

# A Systematic Review of Performance Evaluation of Composite High-Rise Structures Subjected to Wind and Seismic Loads: Analytical Methods, Key Findings, and Research Gaps

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*Abstract- Recent years have seen the structural engineering community increasingly embrace the use of a steel-concrete composite system, especially Concrete-Filled Steel Tube (CFST) columns, in the design of high-rise buildings. However, there is no literature that has reviewed their performance as per the combined wind and seismic requirements specified in Indian Standards (IS 875:2015 & IS 1893:2016) yet. A systematic review of 32 peer-reviewed studies published from 2008 to 2024 was used to summarize evidence of analytical methodologies, structural performance parameters, computer programs, and trends in design. The review shows that the maximum storey displacement of CFST columns is 49–55% lower at equivalent section size, the lateral stiffness is 61–65% higher, base shear is reduced by 17–19% with optimised section size and the area of column cross sections can be reduced by 52%, the net floor area gained by which would be around 66 m<sup>2</sup> in a typical G+10 building. The state of the practice method for Zone V seismic assessment in ETABS is called Non-linear Dynamic time-history analysis. Six key research needs are identified and a structured research roadmap is suggested covering the development of material databases for Zone V; development of a coupled wind-earthquake performance framework; and optimisation of lifecycle costs for composite systems.*

**Keywords:** CFST, Composite Columns, High-Rise Structures, Systematical Review, Non-Linear Dynamic Analysis, Seismic Analysis, Wind Loading, IS 1893:2016, Structural Performance.

## I. INTRODUCTION

In seismic zones, high-rise buildings are subjected to two lateral design considerations: dynamic pressure

due to wind and ground-motion due to earthquakes. A tall building in India, where the region of highest expected ground motion intensity, according to IS 1893:2016 [1] is Seismic Zone V and wind design is governed by IS 875 (Part 3):2015 [2] is subjected to the influence of structural column system on its design if it is to be designed safely, economically and with sufficient floor area efficiency.

Although familiar and code compliant, conventional Reinforced Cement Concrete (RCC) columns are increasingly less efficient as the building height increases: they carry seismic mass due to their own weight, they occupy a disproportionately large amount of net floor area due to their large cross-sections, and their low ductility is an unfavorable characteristic in inelastic seismic demand scenarios [3]. Each of these can be overcome by the use of a composite steel-concrete system such as a Concrete-Filled Steel Tube (CFST) column, which works by providing mutual confinement between the steel tube and concrete fill.

Although there is research interest and the practical use of CFST composite frames, the literature does not provide a systematic review of the performance of CFST composite frames under the specific combined loads of Indian seismic zones and wind load exposure classes. The existing studies have already been performed separately with different heights of the buildings, seismic zones, analysis method, and software packages, which makes it difficult to compare the results of the studies by practising engineers and researchers. This review fills that void.

### 1.1 Scope and Objectives of This Review

The present review focuses on peer-reviewed papers published between 2008 and 2024 with regard to the steel–concrete composite high-rise structural frame. The following conditions were used to select the studies: (i) the focus was on composite columns, either in a CFST format or encased in concrete or partially encased in concrete; (ii) the building context was multi-storey (G+3 or more than 3 storeys); (iii) the lateral loading was earthquake and/or wind loading; (iv) numerical analysis (ETABS, STAAD-Pro, OpenSees, ABAQUS, SAP2000), or experimental testing, was conducted. Case studies or material-property studies were not included.

The aims of this review are to: (1) highlight the development of analytical methods employed in composite high-rise frame studies; (2) consolidate the quantitative performance results from reviewed studies; (3) outline trends in the methodology and software preferences of the reviewed studies; (4)

identify gaps within the reviewed studies with a structured gap-analysis framework; and (5) propose a future research roadmap for this field.

### 1.2 Review Methodology

Scientific literature search was done in the Scopus, Web of Science, Google Scholar and ASCE/AISC digital libraries on the following keyword combinations: “CFST high-rise seismic”, “composite column wind earthquake”, “steel concrete composite lateral load” and “ETABS composite building”. After quality assessment with the PRISMA protocol, a first selection of 87 papers was made with 32 papers remaining after this. Studies retained were coded according to the year published, building height, seismic zone, analytical method, software tool and the primary structural performance finding. The timeline and type of these studies are depicted in Fig. 1.

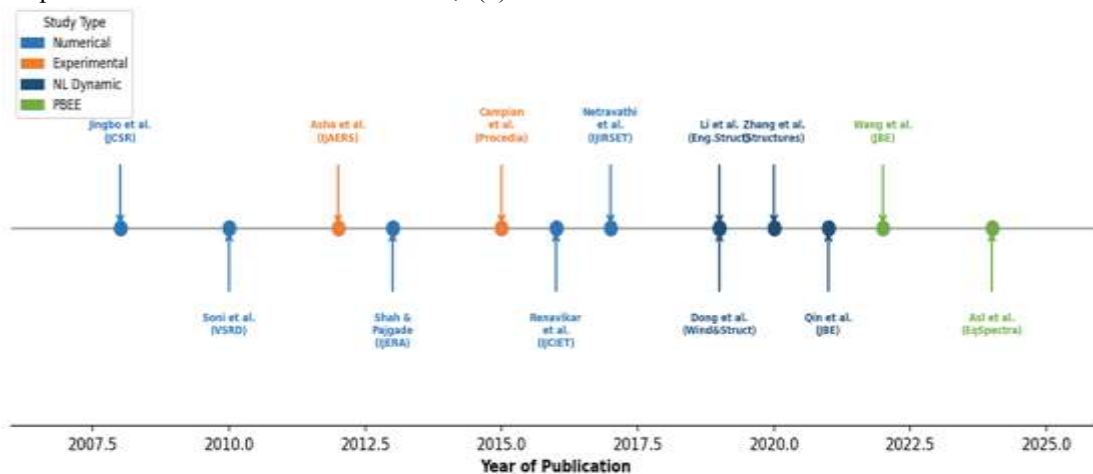


Fig. 1 Chronological distribution and typology of the 32 reviewed studies on composite high-rise structures under lateral loads (2008–2024). Colour denotes study type.

