© JUL 2026 | IRE Journals | Volume 10 Issue 1 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV10I1-1719783

Dynamic Analysis of High-Rise Structures with Combined Shear Wall, Bracing, and Damper Systems Under Lateral Loading: A Review

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Abstract- ***The growth of high-rise construction in seismically active regions has made the control of the lateral response of buildings a governing design concern. Reinforced-concrete (RC) shear walls, steel bracing, and supplemental dampers are the three dominant strategies used to resist earthquake and wind actions, and increasingly they are combined into hybrid systems whose behaviour is evaluated numerically in finite-element platforms such as ETABS.This paper reviews the state of the art on the dynamic analysis of high-rise structures that combine shear walls, bracing, and damper systems under lateral loading. It compares the working mechanisms, analysis methods, and reported performance of these systems, and identifies the technologies and design methods that currently dominate the field.Across the reviewed studies a consistent pattern emerges: stiffness-based devices (walls and bracing) shorten the fundamental period and reduce displacement but attract larger inertial forces, whereas velocity-dependent dampers reduce drift, member forces, and floor acceleration without a comparable increase in stiffness. Hybrid wall–brace–damper systems combine these benefits, and response-spectrum and non-linear time-history analysis, together with the P-Delta effect, are the standard evaluation tools. Recent work is moving from passive devices towards semi-active, adaptive, and machine-learning-assisted design.Priorities identified include soil–structure-interaction-aware design, optimal placement and sizing of dampers, life-cycle and resilience-based cost assessment, and data-driven optimisation of hybrid configurations. These directions frame the motivation for the detailed comparative study reported subsequently by the authors.***

Keywords—High-Rise Buildings, Shear Wall, Steel Bracing, Fluid Viscous Damper, Lateral Load, Seismic Response, Energy Dissipation, ETABS, Response-Spectrum Analysis, Hybrid Lateral System

I. INTRODUCTION

1.1 Overview of the Topic

Urbanisation has been rapid and land in the dense city centres has been limited, resulting in a continuous rise in buildings heights. The lateral forces of the earthquake and wind dominate the design of the main structural system as buildings grow taller. The lateral control of the displacement of a tall building, the inter-storey drift and the internal forces generated due to dynamic excitations are the main structural challenges [1]. The impact of lack of lateral resistance is very big: earthquakes are still one of the most destructive natural hazards, and the collapse of buildings (not the shaking of the ground) is the major cause of casualties as shown in Fig. 1.

Fig. 1. Typical earthquake-induced damage to a building, illustrating the consequence of inadequate lateral-load resistance.

There are three general methods of building seismic control: The first principle involves the stiffening and strengthening of the building elements by reinforced-concrete (RC) shear walls, steel or RC bracing; the second principle applies the principle of dissipating the input energy through the use of supplemental

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damping devices; and the third principle is the elongation of the fundamental period through the use of base isolation. While very effective for stiff low- and mid-rise structures, base isolation is not generally suitable for tall, flexible buildings and for buildings located on soft soils; for tall construction, therefore, the practical option is either stiffness-based or energy-dissipation systems or a combination of the two [2]. These systems are proportioned as per the national standards in seismic design practice, the national standards for Earthquake loading (IS 1893) [3] for RC design (IS 456) [4] and for other loading (IS 875) [5] in the Indian context.

Fig. 2. Classification of the principal seismic-response-control strategies for high-rise structures.

To understand the three families, the combined shear-wall, bracing, and damper system, the focus of this review, is placed in context in Figure 2, showing both stiffness-based and energy-dissipation based components. Any such system has a dynamic behaviour which is controlled by the equation of motion of a multi-degree-of-freedom structure in the presence of ground acceleration in the familiar form of Eq. (1).

$$M\,\ddot{x}(t) + C\,\dot{x}(t) + K\,x(t) = -M\,r\,\ddot{x}g(t) \quad (1)$$

In this equation, M and C are the mass and damping matrices, respectively, x is the vector of relative displacements, r is the influence vector, and $\ddot{x}g$ is the ground acceleration. The 3 control strategies influence the different terms of Eq. (1): the stiffening systems change K, the energy-dissipating devices add C, and the base isolation changes the M-associated period and K. This is a very basic observation from which the comparative discussion in the present review is drawn.

