criteria they adopted; only direct structural losses were considered. El-Hadary et al. [17] evaluated R for regular and irregular, bare and infilled frames of four to seven storeys by pushover analysis under the Egyptian code. Infill raised R by 38% to 75%, shortened the period and increased the base shear, R decreased in higher seismic zones, and the code value overestimated R for bare frames. Kotb [18] computed R by pushover analysis for three- to thirteen-storey frames combined with rectangular walls, L-

shaped walls and cores, and found that R and its components vary with the wall configuration.

These studies are not in conflict. They used different codes and different definitions of adequacy, resilience-based in one case and capacity-based in the others, but they agree that R is not an intrinsic constant of a structural type. For comparisons of lateral systems this matters directly: a study that assigns each system its code R and one that holds R constant answer different questions, and the reviewed literature rarely states which choice was made.

B. Shear Walls and Dual Systems

The finding that walls reduce period, displacement and drift relative to a bare frame is consistent across heights, codes and methods. Abate et al. [19] analysed 15- and 50-storey buildings by response spectrum analysis in ETABS with an EN 1998-1-based spectrum; walls substantially improved the response, openings had a significant effect on drift, stiffness, shear and wall stress, and the influence of openings decreased with height. Mishra and Singh [20] studied a G+15 frame in Zone V by nonlinear time-history analysis in ETABS using the 2015 Gorkha record; the period fell from 1.645 s without walls to 1.36 s with core walls, and the maximum storey displacement from 23.3 mm to 19.6 mm with corner walls. Nayak et al. [21] found for a G+12 building that rectangular walls gave the lowest displacement, drift and period, that T-shaped walls performed worst, and that a dual system with well-placed walls resisted earthquake forces more effectively than the moment frame. Shakeel et al. [22] compared moment frames and dual systems for a seven-storey building under two generations of building code using pushover analysis and quantity estimates; the dual systems showed far smaller displacements and were also more economical, because the walls relieved the beams and columns, while the newer code increased base shear and steel quantities for both systems.

Studies of wall location are less consistent. Shukla and Nallasivam [23] used the equivalent static method of IS 1893 (Part 1):2016 and found that central core-shaped walls performed best, with a top displacement about 2.5 times lower than that of the building without walls, while walls near the corners were least effective. Hosen [24] analysed sixteen ETABS models under four building codes and also found the central box wall gave the lowest displacement and drift. Mishra and Singh [20], however, obtained the smallest storey displacement with corner walls, even though the core gave the shortest period. For a G+10 building on sloping ground analysed by response spectrum analysis to IS 1893 (Part 1):2016, Sahare et al. [25] found a peripheral arrangement most effective: in Zone V the maximum roof displacement fell from 118.6 mm to 74.5 mm, the maximum storey drift from 11.3 mm to 7.1 mm and the torsional irregularity ratio from 1.28 to 1.07. Pranava et al. [26], studying a torsionally irregular T-shaped plan, reported that the layouts with higher modal participation and smaller eccentricity between the centres of mass and stiffness performed best in every zone considered.

Part of this disagreement can be traced to the choice of metric (period, roof displacement, drift or torsional ratio), to plan geometry and to the method, which ranges from equivalent static analysis to a single-record time-history analysis. A mechanical explanation is also plausible, although none of the studies tests it directly: a closed central core gives high flexural stiffness for a given wall area, whereas perimeter

walls provide a larger lever arm against torsion. Where torsion is significant, as on sloping ground or in irregular plans, perimeter layouts may therefore rank higher, which is consistent with the eccentricity finding of [26]. This interpretation is tentative. One further result needs caution: Mishra and Singh [20] reported the largest storey shear for the model without walls, contrary to what the design spectrum would predict for a more flexible building, which probably reflects the single record used.

C. Steel Bracing in RC Frames

Experimental evidence on internally braced RC frames is limited. Youssef et al. [10] tested a 2/5-scale panel taken from a four-storey building under cyclic loading. The braced frame had about 2.5 times the initial stiffness of a ductile moment frame and a lateral capacity of about 140 kN against 55 kN, but a ductility of about 1.9 against 3.0; it failed by buckling of the compression brace followed by beam hinging, and it needed about 35% less reinforcement. The authors judged the system promising but stated that substantial further research was needed before design guidelines could be developed, and no force reduction factor was established for braced RC frames.