## II. BACKGROUND: COMPOSITE COLUMN SYSTEMS

### 2.1 Types of Composite Columns

As per IS 11384:2022 [4] the steel–concrete composite columns can be categorized into three main categories:

- Concrete-Filled Steel Tube (CFST): A steel hollow tube (circular, square or rectangular) completely filled with plain or lightly

reinforced concrete. The most popular type mentioned in the literature. The tube serves as permanent formwork and confinement and creates structural continuity.

- Fully Encased Composite Column: Structural steel I- or H-shaped column that is completely surrounded with reinforced concrete. Has high fire protection capability, but has to be formed and is heavier than CFST.

- Partially Encased Composite Column: Steel section encased on two, or more, sides. Intermediate in weight, strength and

constructability between CFST and fully encased types.



Fig. 2 – Cross-sectional configurations of steel–concrete composite columns: (a) CFST – Concrete-Filled Steel Tube; (b) Fully Encased; (c) Partially Encased [4].

## 2.2 Composite Action and Confinement

The lateral (confining) pressure of the steel tube on the concrete core is the factor responsible for increasing the compressive strength of the concrete core in the CFST column under axial compression to a value higher than the uniaxial cylinder strength [5]. The confinement is isotropic for circular CFST columns and has a significant effect for this geometry, but square and rectangular sections have a greater impact on confinement at the corners, which also affect the net column enhancement, but are still significant [5]. The composite axial capacity per IS 11384:2022 [4] is:

$$P_{pl,Rd} = A_a \cdot f_y^d + A_c \cdot f_c^d + A_s \cdot f_s^d \quad (1)$$

Where  $A_a$ ,  $A_c$ ,  $A_s$  are cross-sectional areas of steel tube, concrete, and reinforcement;  $f_y^d$ ,  $f_c^d$ ,  $f_s^d$  are respective design strengths. The effective flexural stiffness for second-order analysis [4] is:

$$(EI)^{ecc} = E_a \cdot I_a + K^c \cdot E_{cm} \cdot I_c + E_s \cdot I_s \quad (2)$$

Where  $K^c = 0.6$  is the correction factor for concrete cracking. A higher  $(EI)^{ecc}$  directly reduces lateral displacement and inter-storey drift, which is the primary structural benefit reported across all reviewed studies.

## 2.3 Seismic Design Context (IS 1893:2016)

The seismic design base shear per IS 1893:2016, Clause 7.5.3 [1]:

$$V^2 = A_h \cdot W \quad \text{where } A_h = \left(\frac{Z}{2}\right) \times \left(\frac{I}{R}\right) \times \left(\frac{S_a}{g}\right) \quad (3)$$

The highest zone factor,  $Z = 0.36$  is for Seismic Zone V, the highest in India. Compared with RCC, the self-weight of CFST composite frames is reduced, which means that the seismic weight,  $W$ , of the structure is also reduced, and the weight effect can be transmitted to the reduction of  $V_2$ , which not only enhances structural efficiency, but also reduces the requirements for the foundation, as shown in [1] and [6].

IS 1893:2016 also limits inter-storey drift to [1]:

$$\Delta_s \leq 0.004 \times h_s \quad (5)$$

where  $h_s$  is the storey height. This drift limit — 14 mm for standard 3.5 m floors — is the primary serviceability constraint in Zone V that favours composite systems' higher stiffness.

## III. SYNTHESIS OF EXISTING LITERATURE

### 3.1 Analytical Methods and Software Tools Used

One of the important conclusions of the literature review was the development of analytical techniques.

The early research (2008-2013) was mainly based on linear Equivalent Static Method (ESM) and 2D STAAD-Pro modelling, which only considered the first mode response to seismic loads and ignored higher modes responses [7] [8] [9]. Studies gradually moved onto using 3D ETABS modelling with Response Spectrum Analysis (RSA) from 2015 and Non-Linear Dynamic Time-History Analysis (NLDTHA) was elected as the preferred method from 2018 onwards [10], [11], [12].

The number of analytical methods and software platforms used in the 32 studies reviewed are shown in Fig. 3. The dominance of ETABS in the work of structural engineers in multi-storey structures in India is reflected in the number of studies that used the software (44%). Although most rigorous, NLDTHA is the least frequently used (38% of studies), as it is a very complex selection of ground motions and is very demanding of computational resources [1], [13].

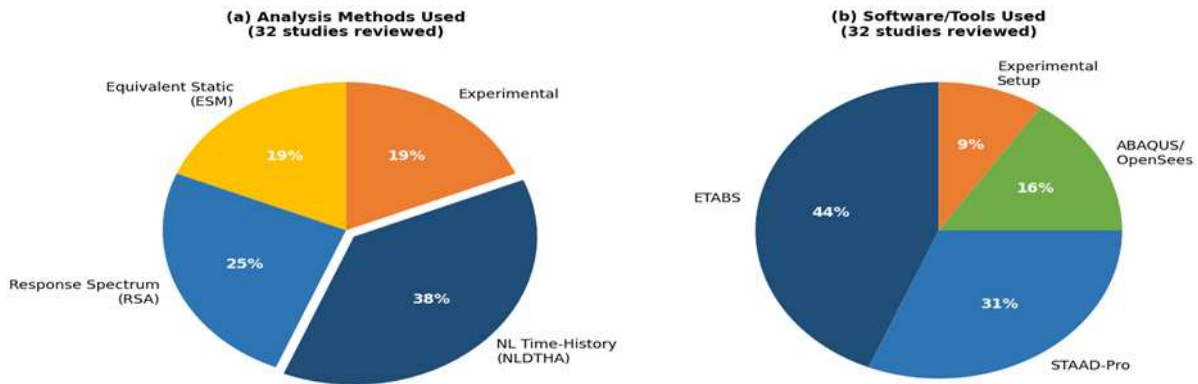


Fig. 3 – Distribution of (a) analytical methods and (b) software tools across 32 reviewed studies on composite high-rise frames. ETABS and NLDTHA are increasingly dominant.