1.2 Importance and Motivation

Much of the Indian subcontinent is in the region of high seismic hazard, along with several of the world's fastest-growing cities. With the growth of high-rise construction in these areas, the engineering economy consideration of selecting an efficient, economical, and architecturally appropriate lateral-load-resisting system becomes a public safety issue as well. Shear walls provide large in plane stiffness, and are the natural backbone of a tall RC building; bracing provides a light path to additional stiffness; and dampers provide a path to limiting response without additional seismic forces. They both have their own advantages and disadvantages, and so are studied not alone, but in the context of their combination in a growing body of work [1, 2].

There are two reasons to provide a focused review. First, there is a body of literature on individual systems that is well-developed but disjointed and the comparative behaviour of combined wall–brace–damper systems has not been gathered under the umbrella of today's dynamic-analysis tools. Second, the landscape is changing quickly: Passive damping is being replaced by semi-active and adaptive damping; machine-learning approaches are starting to be used to guide device placement and sizing. Thus, it is opportune to link these existing findings together with these new trends and directions, and the detailed comparative study follows as reported by the authors.

1.3 Objectives of the Review

With this background, the following goals of this review are set: (i) summarise how shear walls, bracing, and dampers are used as lateral-load-resisting systems for high-rise structures in their working mechanisms; (ii) survey the analysis methods and the software tools used to evaluate their dynamic response; (iii) present a comparative summary of representative studies and the performance reported; (iv) identify current trends and emerging technologies such as semi-active devices and data-driven design; and (v) set out the main challenges, research gaps, and future directions. The review is structured in this way, starting from the individual systems and their analyses, a comparative summary, and discussion of current trends, challenges and future directions.

II. LITERATURE REVIEW

This section summarizes the available literature on the three individual lateral-load-resisting systems (shear walls, bracing, and dampers) and their combination in hybrid systems, the methods used for analysis of the systems, and a summary of a representative number of research studies. The systems are shown schematically in figure 3, inserted in a framed high rise structure.

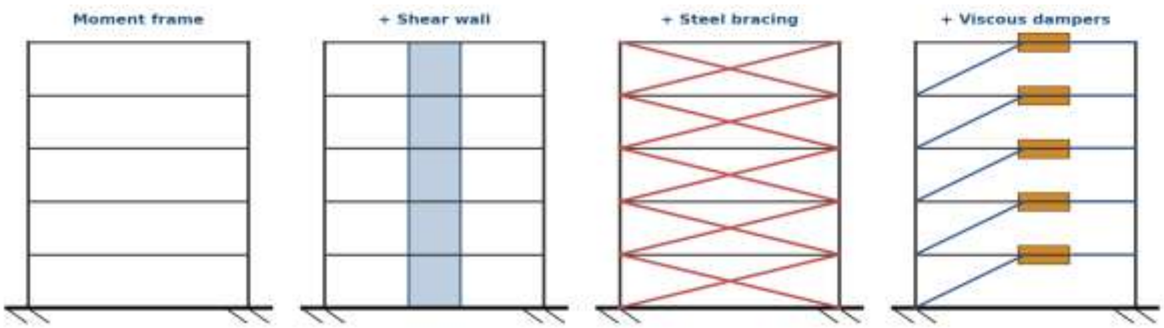

Fig. 3. Schematic of a framed high-rise structure with, from left to right, a bare moment frame, an added shear-wall core, steel bracing, and viscous dampers encased in braces.

2.1 Reinforced-Concrete Shear Walls

Reinforced-concrete shear walls are vertical walls that transfer lateral loads predominantly by in-plane shear and flexure, and act as a slender cantilever to resist overturning moment and transfer it to the foundation. They are very stiff in the plane of the roof and are able to take most of the lateral load in a tall building, which leads to a marked reduction in roof displacement and inter-storey drift (shown in Fig. 4). Another topic that is common in the literature is the sensitivity the response is to the location and shape of the wall. Ali and Aquil evaluated multi-storey residential RC buildings with shear walls located at various locations, and concluded that the deflection and storey drift of the shear wall are significantly affected by its location within the building, with the symmetric and core arrangements showing the best performance [6]. Chittiprolu and Kumar emphasized the importance of shear walls in plan and vertically irregular high-rise buildings and demonstrated that shear walls have a significant effect on the seismic performance of the plan and vertical irregularity frames [7]. Agrawal and co-workers investigated the effect of various shear-wall locations on a high rise irregular floor-plan building and showed that the torsion was minimized when the centre of mass was located at the centre of rigidity in the peripheral and core locations [8]..

