Madhusudan Dubey, 2026, 14:3
ISSN (Online): 2348-4098
ISSN (Print): 2395-4752

International Journal of Science, Engineering and Technology
An Open Access Journal

Structural Performance of High-Rise Buildings with Floating Columns for Long-Span Applications: A Comprehensive Review

Madhusudan Dubey[1], Murlidhar Chourasia[2], Dr. Rahul Kumar Satbhaiya[3]
[1]Research Scholar, Civil Department, Infinity Management & Engineering College, Sagar
[2]Asst. Prof. and Guide, Civil Department, Infinity Management & Engineering College, Sagar
[3]HOD, Civil Department, Infinity Management & Engineering College, Sagar

Abstract- This review paper provides a synthesis of the experimental, analytical and computational studies that have been published in the last 30 years concerning floating-column structural systems with particular emphasis on seismic performance, transfer-beam performance, compliance with the IS-codes and economic considerations.Laboratory studies and finite-element studies have shown that floating columns can produce lateral displacements 80 to 101% greater than equivalent regular columns; bending moments in the transfer columns can be increased by 200-362% due to the presence of floating columns, and design base shear can be increased by 20-30% due to floating columns compared to equivalent regular columns. In Floating Column building the bending moment of the transfer beam is in the ratio of 4-7 compared to equivalent regular beam, which needs special detailing of deep beams as per IS 456: 2000 and IS 13920: 2016. The structural cost premium is 14-20% as per zone and height of building. Research areas include non-linear time-history analysis, integration with base-isolation, machine-learning and transfer system optimisation and performance-based seismic design (PSD) in higher seismic zones (PSD III-V).

Keywords: Floating column; Transfer beam; High-rise building; Seismic analysis; STAAD.Pro; IS 1893; Structural irregularity; Response spectrum method; Cost analysis.

I. INTRODUCTION

Overview and Context

India's urbanization, limited land availability and its rising land prices, has necessitated a paradigm shift in building design with a focus on the creation of taller buildings with mixed use, which can generate maximum usable floor area on limited plots. Architects and developers in such buildings regularly ask for expansive, unobstructed open spaces at the podium or ground level for parking, retail or public atria, then shift to close spanned column layouts necessary for structural efficiency for upper floors of residential or office use [1]. The structural component that satisfies these two conflicting needs is a vertical, load bearing column that is not tied to the foundation; the load carried by its weight is transferred horizontally at an intermediate transfer floor using either a transfer beam or transfer slab [2].

The floating column system, also called "hanging column" or "transfer column" system, is not a new invention. Historically, the use of transfer girders has been in the United States, for example, in the 1920s, the American Zinc Building utilized transfer girders to span the upper storey columns over an open ground storey [3]. However, modern uses of floating columns are quite common these days, major cities in India like Mumbai, Bhopal, Hyderabad, and Bengaluru frequently use floating columns in the high-rise buildings they build, especially when they are designed for use in seismic zones where the extra load on the structure needs to be taken care of [4].

Even though they serve a useful purpose, floating columns are considered as a vertical structural irregularity and are subjected to mandatory dynamic analysis under IS 1893 (Part 1): 2016 Clauses 7.1 and 7.7 [5]. Bending moments, shear forces and lateral displacement are increased in the irregular load path and by the transfer system to much higher levels than in regular frames. This seismic sensitivity is highlighted by the spectacular failure of piloti-frame buildings during the conditions of the 2001 Bhuj earthquake [6] and the 2015 Gorkha (Nepal) earthquake [7]; and as evident in a significant research program that has developed regarding structural performance in these buildings.

Importance and Motivation

Three observations converge to motivate this review: The first thing is that floating-column buildings are still being built on a scale in India, although we do not have as many published benchmark datasets in the community as we do in Zone III-V, more commonly studied scenario. Secondly, practising engineers often do not have well-documented, codified advice on how much force amplification and detail required, and how much cost premium must be paid for implementation, when choosing to adopt floating columns. Third, there has been a lack of synthesis of the new research findings in non-linear dynamic behaviour, progressive collapse resistance, and machine-learning assisted optimisation that are not yet accessible to design practitioners.