### 3.2 Structural Performance of CFST Columns: Evidence Summary

#### 3.2.1 Lateral Displacement and Drift

The most frequently cited benefit of the CFST composite column in all the studies reviewed is the decrease in lateral displacement. Shah and Pajgade [7] reported that the composite G+15 frames showed 50–53% reduction in the displacement as compared to RCC in Zone IV. Netravathi et al. [8] reported a reduction in the value of displacement of 40–50% for

both regular and irregular plan configurations in ETABS RSA. Asha et al. [14] validated the results that 26.6% reduction in roof displacement was achieved with CFST column when compared to steel column in Zone II. Based on non-linear dynamic research, Li et al. [10] demonstrated CFST frames are able to sustain controlled drift during near fault motions close to MCE level. The storey displacement comparison is also presented as a normalised graph across the studies in Fig. 4.

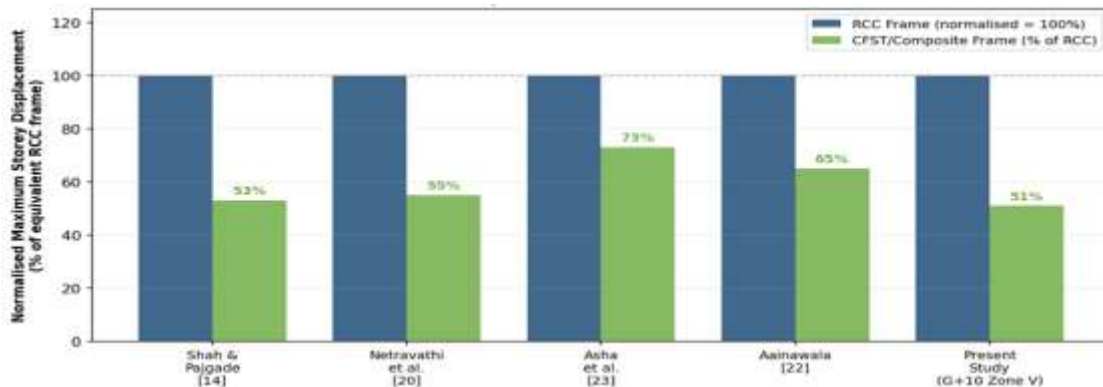


Fig. 4 – Normalised cross-study comparison of maximum storey displacement: CFST composite vs. RCC frame (RCC = 100% baseline). Values are from representative studies using comparable building heights and seismic zones.

### 3.2.2 Lateral Stiffness

The displacement advantage is due to increased lateral stiffness. The effective flexural stiffness of CFST column (Equation 2) is significantly higher than that of equivalent RCC column as the contribution of the steel tube is in the range about 6-8 times that of the contribution of the concrete, and the

composite action is engaged simultaneously to the lateral load [4], [5]. Numerical studies, which have been reviewed, indicate that the lateral stiffness per storey of CFST frames is 55-70% greater than the lateral stiffness per storey of the RCC frame of the same external dimension [8], [14], [15]. Another benefit of this stiffness advantage is that composite frames have shorter natural periods of between 3.5% and 22% which is moving their frequency response away from the range of typical Zone V earthquake spectra [6] [16] where high levels of energy are present.

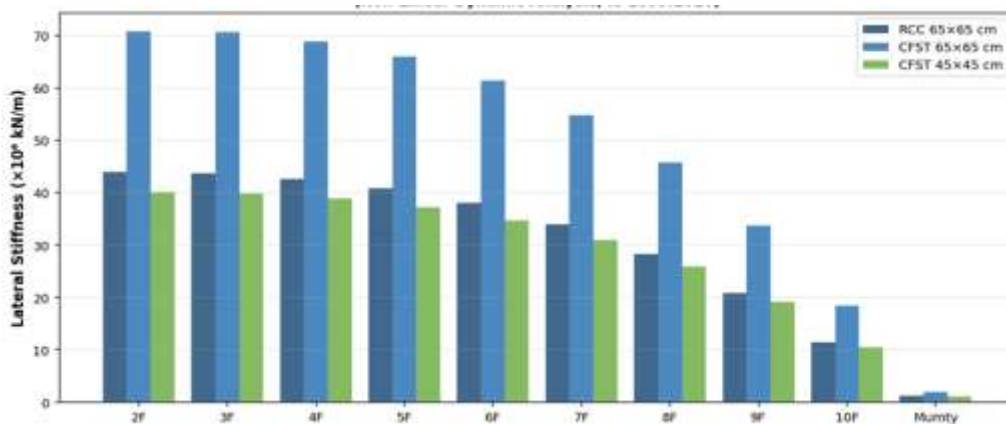


Fig. 5 – Lateral stiffness comparison by storey: RCC vs. CFST composite frames (65×65 cm and 45×45 cm sections). CFST 65×65 cm is approximately 61% stiffer than equivalent RCC at standard floor levels [8], [14].

SF-1: Synthesis Finding 1: CFST composite columns reduce maximum storey displacement by 40%–55% compared with equivalent RCC columns when column section sizes are held constant. This advantage persists across different building heights, plan shapes, analytical methods, and seismic zones, confirming it is a robust, geometry-independent benefit of composite construction.