Analytical studies concentrate on retrofit and on low-rise buildings. Abou-Elfath and Ghobarah [27] analysed a nonductile three-storey building under several records, examined how the distribution of bracing over the height affects performance, and proposed a simplified approach for selecting it. Ali et al. [5] reported for an eight-storey frame, modelled in two dimensions and analysed by pushover in SAP2000, a reduction of about 65% in the fundamental period (from 1.53 s to 0.54 s) and of 77% in the maximum inter-storey drift. Mahmud et al. [4] compared walls, cross bracing and inverted-V bracing at the open ground storey of a G+7 building by pushover analysis in ETABS: walls reduced storey drift by 96% and raised first-storey stiffness 10.6 times, cross bracing by 70% and 2.7 times, and inverted-V bracing by 64% and 1.8 times. Patel and Sinha [28] found for a four-storey soft-storey building in Zone IV that infill RC walls gave the largest reductions in base shear and drift, while steel bracing gave a balanced improvement in strength and deformability. Saadi and Yahiaoui [29] reported capacity increases of about 3.4 times for X-bracing, 2.3 times for zipper bracing and 2.02 times for V-bracing in a five-storey frame, and noted that larger brace sections increased strength and stiffness at the expense of ductility.

Taken together, these studies agree that bracing is an efficient stiffener for the mass it adds, that among concentric layouts the X-configuration gave the largest gain in stiffness or capacity [4], [29], and that walls stiffen more than bracing where the two were compared directly [4], [28]. They also show a trade-off between strength and ductility [10], [29]. The evidence, however, comes almost entirely from buildings of eight storeys or fewer, often in retrofit, analysed by pushover in two dimensions or with the brace-to-concrete connection assumed adequate. A response spectrum comparison of X-bracing in an RC frame of twelve to twenty storeys under IS 1893 (Part 1):2016 was not found among the reviewed studies.

D. Core Walls with Outriggers and Belt Trusses

Outrigger research is concentrated on tall buildings. Khadka et al. [30] analysed 32-storey RC models by response spectrum analysis in ETABS and found that an outrigger with a belt truss was the most effective arrangement for reducing

deflection, drift and period, with the optimum position, considering both deflection and drift, near mid-height (storey 16). Husain et al. [31] analysed a 40-storey, 120 m building in MIDAS-Gen under the El Centro record and found wall-beam outriggers more effective than Vierendeel outriggers, with the best single outrigger at about 0.45 of the height and the best pair at 0.2 and 0.45 of the height; the base overturning moment fell by up to 31.5%. Khalil et al. [32] analysed a 40-storey, 144.5 m core-wall building in ETABS with eleven scaled records and found the best position for a second conventional outrigger at about 0.6 of the height, which reduced the maximum displacement by about 39.9% and drift by about 46.3%; they also showed that diaphragm stiffness is critical for virtual outriggers. Abdollahzadeh et al. [33] proposed an outrigger and belt-truss layout for 30-, 45- and 60-storey buildings with a braced core that reduced both roof displacement and inter-storey displacement and relieved stress concentration at the outrigger floors.

The most recent study reviewed shows how much the conclusion depends on the measure chosen. Inam and Dindar [34] analysed two-dimensional 24- and 48-storey models with RC wall and buckling-restrained brace cores under mainshock-aftershock sequences. Dual outriggers reduced the period of the 48-storey models, but the benefit to a combined drift and damage index depended on the core type and height, some layouts increased the global damage index relative to the building without outriggers, and the RC wall cores performed more consistently. Their models exclude torsion.