Fig. 4. Reinforced-concrete shear wall integrated into a building frame as the primary lateral-load-resisting element.

The message these studies convey is that use of a shear-wall core is an efficient and economical way to provide a backbone for a tall RC structure, but that the benefit of having a shear-wall core relies heavily on the symmetric placement of the core walls and that if the placement is not symmetric, torsional irregularity can offset gains in stiffness.

2.2 Steel Bracing Systems

Steel bracing is a lightweight way to provide a frame with lateral stiffness and strength, which acts as a brace against applied load by means of the pull of the steel diagonal members. It looks nice to new construction as well as seismic retrofit of existing RC frames, where it is not practical to add heavy walls. Alashkar and colleagues [9] compared the seismic strengthening of RC buildings using steel bracing and concrete shear wall, and concluded that the core wall provided the highest stiffness while X-bracing had the lowest added bending moment on the surrounding frame. Badoux and Jirsa showed that steel bracing is an effective method for seismic retrofit of RC frames [10] and Youssef and his colleagues demonstrated that steel bracing in RC frames with concentric internal steel bracing provided better strength and energy dissipation capacity compared to their bare frames [11].

The arrangement of bracing has a significant impact on its effectiveness. The common ones are shown in figure 5. Singla and co-workers investigated a G+10 building in a variety of different schemes of the combination of shear walls and bracings, and concluded that the scheme with cross (X) bracing had the lowest storey shear among the schemes analysed [12]. Bracing stiffness reduces the fundamental period, and Ahmed and co-workers suggested better approximation formulas for the fundamental period of braced-frame systems in irregular steel structures, where code formulae can overestimate the period for braced structures [13].

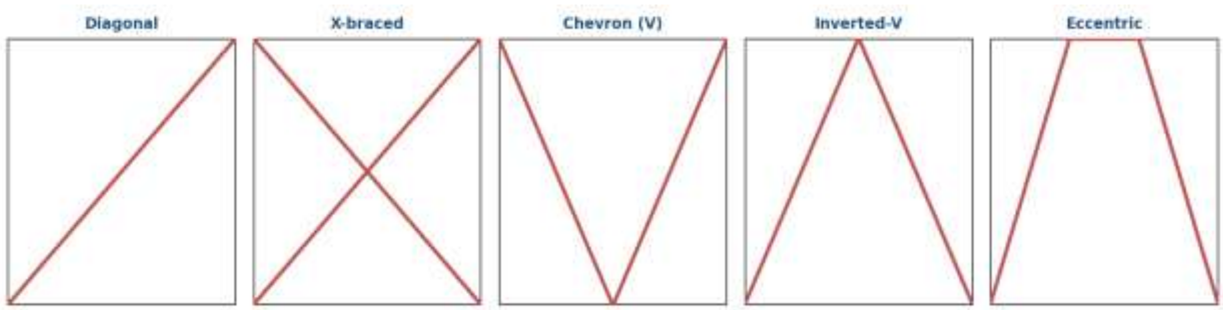

Fig. 5. Common steel bracing configurations: diagonal, X-braced, chevron (V), inverted-V, and eccentric.

A major area of recent research is on the buckling-restrained brace (BRB), which buckles symmetrically in both tension and compression and, therefore, does not lose strength when buckled in compression. Alborzi et al. made a comparison between conventional and hybrid BRB and found that hybrid core has lower residual deformation as compared to the conventional BRB but has achieved high energy dissipation [14]. Sabbagh-Yazdi and co-workers compared the performance of portal steel frames braced with steel, glulam timber and timber–steel BRBs, highlighting the increasing variety of bracing technologies [15]. The BRB thus exists between the unyielding stiffening systems and the hysteretic energy-dissipation systems, which is also emphasized in Section 4.