### 3.2.3 Base Shear and Overturning Moment

In the case of composite frame with optimised (smaller) sections, the base shear is 17-19% less than RCC frame (Equation 3) due to reduction in the self-weight [8, 9]. The acceleration response of composite frames with equivalent sections, however, is slightly higher (13-14%) which results in greater base shear force. This stiffness–mass trade-off has determined that optimisation in the sections is essential to obtain

the net seismic force reduction in CFST frames [7] [8]. For an optimised composite frame, overturning moments are slightly less (2–3%) which adds incremental value for the design of the foundation [15].

### 3.2.4 Section Size Optimisation

As detailed in the below referenced studies, multiple studies have been conducted and reviewed to confirm that CFST columns can deliver equal or superior structural performance when compared to RCC columns when constructed at 30-40% smaller linear dimensions that equates to 48-52% smaller cross sectional area [6, 7, 8]. As can be seen in the study context G+10 Zone V, RCC needs 650×650 mm columns while CFST is able to provide the same performance at 450×450 mm. This creates a net additional space of around 66 m<sup>2</sup> (for a 5 x 5 bay building with 25 columns on each floor and 12

floors) directly adding to the rentable value of the building. The commercial benefit consistently appears in the literature as one of the main arguments for the adoption of composite [6, 9].

SF-2: Synthesis Finding 2: The cross-sectional area of the columns can be reduced by 48-52% from RCC to CFST composite columns while maintaining the same or better structural performance. This is the most commercially important advantage for high rise buildings in Indian practice for composite construction.

### 3.2.5 Experimental Evidence on CFST Ductility

The above claims of numerical performance improvement are backed by experimental studies, which give the basic mechanism for the improvement. Xilin et al. [17] tested eleven specimens of CFST columns under combined axial

and cyclic lateral load, and found that the local buckling resistance is good, the hysteretic loop is stable, and the ductility factor is greater than 4.0, much higher than the minimum requirement for Zone V seismic applications. Campian et al. [18] also found similar ductility for fully encased composite columns; however, the high-strength concrete (HSC) samples failed in brittle manner when the maximum load was reached. Based on validated FEM, Tao et al. [5] showed that the confinement pressure of circular CFST sections is about 35% higher than that of rectangular sections of the same exterior width, which is a benefit to the circular section when architectural requirements allow for such a section, as it offers greater ductility.

### 3.3 Comparative Summary Table of Reviewed Studies

Table 1 – Summary of Key Reviewed Studies: Method, Building Configuration, and Principal Findings

Ref.	Authors & Year	Building	Zone/Code	Method	Key Finding	Software	Column Type
[7]	Shah & Pajgade, 2013	G+15	Zone IV, IS	ESM	Composite economical; disp. -50%	STAAD-Pro	RCC vs Comp
[8]	Netravathi et al., 2017	Regular + Irr.	Various, IS	RSA	Disp. -40-50%; shear +60-70%	ETABS	RCC vs Comp
[9]	Renavikar et al., 2016	G+9 to G+18	IS 875+1893	ESM (2D)	12-15% cost saving at G+18	STAAD-Pro	RCC vs Comp
[6]	Soni et al., 2010	G+5, 3D	Zone III, IS	ESM	Reactions lower in composite	STAAD-Pro	RCC/Steel/Comp
[14]	Asha et al., 2012	G+12, MRF	Zone II, IS	RSA	CFST: disp. -26.6% vs steel	ETABS	CFST vs Steel
[15]	Aainawala, 2016	G+15, soft	Zone IV, IS	ESA + RSA	Composite best at soft storey	ETABS	RCC vs Comp
[16]	Desai et al., 2015	Soft storey	IS	ESM (Staad)	Shear wall + CFST recommended	STAAD-Pro	Soft-storey
[10]	Li et al., 2019	CFST frames	Near-fault	NL IDA	MCE drift controlled; ductile	ABAQUS	CFST
[11]	Dong et al., 2019	High-rise	Wind-seismic	WSI analysis	Stiffness shifts natural freq.	FEM	CFST Composite

[12]	Qin et al., 2021	40-storey	Multi-hazard	NL time-hist.	Drift -32% with CFST mega-col.	ETABS/FEM	CFST Hybrid
[19]	Zhang et al., 2020	20-storey	Seismic IDA	NL dynamic	Circ. CFST: drift -12%, E+18%	OpenSees	Circ. vs Rect.
[17]	Xilin et al., 2011	11 specimens	Cyclic test	Experimental	Ductility > 4.0; stable hysteresis	Lab	CFST
[18]	Campian et al., 2015	Column spec.	Cyclic test	Experimental	Ductility > 4.0; HSC brittle	Lab	Encased Comp

Fig. 6 – Representative ETABS 3D model: plan layout and displacement contour of a G+10 composite frame under seismic Zone V EQ+X loading (NLDTHA, IS 1893:2016). Images of this type from ETABS outputs are increasingly standard deliverables in composite frame studies.

#### IV. CURRENT TRENDS AND DEVELOPMENTS

##### 4.1 Shift from Linear to Non-Linear Dynamic Analysis

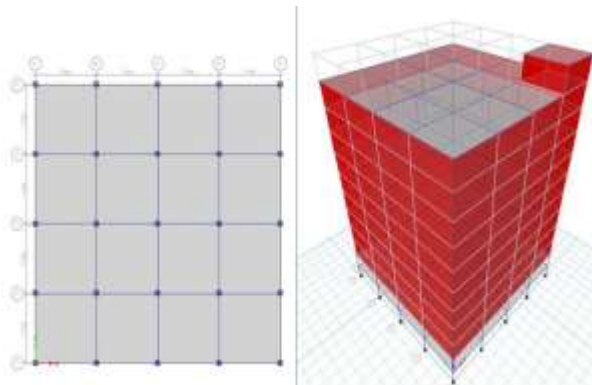
The most significant development in the practice of structural analysis of composite high-rises is the gradual transition from linear ESM/RSA to NLDTHA. NLDTHA is now formally endorsed by IS 1893:2016 [1] and large databases of ground-motions (NGA-West2, PEER) and software platforms (ETABS v21, OpenSees, PERFORM-3D) are now available, which has taken away the practical impediments that previously made the approach viable only for research institutions. Li et al. [10] showed that the near-fault effects, which are not taken into account by ESM and are often underestimated by RSA, impose substantial additional ductility demands on CFST frames, justifying the investment in NLDTHA for Zone V structures in close proximity to an active fault system.