For a single outrigger in buildings of 32 to 40 storeys, the reviewed studies agree on an optimum near mid-height for drift and deflection [30], [31], which fits the parametric framing of [11]. They disagree on the optimum for a second outrigger and for damage-based measures [32], [34]. All of them concern buildings of 24 storeys or more. At about sixteen storeys the core is less slender, fewer storeys are available for the trusses, and the outrigger storey introduces a local stiffness change that must be checked against the vertical irregularity provisions of IS 1893 (Part 1):2016 [1]; how these factors balance has not been established in the reviewed literature. Alhaddad et al. [6] also note that architectural constraints often confine outriggers to mechanical or refuge floors, which may not coincide with the structural optimum.

E. Analysis Methods and Modelling Assumptions

The method of analysis is closely tied to the system studied (Fig. 3). Linear response spectrum analysis captures higher modes and the actual distribution of mass and stiffness, and it is the standard design-level method, but it gives no information on inelastic behaviour. Pushover analysis reveals weaknesses that elastic analysis cannot, but Krawinkler and Seneviratna [35] cautioned that invariant load patterns may miss them when higher modes are important. Chopra and Goel [36] addressed this with modal pushover analysis, which uses the inertia force distribution of each mode and reduces to response spectrum analysis for elastic systems. Kuria and Kegyes-Brassai [7] concluded that nonlinear static procedures are far less demanding than nonlinear response history analysis but often fall short for bidirectional response, torsion and soil-structure interaction, and that conventional pushover analysis is limited for high-rise buildings. Time-history analysis is the most complete method, but its conclusions depend on the records: two of the studies reviewed relied on a single record [20], [31],

whereas others used suites of five to eleven records or sequences [16], [32], [34].

ETABS was used in most of the numerical studies reviewed. The developer publishes verification examples [37], but these do not cover model-level choices that strongly affect the results, such as cracked-section stiffness modifiers (for which IS 1893 (Part 1):2016 specifies reduced moments of inertia for RC frame members [1]), diaphragm rigidity, brace end releases, the mass source and the scaling of response spectrum results. These choices are often not reported, and

Khalil et al. [32] showed that at least one of them, diaphragm stiffness, can change the effectiveness of an outrigger system.

V. CRITICAL COMPARATIVE ANALYSIS

Table I summarises the principal studies reviewed, and Table II groups their findings by response parameter, separating those that are consistent across studies from those that are conditional or contradictory. Fig. 3 places the studies by building height and method. Four patterns emerge from this comparison.