2.3 Supplemental Damping Systems

A part of the seismic input energy is dissipated by using supplemental damping devices, which do not necessarily increase the stiffness. They can broadly be classified into velocity dependent devices (fluid viscous and viscoelastic dampers), displacement dependent devices (metallic-yielding and friction dampers), and motion based devices (tuned mass and tuned liquid dampers). The idealised force–displacement behaviour of these families is compared in Figure 6. The fluid viscous damper (FVD) is the most popular damper, dissipating energy over a wide frequency range, and functioning at small displacements, while, for the pure viscous type, it introduces very little stiffness which does not increase the seismic force that is attractive to the structure [1, 16].

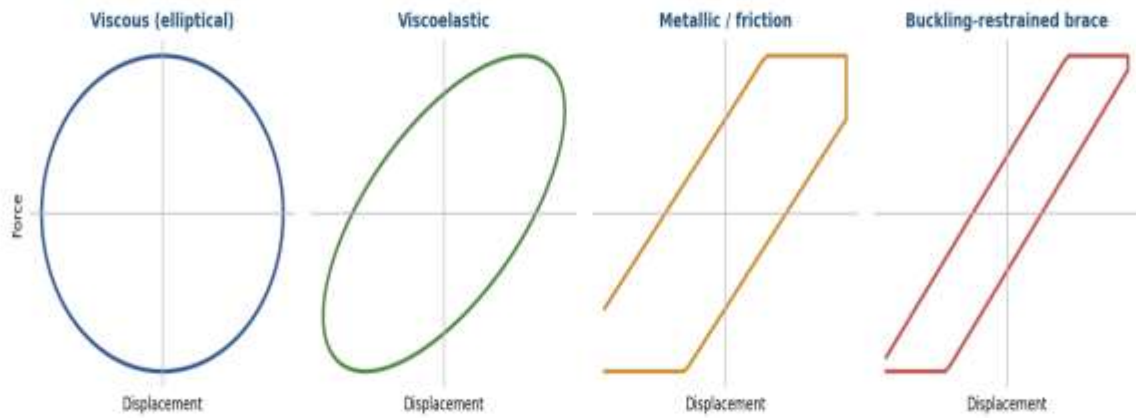

Fig. 6. Idealised force–displacement response of damper families: velocity-dependent (viscous, viscoelastic) and displacement-dependent (metallic/friction, buckling-restrained brace).

A non-linear fluid viscous damper has a force developed by a velocity power law, similar to that used in most finite-element packages, as shown in Eq. (2):

$$FD = C\,|\dot{x}|\alpha\ sgn(\dot{x}) \quad (2)$$

where FD is the damper force, C is the damping coefficient, $\dot{x}$ is the relative velocity across the device, α is the velocity exponent (α = 1 for linear damper; α < 1 for the non-linear devices that are typically preferred in seismic applications), and sgn represents the signum function. The damper force is also velocity dependent, thus the peak of the damper force occurs at a time when the internal member forces are at their peak, which is due to displacement — a characteristic that is ideal for damping a flexible structure [2], [16].

The technology is well-developed, with in-depth reviews confirming its readiness. De Domenico and co-workers reviewed the design, location, and dimension of fluid viscous dampers and explained the different approaches in terms of energy balance, showing that energy-based approaches offer the best promising path towards an optimal damper distribution [1]. Lee and Taylor described how the viscous damper evolved from military use to civil applications, and predicted many of today's trends [16]. On the application level, Pathan et al. used a "friction damper coupled with a shear wall to control response of asymmetric building and stated that the displacement was drastically reduced when the devices were located at the periphery of the building [17]. Riaz and co-workers found large reductions in drift and bending moment by introducing non-linear viscous dampers to an existing RC building [18] and Sharma and co-workers studied the seventeen viscous-damper configurations and vertical damping-coefficient distributions, concluding that placement and cost jointly determine the most effective choice [19]. Esfandiyari and co-workers investigated the protection of structural and non-structural elements with viscous dampers [20] while Zhang and co-workers presented non-linear response analysis of RC frames retrofitted with viscous dampers [21] and Kumar and Kumar performed analysis of an irregular building with RC diaphragm and equipped with fluid viscous dampers [22]. For the smart retrofit of irregular joints in traditional buildings, Qi and collaborators adopted the viscous dampers technology and applied it to heritage buildings [23].