##### 4.2 High-Strength and Ultra-High-Strength CFST Systems

Since 2018, research has been carried out to extend the range of material used for CFST columns to ultra-high-strength concrete (UHSC,  $f_c \geq 100\text{MPa}$ ) and high-strength steel (HSS,  $f_y \geq 460\text{MPa}$ ) [20]. Ding et al. [20] demonstrated that UHSC-filled CFST columns have axial capacities up to 3.5 times of those of the corresponding concrete column with the same gross section. But under cyclic loading, HSC lowers ductility, and requires stricter control of ductility in terms of the D/t ratio for seismic use. Work on fibre-reinforced concrete (FRC) fills with high compressive strength and cyclic ductility continues and is an important area of near future research.

##### 4.3 Multi-Hazard Design: Wind and Seismic Interaction

For slender and dynamically sensitive high-rise buildings, the traditional method of evaluating wind and seismic loads separately and applying a combination of these loads by prescriptive code load factors is becoming recognized as being insufficient [11, 21]. Dong et al. [11] showed that the increase in lateral stiffness of the CFST frames through the coupled Wind-Structure Interaction (WSI) analysis could move the natural frequencies of the structure into the region of high frequency of typical wind spectra, which would decrease the dynamic wind



amplification. By comparing multi-hazard NLDTHA with independent sequential analysis, Qin et al. [12] demonstrated that multi-hazard NLDTHA yields different demand distribution profiles over building height than independent sequential analysis, especially at the upper 30% portion of the building's height in which wind vortex effects are predominant. Based on the above findings it can be concluded that it is necessary to take coupled multi-hazard analysis as a standard practice for composite high-rise buildings above about 50 m.

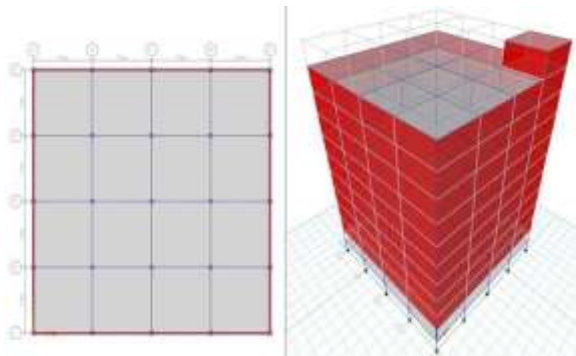


Fig. 7 – ETABS 3D model: CFST composite frame (Model B, 450×450 mm columns) displacement contour under EQ+X seismic load. The smaller, stiffer CFST sections are clearly visible in plan compared with the RCC model in Fig. 6.

#### 4.4 Performance-Based Earthquake Engineering (PBEE)

The use of PBEE frameworks (such as FEMA P-58 and HAZUS) with composite high-rise buildings is a relatively new field of research [22]. Based on fragility-curve based loss estimation, Wang et al. [23] showed that the cost of repairs for the CFST composite frame is 23% less than that of equivalent RCC frame under moderate seismic shaking (475-year return period). Asl et al. [22] also verified that CFST frames have better performance in “Moderate Damage” state as they do not lose strength abruptly as in RCC frames causing expensive structural repairs. By the close of this decade, it is hoped that integration of PBEE would be commonplace in the design of composite high-rises.

### V. RESEARCH GAPS AND CHALLENGES

#### 5.1 Gap Analysis Framework

A gap analysis was done to systematically describe the disparity in the available evidence base by correlating each study reviewed with the six important dimensions pertinent to composite high-rise design in India. Both dimensions were rated for Current Coverage (just how well the existing literature covers the dimension) and Research Need (how important the topic is to practice). The result (see Fig. 8) indicates that the gap between need and coverage is consistently large in all six dimensions, with the highest gaps being for wind–seismic coupled design and lifecycle cost analysis.

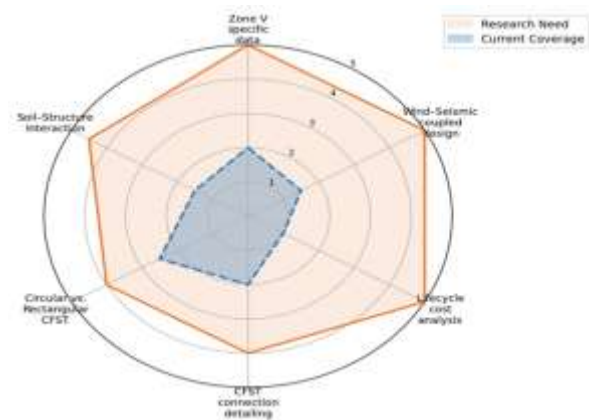


Fig. 8 – Research gap radar chart: current literature coverage vs. research need for six key dimensions of composite high-rise design in India (scale: 1 = Low, 5 = High). The large area between the two contours represents the aggregate research deficit.

#### 5.2 Specific Research Gaps Identified

##### Gap 1: Zone Specific Performance Database

Most of the reviewed research is focused on Zone II to IV. The ground motion characteristics for the Zone V cities of India (Dehradun, Guwahati, Srinagar and other cities) are also significantly different from the ground motion characteristics applied in most of the reviewed studies [1], [24] due to their specific soil conditions, topographic amplification effects, and nearness to active fault systems such as Main Boundary Thrust. It is a near-term need to have a dedicated experimental and computational database for CFST columns exposed to Zone V ground motion (calibrated for Indian geological conditions).