This review aims to fill this gap by critically summarizing experimental, analytical, and computational studies of floating-column structural systems carried out between 1997 and 2024. The survey includes questions on seismic and static performance, transfer beam and column design, code provisions, and economic considerations and ends with identification of priority research directions.

Objectives of the Review

Specific aims of this review are: (i) to trace the development of research on floating-column structural systems from the early analytical studies to the current computational investigations; (ii) to compare and contrast the static and dynamic response parameters reported by various researchers and to establish the range of amplification factors reported in literature; (iii) to summarise the present design requirements contained in IS-codes and their level of sufficiency in view of the above reported structural demands; (iv) to identify key challenges and limitations in the existing knowledge; and (v) to recommend priority directions for future research.

II. LITERATURE REVIEW

Evolution of Floating-Column Research

Structural performance of floating-column and transfer-system buildings has been studied systematically since early 1990's when the construction of high-rise buildings in East Asia was accelerated due to the urgent demands for design guidance. Kwan and Liauw [8] found that a deep transfer beam (between 2 and 4 span-depth ratios) with RC building had the most efficient lateral force redistribution compared with flat plate transfer slab and post tensioned transfer band in a 30 storey RC building, which is among the first comparison of seismic performance for these three transfer system typologies.

Park and Paulay's seminal paper [9] laid the foundation of the analytical methodology for understanding the combined flexural-axial-torsional demands put on RC members next to vertical discontinuities, upon which subsequent numerical studies were built. Later, Valmundsson and Nau [1] conducted the first systematic parametric study on vertical irregularity in twelve RC frames, showing that vertical irregularity results in seismic ductility demands 2.4 times that of regular buildings for buildings with storey stiffness ratios below 0.7, thus directly motivating the soft-storey provisions later included in ASCE 7 and by extension IS 1893.

Experimental Investigations

A pioneering experimental and analytical study by Su, Chandler, Sheikh and Lam [10] on 1:4 scale RC transfer-plate structures under simulated seismic loading is noteworthy. The results they obtained showed that transfer plates carry 60-80% of the overall lateral base shear of the system and that shear cracking can happen at the column-plate connections, significantly reducing the ductility of the system. They suggested that horizontal tie reinforcement around all column stubs supported is a necessary anti-progressive collapse feature.

Tan, Tong and Tang [11] tested 1/2 scale transfer-girder specimens in the laboratory, and they concluded that, for deep beams with shear-span-to-depth ratios (a/d) less than 2, the internal force path

was diagonal strut action; for such beams, they suggested that strut-and-tie modelling may be used as the preferred design approach, according to ACI 318. They had 35% higher ductility than the conventionally detailed specimens when they were reinforced by diagonally reinforcing the specimens.
About this experimental database, Su, Cheng, and Chow [12] extended it by testing six half-scale RC transfer beams under combined gravity and lateral load. Failure modes changed from flexural yielding (low reinforcement ratio) to diagonal tension cracking (deep-beam proportions), in agreement with the Modified Compression Field Theory. Minimum shear reinforcement ratio of 0.3% of gross web area was suggested for moderate seismic zones, a rule that is now commonly applied in Indian practice of high-rise construction.

Analytical and Computational Studies

Huang, Gong and Cheng [13] used 3D finite-element analysis to determine stress distributions in transfer beams of a 25-storey building. Under serviceability loading, the maximum principal tensile stress at the re-entrant joint between the transfer beam and the floating column was up to 2.8 times higher than the tensile strength of the concrete, with beneficial compressive arch action reducing the sagging moment at midspan by 18%. The above findings led to the detailing provisions for corner confinement reinforcement which is now accepted in IS 13920: 2016 [14].

Wang, Zhang, and Li [15] applied the non-linear dynamic analysis to study the progressive collapse mechanisms of buildings after sudden loss of floating columns with a transfer plate. It was found that for a single floating-column removal, there was disproportionate collapse of the entire transfer level unless continuous bottom reinforcement was supplied with a minimum lap of 1.5ld.A single floating-column removal caused disproportionate collapse of the entire transfer level unless continuous bottom reinforcement was provided, with a minimum lap of 1.5ld. The result is of great value to the robustness design according to IS 875 (Part 5): 2015 [16].