The energy argument for supplemental damping is summarized in the seismic energy-balance equation, Eq. (3):

$$EI = EK + ES + EH + ED \qquad (3)$$

The seismic input energy (EI) and the energies of the kinetic (EK), recoverable strain (ES), structural hysteretic (damage) (EH), and supplemental damping (ED) are indicated. The goal of the design of a damping system is to maximize E. EH is a hysteretic term that corresponds to inelastic deformation of the structure itself, and is to be minimized. This division is depicted in the schematic of figure 7.

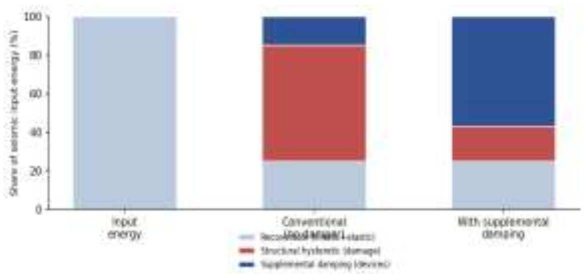

Fig. 7. Conceptual partition of seismic input energy: supplemental damping increases the device-dissipated share and reduces the damaging structural-hysteretic share.

2.4 Combined (Hybrid) Systems

The three systems are increasingly used in combination as each system complements the other and has advantages. The overall deflected shape and overturning moment is provided by a shear-wall core; bracing provides stiffness as needed; and dampers provide control of drift and provide control of member forces without imposing additional seismic force. Explicitly considering the soil–structure interaction, Kontoni and Farghaly investigated the benefits of using tuned mass dampers, shear walls, and bracings to increase the seismic resistance of RC and steel high-rise structures, and demonstrated that the soil surrounding the foundation can significantly affect the performance of each system. The shift towards resilience based hybrid design was demonstrated by Kent, Zhong and Christopoulos who suggested a steel flexure and shear yielding base mechanism for the seismic strengthening of RC core wall high-rise structures [25]. Vishal et al. [26] studied various structural systems of an irregular multi-storey building and found that both the dual system and the braced system significantly reduced the top-story drift as compared to the bare frame [26].

These studies have demonstrated that combined systems can be superior to any single system but they have also demonstrated that the interactions among the components — and between the structure and the soil that supports it — are complicated and dependent on the configuration and that detailed dynamic analysis is necessary for each of these.

2.5 Analysis Methods and Tools

The three procedures are the dominant ones in the seismic analysis of the analyzed structures. The equivalent static lateral force method applies a code-based base shear to the height of the building, and only applies to regular, low-rise buildings. The response-spectrum method integrates the peak modal responses from a design acceleration spectrum and is able to encompass the multi-modal response behaviour of tall buildings. The non-linear time-history method involves numerically solving the equation of motion under recorded or simulated ground motions and is the most complete (but also most complicated) description of the response. The response-spectrum method is almost always used in conjunction with a second-order (P-Delta) method to account for the increase in demand from gravity loads on the laterally displaced structure, and is the most economical and accurate method for tall buildings.

The code-based base shear that seeds these analyses is obtained, in the Indian standard, from Eq. (4) and Eq. (5):

$$VB = Ah\,W \qquad (4)$$

$$Ah = \frac{Z\,I\,Sa}{(2\,R\,g)} \qquad (5)$$

VB is the design base shear, W the seismic weight, Ah the design horizontal seismic coefficient, Z the zone factor, I the importance factor, R the response reduction factor and Sa/g the spectral acceleration coefficient, which is taken from the design spectrum at the fundamental period. Serviceability of the design is then mainly governed by the inter-storey drift ratio, Eq. (6):

$$DRi = \frac{(\delta i - \delta i{-}1)}{hi} \quad (6)$$

where δi is the lateral displacement of the storey i and hi is the height of the storey i, the ratio is usually limited to a small fraction of the height of the storey in the codes. The finite-element platform most commonly used in the reviewed studies to construct the model, to incorporate the spectrum, and to derive these quantities is ETABS while the platform most commonly used is STAAD.Pro and SAP2000 and similar packages also were present. The results reported are generally comparable as the modelling approach is consistent throughout the studies by creating rigid floor diaphragms, shell elements for walls and slabs, frame elements for beams and columns, and link elements for dampers.