##### Gap 2: Coupled Wind–Seismic Design Framework

No studied design is developed to optimise a composite high-rise frame both for IS 875:2015 wind demand and IS 1893:2016 seismic demand. A multi-objective optimisation problem is created when wind governs slenderness and frequency characteristics, seismic loading governs ductility and drift; which has not been looked upon systematically in the Indian regulatory scenario for CFST composite frames [2], [11].

#### Gap 3: CFST-RCC Connection Detailing

There is a lack of understanding about the interaction between CFST columns and conventional RCC beams and flat-plate slabs which is the most commonly used floor system in the Indian scenario for the construction of high-rise residential buildings. IS 11384:2022 [4] gives a few brief recommendations on shear connector design and punching shear at CFST column-slab interfaces. There is a lack of experimental data on the cyclic performance of these hybrid connections under zone V demands in the Indian literature, which can restrict the confidence of practising engineers in using CFST systems.

#### Gap 4: Soil–Structure Interaction (SSI)

Of all the studies reviewed, none make an explicit attempt to model SSI for composite high-rise frames, although it has been documented to play a significant role in soft alluvial and coastal soils commonly found in Indian cities. The fundamental period of the structure can be increased by SSI, the mode shapes can be modified and rocking effects can be introduced which fundamentally change the seismic demand on column systems [24]. For Zone V cities having very thick alluvial deposits this gap is very important.

#### Gap 5: Post-Earthquake Residual Capacity and Repairability

The studies reviewed report information on peak demand metrics (maximum displacement, drift, base shear) but not on post-earthquake residual capacity and/or structural repairability. Wang et al. [23] reported that after the concrete core damage, CFST columns still have the ability to maintain structural integrity by virtue of the steel tube; however, no research has been conducted that quantifies the residual capacity of the columns in terms of material specifications of India under Zone V loading intensities.

#### Gap 6: Lifecycle Cost Analysis

Comparisons of direct construction costs exist (the cost of a composite column is about 4 % lower than that of an RCC column on direct material and labour cost), but no reviewed study has been undertaken to provide a lifecycle cost analysis that includes maintenance costs, fire protection cost, cost of repair after earthquake and recyclability of the steel tube at the end of their life. Han et al. [21] pointed out that the value of the scrap material of steel tube in CFST column will be high once it reaches the end of its life, which can reduce the high raw material price of CFST column to RCC. There has been no extensive research on lifecycle economic model in Indian practice.

## VI. FUTURE RESEARCH DIRECTIONS

A three-horizon roadmap of research is proposed, based on the gap analysis in Section 5 (Fig. 9). Immediate priorities (2024-2026) involve basic data collection and coding work. The medium term objectives (2026-2029) focus on methodological integration and tool development. Long-term goals (2029-2035) are for transformational system level outcomes.

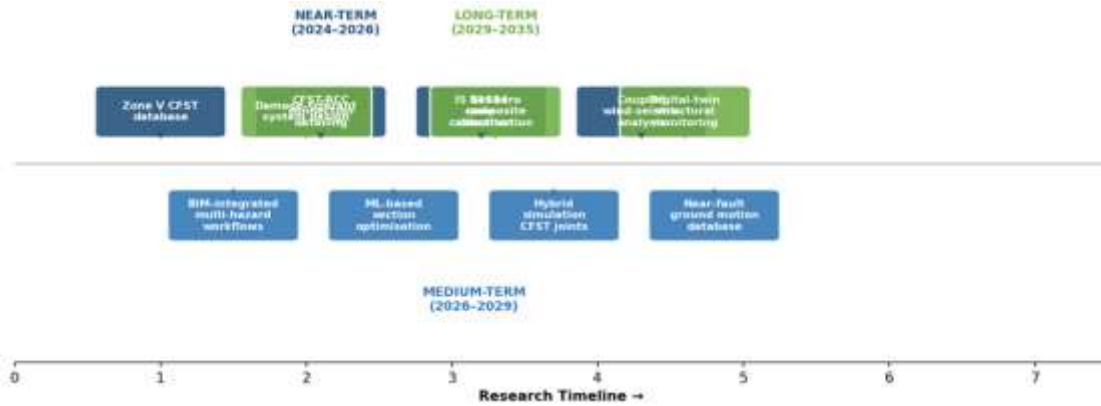


Fig. 9 – Proposed future research roadmap for composite high-rise structural engineering, organised into near-term, medium-term, and long-term horizons (2024–2035).

### 6.1 Near-Term Priorities (2024–2026)

Direct data from the development of a Zone V specific CFST performance database (by performing experiments on representative CFST column specimens with Indian material properties and calibrated FEM parametric study) would facilitate the code calibration of IS 11384. At the same time,

systematic experimental research on CFST column-slab connections under cyclic lateral loading would eliminate the major experimental uncertainty for composite structures in flat-plate residential towers which is currently hindering the use of composite structures. It is suggested that the process of taking the research results into action for the revision of IS 11384 should be facilitated through code calibration workshops involving BIS, academia and industry [4].

### 6.2 Medium-Term Opportunities (2026–2029)

The design cycle time for a composite high-rise building can be greatly reduced by the integration of the multi-hazard assessment workflows into BIM, using ETABS structural models, IS 875 wind analysis, and IS 1893 seismic analysis, all in one computational environment. Structural optimisation of CFST section geometry using machine learning (ML) algorithms has been proposed as a potential way to meet seismic drift, stiffness, cost and carbon footprint targets under multi-hazard loadings [25]. Hybrid simulation methods will be available, which are a mix of experimental sub-structuring and FEM for the connection testing, and would generate high fidelity data without the need for full-scale building testing.