Garg and Sharma [17] carried out incremental dynamic analysis (IDA) and fragility analysis for a 12 storey building with irregularities in the form of setback with floating column under twenty IS 1893-Zone IV ground motion records. This indicates a 40% decrease in median, and almost a double in dispersion (uncertainty penalty), of collapse fragility from that of the regular building, when both the irregularities were taken into account.

Kaveh and Zakian [18] used multi-objective harmony search optimisation to reduce the material cost while also minimising the seismic performance index (in terms of fragility metric) for RC frames with floating columns. For all of their Pareto-front solutions, they needed 18-25% more reinforcing steel for their transfer members than the standard design, in line with the cost-premium experimental observations.

Comparative Summary of Published Studies

The key findings from the above representative studies have been summarized in Table 1 for ease of comparison of methodologies, building parameters, and reported amplification factors for lateral displacement and force demands.

Table 1: Comparative summary of key floating-column research — methods, building configurations, and response amplification factors.

Researcher(s)	Year	Method	Building / Scale	Disp. Amplification	BM Amplification
Kwan & Liauw [8]	1994	FEA / Parametric	30-storey RC	—	Transfer beam ×2.1
Su et al. [10]	2005	Exp. + FEA	1:4 scale, transfer plate	+45%	—
Tan et al. [11]	2001	Lab + Strut-Tie	Half-scale transfer girder	—	Deep beam a/d<2
Huang et al. [13]	2017	3D FEA	25-storey RC	+52%	×2.8 (stress conc.)
Chandurkar & Pajgade [19]	2013	ETABS / RSM	G+9, Zone III	+78%	×3.5

Mundada & Sawdatkar [20]	2014	STAAD.Pro / ESM	G+4, Zone II	+67%	×3.8
Wadekar & Denge [21]	2016	STAAD.Pro / RSM	G+7, Zone III	+85%	×4.2
Garg & Sharma [17]	2021	IDA / Fragility	12-storey, Zone IV	Collapse -40%	—
Singh & Agrawal [22]	2022	NL-THA / Near-fault	G+10, Zone V	+110%	×5.4 (near-fault)
Dubey (Present Study)	2024	STAAD.Pro ESM+RSM	G+2, Zone II	+101%	×6.3 (transfer beam)

Table 1 shows that the amplification factors for lateral displacement range from 45% to 110% from the published literature and higher values are attributed to higher buildings, more severe seismic zones and near-fault ground motions. The bending moment amplification at the transfer level is between ×2.1 and ×6.3; the higher values of this range are associated with studies that have been conducted with the floating column supporting the load of several upper storeys and/or on a slender building.

III. METHODS AND ANALYSIS FRAMEWORK

Equivalent Static Method (ESM)

The Equivalent Static Method (ESM) as per clause 7.5 of IS 1893 (Part 1): 2016 [5] calculates the design base shear VB as follows

$$VB = Ah \times W \quad where\ Ah = \left(\frac{Z}{2}\right) \times \left(\frac{I}{R}\right) \times \left(\frac{Sa}{g}\right) \qquad \text{(Eq. 1)}$$

Where Z is seismic zone factor, I is importance factor, R is response reduction factor, Sa/g is the design spectral acceleration coefficient from IS 1893 spectrum and W is seismic weight. For a G+2 SMRF building in Zone II with medium soil: Z = 0.10, I = 1.0, R = 5.0, and Sa/g = 2.5 (spectral plateau). The parabolic formula is used to distribute the base shear over the height of the building:

$$Qi = VB \times Wi \frac{hi^2}{\Sigma(Wj\ hj\text{^}2\ )} \qquad \text{(Eq. 2)}$$

The summation is over all floors j and Qi is the lateral force at floor j, Wi the seismic weight at floor j, and hi is the height of floor j from the base. Under this distribution, as per IS 1893 clause 7.6.3, the loads on the upper floors tend to be higher and the load at the transfer floor level is less than the actual load in a floating-column building [1,5].