2.6 Comparative Summary

Table 1 provides a summary of the studies that were reviewed, making the following points: the lateral system analyzed, the analysis tool and method used, and the main finding. The table illustrates the evolution from single wall-systems study to dual wall- and bracing systems and then to the recent studies using damper systems and interaction-aware studies, and it demonstrates the dominance of ETABS and response-spectrum or non-linear time-history analysis as the analyses performed.

Table 1. Comparative summary of representative studies on lateral systems for high-rise structures.

Study	Lateral system	Tool / method	Principal finding
Ali & Aquil [6]	RC shear wall (locations)	Seismic-coefficient	Wall position governs drift; core best
Alashkar et al. [9]	Shear wall vs. bracing	Static analysis	Core wall stiffest; X-brace least moment
Youssef et al. [11]	RC frame + concentric brace	Non-linear analysis	Bracing raises strength and energy dissipation
Singla et al. [12]	Walls + bracing (G+10)	STAAD.Pro	Cross-bracing gives lowest storey shear
Pathan et al. [17]	Shear wall + friction damper	ETABS	Peripheral dampers cut displacement most
Riaz et al. [18]	RC frame + non-linear FVD	ETABS / NLTHA	Large drift and moment reduction
Sharma et al. [19]	FVD (17 configurations)	ETABS / FNA	Placement and cost jointly govern choice
Kontoni & Farghaly [24]	Wall + brace + TMD + SSI	Finite element	Soil interaction alters system efficiency
Vishal et al. [26]	Dual / braced systems	ETABS / RSA	Dual system cuts top drift substantially

III. CURRENT TRENDS AND DEVELOPMENTS

3.1 Recent Advancements

The most salient change in the recent literature has been from passive devices with a predetermined response to semi-active, adaptive devices that adapt their response to the strength of the excitation. Zoccolini and co-workers summarized this evolution in the case of fluid viscous dampers, from classical passive dampers, to semi-active electrorheological, magnetorheological and variable-orifice dampers, and to adaptive devices that adjust their behavior by adapting their own response using a purely mechanical system without external energy [2]. Passive devices are tuned to a single design earthquake and are limited in that they cannot act optimally on the more common and less intense earthquakes that affect non-structural components; semi-active and adaptive devices attempt to extend the range of intensities which may cause damage to the device.

The evolution of the field is summarised in figure 8. Passive dampers and bracing were first studied in early work, most of which focused on the optimal placement and sizing of these devices, while the majority of the work in the following periods were based on semi-active and adaptive hardware, and the latest work are based on data-driven and machine-learning methods in designing the devices. For instance, Kazemi and co-workers were able to predict seismic response and performance of RC buildings using machine-learning models, which provided a way to quickly assess the performance of many configurations without conducting a repeated non-linear analysis [27]. These surrogate models can be particularly useful for hybrid wall–brace–damper systems, where the large design space can be costly to traverse by direct simulation.