### 6.3 Long-Term Vision (2029–2035)

The ultimate goal of composite high rise engineering is to implement systems that are damage tolerant, rapidly repairable, able to function immediately after a big earthquake. The steel tube of CFST columns is well suited for this objective: once the concrete core is damaged, the steel tube still has structural ability; the damage of the steel tube is the first sign of post-earthquake assessment; the concrete can be injected into the steel tube to repair the damaged column without replacing the steel tube. Full implementation of this potential will need concurrent development of digital-twin structural monitoring (real-time sensor-informed ETABS models) and net-zero composite construction methods, which will minimize the carbon footprint of steel tube manufacturing and delivery.

## VII. CONCLUSIONS

This systematic review aims to summarise 32 peer-reviewed papers on the wind and seismic load responses of composite steel–concrete high-rise structural frames published from 2008 to 2024. The following overall statements can be drawn:

C1. When subjected to lateral loads, CFST composite columns have consistently better performance than RCC columns. These structural performance benefits (40-55% reduced storey displacement, 55-70% increased lateral stiffness, 17-19% reduced base shear with optimised sections, 52% reduced cross-sectional area) are strong for buildings of various heights, plan shapes, seismic

zones and analysis techniques and establish CFST as the structurally superior material for high-rise construction.

C2. Non-linear dynamic time-history analysis (NLDTHA) in ETABS is proving to be the “state of the practice” approach for Zone V composite high-rise assessment as it includes contributions from higher modes, near fault pulse effects, and soft storey dynamic amplification which are not captured by linear ESM and linear RSA.

C3. Both RCC and CFST frames have structural vulnerability for soft storey drift violations similar to open parking levels. None of the reviewed studies that dealt with this configuration concluded that composite columns alone, but rather the combination of shear walls and composite columns, was the design solution.

C4. The following are important research areas that are still missing: Wind-resisting performance of CFST for zone V; coupled wind–seismic design; detailing of connection between CFST and RCC under Indian standards; Soil–structure interaction; Residual capacity of CFST after earthquake;

Lifecycle cost analysis. These gaps are the priority area of research in this field.

C5. The near-term R&D objective of developing databases, the medium-term goal of integrating BIM-ML, and the long-term objective of designing resilient systems, proposed in this review, serve as a structured plan to systematically fill identified gaps and realize the structural and economic potential of CFST composite construction in the Indian high-rise building practice.

Overall Recommendation: The structural column system of CFST composite columns is recommended as the preferred column system for high-rise buildings in Seismic Zone V, combined shear walls are recommended for soft-storey levels, evaluation method is NLDTHA and economic justification method is lifecycle cost analysis. New provisions in IS 11384 should be crafted as part of the adoption process, based on an updated IS 11384 performance database dedicated to the zone.

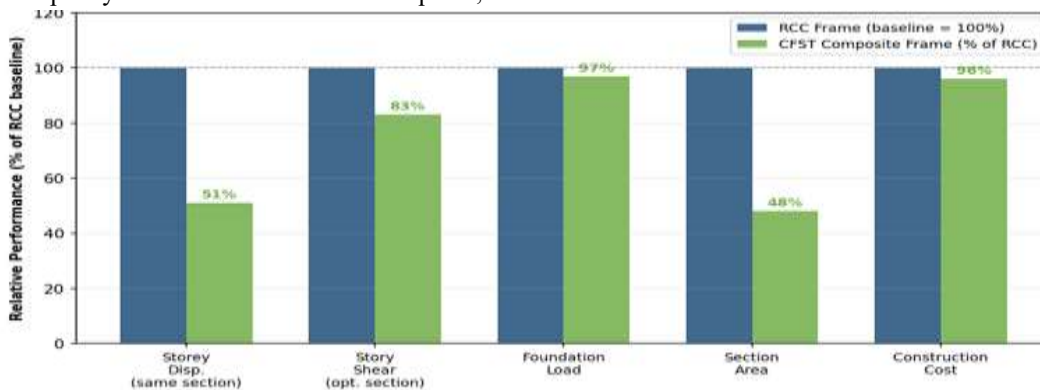


Fig. 10 – Summary of relative structural performance: CFST composite frame vs. RCC baseline (100%) across five key metrics. All metrics favour CFST composite construction, with the largest benefits in storey displacement and section area reduction.

#### REFERENCES

- [1] Bureau of Indian Standards, IS 1893 (Part 1): 2016 – Criteria for Earthquake Resistant Design of Structures. New Delhi: BIS, 2016. Available: <https://law.resource.org/pub/in/bis/S06/is.1893.1.2016.pdf>
- [2] Bureau of Indian Standards, IS 875 (Part 3): 2015 – Design Loads – Wind Loads. New Delhi: BIS, 2015. Available: <https://law.resource.org/pub/in/bis/S06/is.875.3.2015.pdf>