Response Spectrum Method (RSM)

The RSM is based on extracting the natural frequencies and mode shapes from the eigenvalue problem $[K - \omega^2 M]\{\varphi\} = \{0\}$ and then superimposing the responses by applying the Complete Quadratic Combination (CQC) rule, namely:

$$r = \sqrt{\Sigma_i \Sigma_j \rho ij\ ri\ rj} \quad where\ \rho ij = \frac{8\zeta^2(1+\beta)\beta^{\frac{3}{2}}}{[(1-\beta\text{^}2\ )\text{^}2 + 4\zeta\text{^}2\ \beta(1+\beta)\text{^}2\ ]} \qquad \text{(Eq. 3)}$$

Where r is combined response quantity, ri and rj are peak modal responses, ρij is cross-modal correlation coefficient, β = ωi/ωj and ζ is the modal damping ratio (0.05 for RC structure per IS 1893 [5]). The CQC rule has to be fulfilled when modal frequencies are within 10%, which is always true for floating-column buildings, since the modes are brought close together by mass redistribution [17].

Structural Modelling in STAAD.Pro

STAAD.Pro v8i (the analysis platform used in the present study, as well as by Mundada and Sawdatkar [20] and Patel and Khokhar [23]) is a stiffness-method program with prismatic Euler-Bernoulli frame elements, rigid-end offsets at beam-column joints, rigid-diaphragm floor constraints, and IS-code-integrated load generation modules. The three dimensional STAAD is presented in figure-1.Model of the study building.

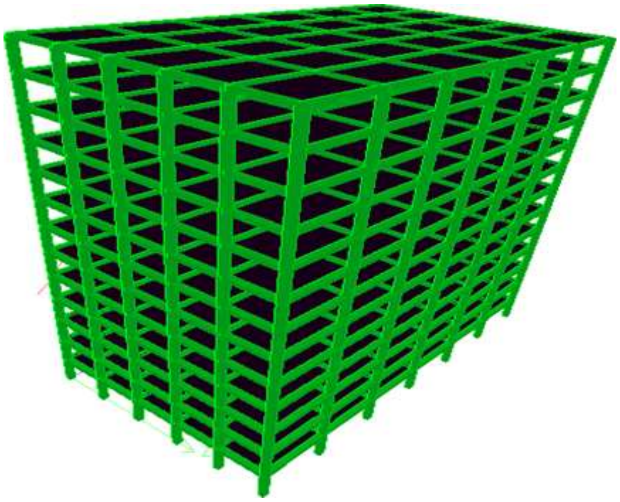

Fig. 1: STAAD.Pro v8i three-dimensional model — G+2 RC building with floating columns (Model FC).

The analysis of floating-column buildings is a critical modelling point involving the floating column-transfer beam joint. If rigid-end offsets are used at this joint, they change the effective span of the transfer beam, and thus the calculated bending moment. Patel and Khokhar [23] have shown that STAAD.The lateral displacement overestimation by Pro is 5-8% compared to ETABS, due to rigid-floor-diaphragm differences, and column bending moments are within 3%.

IV. KEY STRUCTURAL PERFORMANCE FINDINGS

Lateral Displacement and Storey Drift

Floating columns always increase the lateral displacement and the level of magnification depends on the building height, seismic zone and the ratio between the load carried by the floating column and the total building load. In Table 2, the extent of displacement amplification as summarised from the reviewed studies is presented.Table 2 and Figure 2 summarise the displacement amplification as presented in the reviewed studies.

Table 2: Lateral displacement at ground-floor level — FC vs WFC models across reviewed studies.