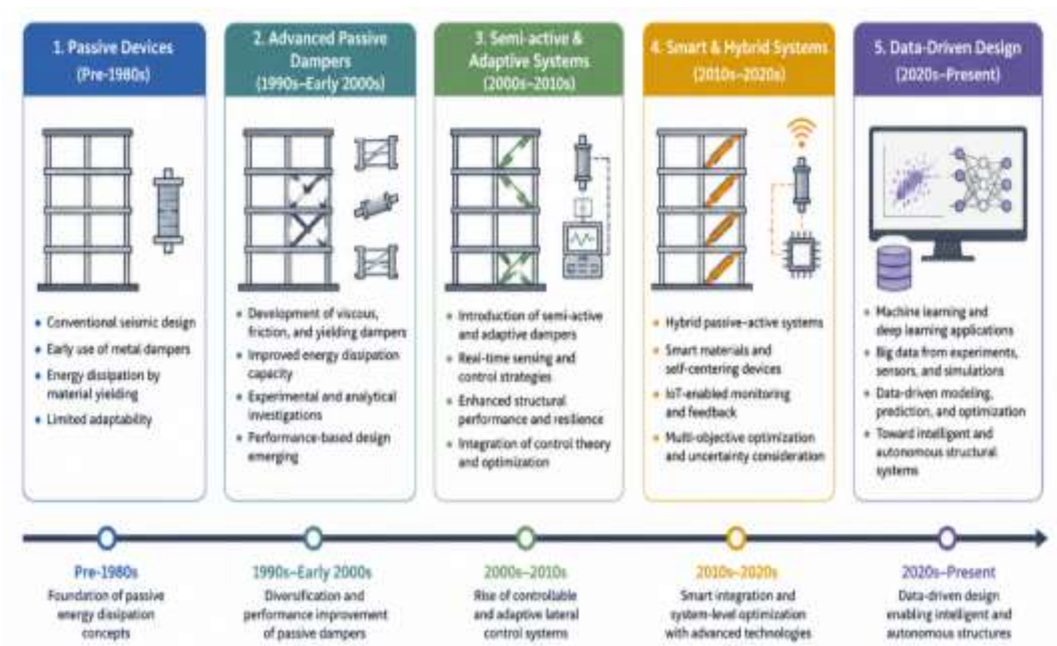

Fig. 8. Evolution of research on lateral systems and dampers, from passive devices to data-driven design.

3.2 Emerging Technologies

There are a number of emerging technologies appearing in recent literature. The Rheological dampers (semi-active) are those whose apparent viscosity changes in milliseconds due to a magnetic or electric field, and which require only a small power supply, making it possible to control the damping force in real-time [2]. The relay principle of the adaptive viscous dampers provides a similar variation with relief valves and multi-stage orifices, but no external equipment. On the bracing side, the buckling-restrained brace keeps evolving; Hariri and co-workers introduced a viscoelastic BRB to add viscoelastic dampers into an inverted-V BRB configuration, which increases post-elastic stiffness and reduces the drift concentration, induced by P-Delta effects, that limits the height of conventional braced frames in high-Seismicity regions [28]. This convergence of the two energy paths described in Section 2 is typified by this hybridisation of bracing and damping in a single device.

The second theme that has come to light is the explicit representation of soil–structure interaction (SSI) in hybrid systems evaluation. This assumption of a solid base is not valid for the increasing installation of tall buildings on soft or reclaimed ground, and as is illustrated by the studies of Kontoni and Farghaly [24] the competition of lateral systems can be altered with SSI. A third theme is resilience- and performance-based design, where the goal is not to stop the collapse but to reduce the damage caused and to allow for fast re-occupancy, for example with self-centring braces and dampers that limit the residual drift [25], [28].

IV. CHALLENGES AND LIMITATIONS

4.1 Technical Issues

Although the individual technologies are well developed, there are a number of technical challenges that hinder the confident design of combined systems. The optimum location and size of dampers has yet to be fully determined, the solution is dependent on the location of the dampers with respect to the total height of the building, and the number of possible layouts increases combinatorially as the number of dampers increases, making it difficult to consider all possible combinations [1, 19]. Fluid viscous dampers can dissipate energy as heat, and the increase in internal temperature under long-duration or large amplitude motions can lead to a decrease in the viscosity of the fluid and change the device response, which may not be represented in the design level models [2]. The problem of residual drift is not entirely eliminated by buckling-restrained and self-centring braces, although their contribution is to reduce strength and stiffness degradation upon buckling in compression load for conventional steel braces, which makes them susceptible to aftershocks [14, 28]. In shear-wall systems, the answer is very much dependent on the location of the walls, and the placement of poor quality walls can cancel out any benefits [7] and [8].

Sources of uncertainty at the modelling level are also the idealisations that enable the results of the reviewed studies to be compared: rigid diaphragms, linear-elastic materials in the context of response-spectrum analysis, and a fixed base. For slender high-rise buildings, the P-Delta effect should always be considered, as a first order analysis would underestimate the damping in the lower floors of the building, and this interaction is not necessarily studied.

4.2 Research Gaps

Based on the literature reviewed several gaps came up. Most comparative studies are based on comparing one system to another using a single benchmark building, and very few studies compare the three system combinations (shear walls, bracing, and dampers) in a single structure based on a consistent analysis protocol. Second, although soil–structure interaction can influence the relative performance of competing systems [24] it is often ignored. Third, comparisons of cost are generally based on the quantity of materials and not the cost of the damper hardware, damper foundation, or the life-cycle repair savings realized from reduced drift. Fourth, it is not always the case that the optimal placement and sizing of dampers in a hybrid system is analysed with rigorous optimisation; most studies test a few configurations by trial and error instead of systematically searching the design space for the optimal configuration [19, 27]. These gaps represent the space for continued research, including the authors' comparative study.