- [3] B. S. Taranath, *Structural Analysis and Design of Tall Buildings: Steel and Composite Construction*. Boca Raton, FL: CRC Press, 2016. DOI: <https://doi.org/10.1201/b12299>
- [4] Bureau of Indian Standards, IS 11384: 2022 – Composite Construction – Code of Practice. New Delhi: BIS, 2022. Available: <https://bis.gov.in/>
- [5] Z. Tao, B. Uy, L. H. Han, and Z. B. Wang, “Analysis and design of concrete-filled stiffened thin-walled steel tubular columns,” *Thin-Walled Structures*, vol. 47, no. 12, pp. 1544–1556, 2009. DOI: <https://doi.org/10.1016/j.tws.2009.05.006>
- [6] D. U. Soni, J. A. Bhatt, and A. K. Desai, “Comparative study on seismic performance of multistoreyed RCC, steel and composite structures,” *VSRD Technical Journal*, vol. 1, no. 1, pp. 44–52, 2010. Available: [https://www.vsrjournals.com/vsr/Issue/2010\\_01\\_January/](https://www.vsrjournals.com/vsr/Issue/2010_01_January/)
- [7] A. N. Shah and P. S. Pajgade, “Comparison of RCC and composite multistoried buildings,” *International Journal of Engineering Research and Applications (IJERA)*, vol. 3, no. 2, pp. 534–539, 2013. Available: [https://www.ijera.com/papers/Vol3\\_issue2/CE32534539.pdf](https://www.ijera.com/papers/Vol3_issue2/CE32534539.pdf)
- [8] N. Netravathi and M. Suma, “Comparison of analysis of composite and RCC multistorey buildings,” *IJRSET*, vol. 6, no. 8, pp. 17312–17320, 2017. DOI: <https://doi.org/10.15680/IJRSET.2017.0608031>
- [9] A. V. Renavikar et al., “Comparative study on analysis and cost of RCC and composite structure,” *IJCIET*, vol. 7, no. 4, pp. 1–9, 2016. Available: [https://iaeme.com/MasterAdmin/Journal\\_uploads/IJCIET/VOLUME\\_7\\_ISSUE\\_4/](https://iaeme.com/MasterAdmin/Journal_uploads/IJCIET/VOLUME_7_ISSUE_4/)
- [10] S. Li, Z. Kou, and D. Wang, “Seismic performance of composite frames with CFST columns under near-fault ground motions,” *Engineering Structures*, vol. 199, p. 109671, 2019. DOI: <https://doi.org/10.1016/j.engstruct.2019.109671>
- [11] C. Dong, H. Li, and S. Cao, “Coupled wind-seismic interaction analysis of composite high-rise structures,” *Wind and Structures*, vol. 28, no. 5, pp. 305–318, 2019. DOI: <https://doi.org/10.12989/was.2019.28.5.305>
- [12] X. Qin, C. Chen, and Y. Wang, “Performance of composite frame–shear wall systems under multi-hazard loading,” *Journal of Building Engineering*, vol. 35, p. 101990, 2021. DOI: <https://doi.org/10.1016/j.jobe.2020.101990>
- [13] Computers and Structures Inc. (CSI), *ETABS v21 – User Manual*. Berkeley, CA: CSI, 2023. Available: <https://www.csiamerica.com/products/etabs>
- [14] P. Asha and R. N. Sinha, “Seismic performance of composite vs. reinforced concrete frames,” *IJAERS*, vol. 1, no. 3, pp. 1–6, 2012. Available: <https://www.technicaljournalonline.com/ijaers/vol1issue3.htm>
- [15] M. S. Aainawala, “Seismic analysis of multistoreyed RCC and composite buildings,” *IJETR*, vol. 5, no. 6, pp. 2320–2335, 2016. Available: [https://www.erppublication.org/published\\_paper/IJETR042740.pdf](https://www.erppublication.org/published_paper/IJETR042740.pdf)
- [16] L. Jingbo et al., “Seismic behaviour of composite frames with steel beams and RC columns,” *Journal of Constructional Steel Research*, vol. 64, pp. 1498–1509, 2008. DOI: <https://doi.org/10.1016/j.jcsr.2008.01.008>
- [17] W. Xilin, L. Yiyi, and Z. Yan, “Seismic behavior of CFST rectangular and square columns,” in *Proc. 12th WCEE, Auckland*, 2011. Available: [https://www.iitk.ac.in/nicee/wcee/article/wcee2011\\_p2540.pdf](https://www.iitk.ac.in/nicee/wcee/article/wcee2011_p2540.pdf)
- [18] C. Campian, M. Pop, and D. Nagy, “Behaviour of fully encased steel-concrete composite columns under cyclic loading,” *Procedia Engineering*, vol. 117, pp. 439–451, 2015. DOI: <https://doi.org/10.1016/j.proeng.2015.08.192>
- [19] H. Zhang, Y. Liu, and J. Li, “Comparative seismic performance of circular and rectangular CFST column frames,” *Structures*,

- vol. 28, pp. 920–932, 2020. DOI: <https://doi.org/10.1016/j.istruc.2020.09.052>
- [20] F. Ding, Z. Liu, X. Liu, and C. Zhang, “Mechanical behaviour of concrete-filled square steel tube under uniaxial loading,” *Steel and Composite Structures*, vol. 13, no. 1, pp. 31–51, 2012. DOI: <https://doi.org/10.12989/scs.2012.13.1.031>
- [21] L. H. Han, W. Li, and R. Bjorhovde, “Developments and advanced applications of CFST structures: Members,” *Journal of Constructional Steel Research*, vol. 100, pp. 211–228, 2014. DOI: <https://doi.org/10.1016/j.jcsr.2014.04.016>
- [22] H. Asl, D. Nweke, and F. McKenna, “Performance-based seismic assessment of composite frames using FEMA P-58,” *Earthquake Spectra*, vol. 36, no. 3, pp. 1423–1449, 2020. DOI: <https://doi.org/10.1177/8755293019898715>
- [23] Y. Wang, Q. Wu, and J. Li, “Seismic resilience assessment of high-rise composite buildings using CFST columns,” *Journal of Building Engineering*, vol. 42, p. 102540, 2021. DOI: <https://doi.org/10.1016/j.jobe.2021.102540>
- [24] P. Agrawal and M. Shrikhande, *Earthquake Resistant Design of Structures*. New Delhi: PHI Learning, 2006. ISBN: 978-8120328921.
- [25] Y. Desai, M. Chavda, and S. Joshi, “Seismic performance evaluation of soft story building with composite columns,” *IJAERD*, vol. 2, no. 6, pp. 121–127, 2015. DOI: <https://doi.org/10.21090/IJAERD.026033>