TABLE I. SUMMARY OF PRINCIPAL REVIEWED STUDIES

Ref.	System(s)	Storeys	Method / software	Code basis	Principal finding (as reported)	Main limitation
[16]	SMRF designed with $R = 3$ to 6	G+10	Nonlinear time-history; fragility	IS 13920:2016	Higher R gave higher ductility demand and lower resilience; $R = 6$ acceptable under adopted criteria	One symmetric frame; direct losses only
[17]	Bare and infilled, regular and irregular frames	4 to 7	Pushover	Egyptian	Infill raised R by 38% to 75%; code R high for bare frames	Low-rise only
[18]	Frames with rectangular, L-shaped and core walls	3 to 13	Pushover, SAP2000	Egyptian	R and its components vary with wall configuration	No high-rise cases
[19]	Frame vs walls with and without openings	15, 50	Response spectrum, ETABS	EN 1998-1 based	Walls improve response; openings affect drift, stiffness and wall stress	Linear; non-Indian code
[23]	Alternative wall layouts	High-rise	Equivalent static, ETABS	IS 1893:2016	Central core best; corner walls least effective	Static method
[24]	Peripheral, corner and central box walls	-	ETABS, 16 models	Four codes	Central box wall gave lowest displacement and drift	Height not recorded here
[20]	Walls at corners, core and edges	G+15	Nonlinear time-history, ETABS	IS 1893 (Zone V)	Core: period 1.645 to 1.36 s; corner: displacement 23.3 to 19.6 mm	Single record
[21]	Rectangular, L, C and T walls	G+12	Response spectrum, ETABS	-	Rectangular walls lowest drift and period; T-shape worst	Mid-rise only
[22]	MRF vs dual system	7	Pushover, ETABS; quantities	UBC 97, IBC 2021	Dual: much smaller displacement and more economical	One building
[25]	Core, corner and peripheral walls, sloping ground	G+10	Response spectrum, ETABS	IS 1893:2016	Peripheral best; roof displacement 118.6 to 74.5 mm	Sloping site
[26]	Wall layouts in T-shaped plan	-	Response spectrum	IS 1893:2016	Higher modal participation, lower eccentricity best	Irregular plan
[10]	Ductile MRF vs internally braced RC frame	4 (scaled panel)	Cyclic tests	ACI 318-02	Braced: stiffness about 2.5 times; ductility 1.9 vs 3.0	Two specimens
[27]	Concentric bracing retrofit	3	Nonlinear dynamic, several records	-	Brace distribution over height affects performance	Nonductile, low-rise
[5]	Three bracing layouts, two sizes	8	Pushover, SAP2000 (2D)	-	Period reduced 65%; maximum drift reduced 77%	2D, pushover only
[4]	Walls, cross and inverted-V bracing at open ground storey	G+7	Pushover, ETABS	-	Drift reduced 96% (walls), 70% (cross), 64% (inverted-V)	Soft-storey case
[28]	Bracing, jacketing, infill walls	4	Pushover, time-history	IS 1893 (Zone IV)	Walls largest gains; bracing balanced	Retrofit, low-rise
[29]	X, V and zipper bracing, steel caging	5	Pushover	RPA 2003 reference	Capacity 3.4 (X), 2.3 (zipper), 2.02 (V) times	Pushover only
[30]	Core, outrigger, belt and cap trusses	32	Response spectrum, ETABS	-	Outrigger with belt truss best; optimum near storey 16	Linear
[31]	Wall-beam vs Vierendeel outriggers	40	Time-history, MIDAS-Gen	-	Best single outrigger near 0.45 H; base moment reduced 31.5%	Single record
[32]	Conventional and virtual outriggers	40	Nonlinear time-history, ETABS, 11 records	-	Second outrigger best near 0.6 H; drift reduced 46.3%	One geometry
[33]	Outrigger and belt truss, braced core	30, 45, 60	Nonlinear time-history and spectral	-	Proposed layout reduced roof and inter-storey displacement	Abstract-level detail
[34]	RC and BRB cores, outrigger levels	24, 48	Nonlinear time-history, ETABS, 5 sequences	Turkish	Benefit depends on metric; some layouts increased damage	2D, no torsion

A dash (-) indicates a value not reported in the source or not recorded in this review. H: total building height. Values apply only to the original buildings and baselines.

TABLE II. CONSISTENCY OF REPORTED FINDINGS BY RESPONSE PARAMETER

Parameter	Consistent finding	Conditional or divergent finding	Main source of divergence
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Parameter	Consistent finding	Conditional or divergent finding	Main source of divergence
Fundamental period	Shortened by walls, bracing and outriggers [5], [20], [21], [30], [31], [34]	Magnitude ranges from about 17% for core walls in a G+15 frame [20] to about 65% for bracing in a 2D eight-storey frame [5]	Height, 2D or 3D model, stiffness modifiers, baseline
Displacement and drift	Reduced relative to the bare frame or the core alone [4], [19], [20], [25], [28], [32]	Best wall location: core [23], [24], corner [20] or perimeter [25]; second-outrigger level [31], [32]	Metric chosen, torsion and plan shape, method of analysis
Base and storey shear	Stiffer and heavier systems generally attract larger forces; infill raised base shear [17]; newer code raised base shear [22]	Largest storey shear in the frame without walls under one record [20]; walls relieved frame members [22]	Record-specific response; scaling of results rarely stated
Storey stiffness	Walls gave the largest first-storey stiffness gain, then cross and inverted-V bracing [4]; braced panel about 2.5 times stiffer [10]	Effect of local stiffness at outrigger levels on drift distribution seldom quantified [31], [33]	Stiffness profiles rarely reported
Ductility, R and damage	R depends on configuration, infill and zone [17], [18]; higher R raises ductility demand [16]	Bracing raises strength but lowers ductility [10], [29]; outriggers can increase a damage index [34]	Nonlinear models, record suites, damage definitions
Cost and quantities	Dual system more economical than MRF in one case [22]	Rarely reported for bracing and outriggers	Few studies

First, the systems have been studied at different heights. Bracing studies lie between three and eight storeys, outrigger studies between 24 and 60 storeys, and wall studies span the widest range, from three to fifty storeys. Within the band of twelve to twenty storeys shaded in Fig. 3, only wall and dual systems are represented [18]–[21].