V. FUTURE RESEARCH DIRECTIONS

5.1 Potential Improvements

The above identified gaps are followed by several improvements. Energy-based optimization of damper placement and sizing, and more recently machine-learning surrogate, could bring out greater performance from limited amount of devices [1] [27]. An explicit representation of soil–structure interaction (SSI) in the design of the hybrid systems would eliminate one important source of uncertainty, and in certain cases, alter the preferred configuration [24]. If the extension of cost comparisons to a full life-cycle basis could be done, that is, the cost of the device hardware, foundation demand, and repair cost avoided due to reduced drift, would put the option of braced versus damped in a more economically balanced position. Lastly, use of the response-spectrum method along with the wider use of non-linear time-history analysis would provide a more comprehensive understanding of the inelastic response of combined systems to realistic ground motions.

5.2 Opportunities for Future Work

The field presents other opportunities for incremental improvement. When combining bracing and damping into single hybrid devices, as demonstrated by the viscoelastic buckling-restrained brace, a new class of bracings is brought up that are both stiffer and damped at the same time [28]. Resilience-based and self-centring systems, which reduce residual drift and allow for prompt re-occupancy, fulfill the structural goal and society's demand for functional recovery following an earthquake [25]. The use of surrogate models trained from simulation data to explore the large configuration space of hybrid systems is the promise of data-driven design, and could render the actual optimisation tractable [27]. The extension of these methods to wind as well as seismic loading — given the fact that tall buildings are often controlled by wind serviceability — would extend the applicability. The comparative study reported by the authors below – which is based on a common high-rise benchmark, and compares combined shear-wall, bracing, and damper systems using response-spectrum analysis and P-Delta analysis in ETABS – falls in this space and is designed to be a step towards the consolidated, comparable evidence that the field currently lacks.

VI. CONCLUSION

6.1 Summary of Findings

This review has compiled the literature available on the dynamic analysis of tall buildings with shear walls, bracings and damper systems under lateral loading. There are three points of conclusion. First of all, the three lateral systems provide the response differently: shear walls and bracing provide stiffness; they shorten the fundamental period, reduce the displacement, but increase the inertial forces; energy-dissipation capacity is provided by velocity-dependent dampers, resulting in a reduction of drift, reduction of member forces and floor accelerations without a corresponding increase in stiffness [1], [2], [16]. Secondly, these mechanisms are complementary and a combination of wall and brace/ damper mechanisms can perform better than any single mechanism but the behaviour of these mechanisms is configuration-dependent and should be carefully analysed in terms of dynamic effects (namely response-spectrum or non-linear time-history; typically performed in ETABS or similar software) [24, 25, 26]. Third, the field is quickly shifting towards semi-active, adaptive, and machine-learning-assisted design and toward resilient targets that seek to mitigate harm instead of simply averting failure [2], [27], [28].

6.2 Key Recommendations

Based on this synthesis, the following recommendations are proposed for design and research of combined lateral systems in high-rise structures:

- The position of a symmetric shear-wall core should be studied to be placed in the centre of mass of a tall RC building to avoid any torsional irregularity [7], [8].
- If minimum material cost and maximum stiffness are critical, the core should be supplemented by concentric steel bracing, preferably in the X configuration, which will attract the lowest additional flexural demand [9] [12].
- For those cases where drift, member forces and floor acceleration control, the core needs to be backed up with fluid viscous dampers (FVD), which should be optimised and not trial and error.
- For slender high-rise buildings a second order (P-Delta) analysis should always be performed in conjunction with analysis of the building dynamics; and soil–structure interaction should be taken into account if the founding soil is soft [24], [28].

Since the structural benefits are split between the two systems and material costs are not always a determining factor [19] [26], the choice between the two should be based on a combined performance-and-life-cycle-cost assessment.

These recommendations are echoed in studies of vertically and plan-irregular structures, which demonstrate that the advantages of walls, bracing and dampers are greatest, and most sensitive to configuration, in those areas where irregularity is focused to produce the greatest demands [29, 30, 31]. The combined consideration of the reviewed evidence demonstrates both the effectiveness of the combination of shear-walls, bracing and damper systems and the need for the ongoing research (including by the authors) to move towards the consolidation, comparison and optimisation of such studies.

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