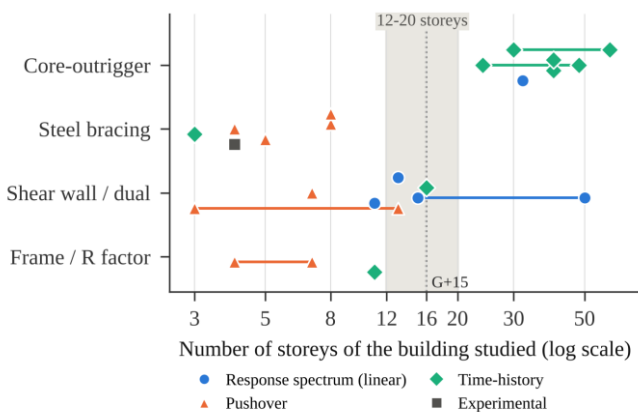


Fig. 3. Reviewed studies by lateral system, building height and analysis method. Lines join the smallest and largest building in a study; the shaded band marks twelve to twenty storeys and the dotted line sixteen storeys (G+15). Studies whose storey count was not confirmed [23], [24], [26] are omitted.

Second, the method follows the system: bracing has been studied mainly by pushover analysis, outriggers mainly by time-history analysis, and walls mainly by response spectrum analysis. A comparison of systems assembled from different studies therefore confounds the effect of the system with the effect of the method. Third, the baseline differs. Reductions are reported relative to an open ground storey [4], a bare frame [5], [20] or a core without outriggers [32], so the percentages are not commensurable even where the response measure has the same name. Fourth, the codes differ: Indian [16], [20], [23], [25], [26], [28], Eurocode-based [19], Egyptian [17], [18], United States-based [10], [22] and Turkish [34], with one study comparing four codes [24]. Period and displacement are reported almost everywhere, whereas storey stiffness profiles, the share of shear carried by the frame in dual systems and whether response spectrum results were scaled are reported only occasionally.

VI. SYNTHESIS OF RESEARCH FINDINGS

Four conclusions are well supported, although the second and third rest on a narrower range of buildings than the first. Adding walls, bracing or a core with outriggers to an RC frame

shortens its period and reduces its displacements and drifts. Where walls and bracing were compared directly, walls gave the larger increase in stiffness and the larger reduction in drift [4], [28], while bracing achieved substantial gains with little added mass and a better balance between strength and deformability [28], although with lower ductility than a ductile moment frame [10]. In tall core buildings a single outrigger near mid-height is efficient in controlling drift [30], [31]. The response reduction factor depends on configuration, infill and seismic zone [16]–[18].

Other conclusions are conditional. The best wall location depends on the response measure and on the importance of torsion. The effect of stiffening on base shear depends on added mass, on the position of the period on the spectrum and on whether the results were scaled to the empirical period. The effectiveness of outriggers in buildings below about twenty storeys has not been established. The reported percentage reductions describe particular buildings and baselines and should not be used to rank systems across studies. Finally, the relative ranking of all four systems in one building, the share of shear carried by the frame in each, and the interaction of that ranking with the base-shear scaling of IS 1893 (Part 1):2016 remain unresolved.

VII. RESEARCH GAPS AND FUTURE DIRECTIONS

Table III lists the gaps that follow from the review, why each matters, and how future work could address it.

TABLE III. RESEARCH GAPS AND POSSIBLE APPROACHES

Gap	Why it matters	Possible approach
G1. No controlled comparison of frame, wall, braced and core-outrigger systems in one building	Percentages from different studies are not commensurable	Same frame, loads, mass source, R and scaling; change only the lateral system
G2. No bracing or outrigger studies found at 12 to 20 storeys (Fig. 3)	Mid-rise buildings are common; outrigger efficiency at low slenderness is unknown	Parametric studies of storey count, outrigger level and brace size
G3. Modelling and scaling assumptions seldom reported	Results cannot be reproduced or compared	Report R, scaling factors, stiffness modifiers, mass participation and diaphragms
G4. R not established for braced RC frames [10] and seldom discussed for core-outrigger systems	R changes the design force of every model	R sensitivity cases; pushover-based estimation of R [17], [18]
G5. Single-record time-history analyses; directional effects [8]	Conclusions may be record-specific	Record suites and incidence-angle studies

Gap	Why it matters	Possible approach
G6. Linear measures only; little on ductility, damage or cost	Lower drift is not a proportionally lower risk	Modal pushover and nonlinear time-history analysis with quantity estimates [22], [36]
G7. Torsion, soil flexibility, brace connections and infill seldom modelled	These can change the ranking of systems	Three-dimensional irregular models, flexible base, connection models [7]

The first author's ongoing dissertation is designed to address gaps G1 to G3 for a regular G+15 RC building, 20 m by 15 m in plan and 51.2 m high, in Zone V on medium soil. The four systems of Fig. 1 share a common frame, common gravity loads and a constant R , and they are to be analysed by modal and response spectrum analysis to IS 1893 (Part 1):2016, with a sensitivity case using a reduced R for the braced and outrigger models. The problem has been defined and the use of the software checked against analytical benchmarks, but the comparative analysis has not yet been carried out, and no results from it are reported or implied in this paper. Gaps G4 to G7 lie largely outside its linear scope and are left to nonlinear follow-up work.

VIII. ENGINEERING IMPLICATIONS

The reviewed evidence suggests several points for analysis and design practice, subject to the limitations already noted.

- A lateral system should be selected on several criteria together, namely drift compliance, displacement, the distribution of stiffness over the height, added weight and base shear, the frame share and cost, rather than on a single response quantity [22].
- Wall layouts should be checked for torsion as well as for translational stiffness; the reviewed studies indicate that the most effective layout changes when torsion is significant [25], [26].
- Braced RC frames require explicit attention to the additional column axial forces, the brace-to-concrete connections and the reduced ductility [10], [29].
- Outrigger levels should be checked for vertical stiffness irregularity and for diaphragm stiffness, and their location reconciled with architectural constraints [6], [32].
- Comparative studies should report R , base-shear scaling, stiffness modifiers, mass source and diaphragm assumptions so that their results can be compared and reproduced.
- Reductions in elastic displacement do not by themselves demonstrate a proportional reduction in damage or risk; that requires nonlinear assessment [7], [34].

IX. CONCLUSION

This review compared published research on four lateral load-resisting systems for multi-storey RC buildings: moment frames, frames with shear walls, frames with steel bracing, and cores with outriggers and belt trusses. The evidence consistently shows that each stiffening system shortens the period and reduces displacement and drift relative to a bare frame, that walls stiffen more than bracing where the two were compared directly, that a single outrigger near mid-height is

efficient in tall core buildings, and that the response reduction factor depends on configuration. The evidence is weaker or contradictory on the best location of walls and of multiple outriggers, on the effect of stiffening on base shear, and on any ranking of the four systems, because the studies differ in height, code, baseline and method. The most important gaps are the absence of a controlled comparison of all four systems in the same building, the lack of bracing and outrigger studies in the range of twelve to twenty storeys, incomplete reporting of modelling and scaling assumptions, and the reliance on linear measures without nonlinear verification. Closing these gaps would give designers of mid-rise buildings in high seismic zones a consistent basis for choosing among the systems.

ACKNOWLEDGMENT

The authors thank the Department of Civil Engineering, Chhotubhai Gopalbhai Patel Institute of Technology, Uka Tarsadia University, for the facilities and support provided for the M.Tech dissertation from which this review is drawn.

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