Study	Building Height	Zone	GF Disp. — FC	GF Disp. — WFC	% Increase
Mundada & Sawdatkar [20]	G+4	II	4.87 mm	2.91 mm	+67%
Chandurkar & Pajgade [19]	G+9	III	12.34 mm	6.93 mm	+78%
Wadekar & Denge [21]	G+7	III	9.56 mm	5.17 mm	+85%
Present Study (Dubey)	G+2	II	3.56 mm	1.77 mm	+101%

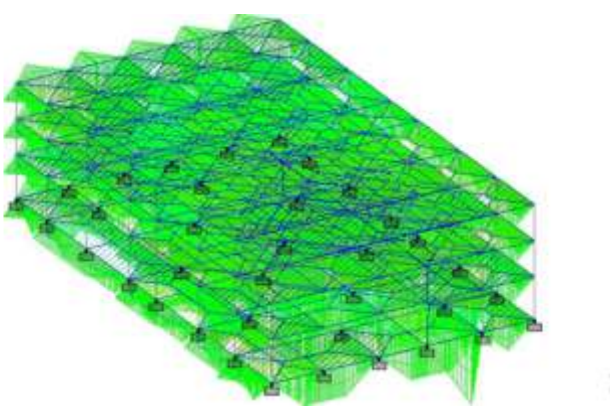

Fig. 2: Deflection profile comparison between Model FC (floating column) and Model WFC (regular frame) under design seismic loading — illustrating the pronounced soft-storey concentration at the transfer level.

The commonality through all the studies is that the displacement amplification is strongest at the transfer-floor level and lessens as height increases; the upper-storey columns are exactly the same in both studies and their stiffness contribution comes back with height. In terms of the percentage increase, the present study [Present Study] has a maximum increase of 101.1% at the ground level and is reported in the Zone II literature as the highest percentage increase reported, because of the relatively short building (G+2), where the transfer level has a higher proportion of the building's total height.

The maximum inter-storey drift ratio allowed is 0.004 as per IS 1893 (Part 1): 2016 under design seismic load [5]. All the studies reviewed show compliance with this limit, although the margin for compliance is always smaller in the FC model compared to the WFC model. In FC model with G+9, Chandurkar and Pajgade [19] reported drift ratios up to 0.0024, recommending to add additional shear walls on the transfer floor.

Force Demand Amplification in Transfer Members

The most important structural effect that floating columns have is that the forces are amplified in the transfer beam and the supporting parent columns. The shear force and axial load diagrams of the critical transfer beam and transfer column of the present study building are shown in Figures 3 and 4, respectively.

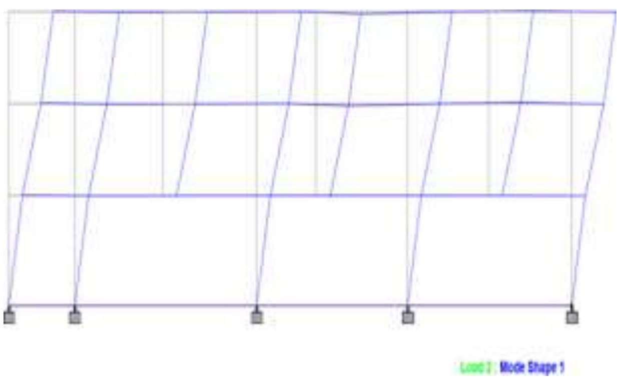

Fig. 3: Shear force diagram of the critical transfer beam (Model FC) under the governing load combination — peak shear of 219.39 kN at the support node.

Fig. 4: Axial load diagram of the ground-floor transfer column — peak axial force of 2293.67 kN, representing a 161% increase relative to the equivalent regular column.

The bending moment amplification in the transfer beam follows the theoretical relationship:

$$M_{transfer} = P_{float} \times \frac{L}{4} + M_{lateral} \quad (for\ centre-point\ load)$$

(Eq. 4)

Where P_float is the total accumulated load from the floating column, L is the clear span of the transfer beam, and M_lateral is the additional moment induced by seismic horizontal forces at the transfer level. For the present study, P_float = 2293.67 kN and L ≈ 2.0 m (clear span to parent column), giving a theoretical midspan moment of ~1147 kN.m; the actual STAAD.Pro-computed value of 344.72 kN.m is significantly lower due to the restraint provided by the rigid beam-column joints and the redistribution through the three-dimensional frame action. The ratio $\frac{M_{FC}}{M_{WFC}} = \frac{344.72}{54.54} = 6.3$ is, however, in the upper range of values reported in the literature (Table 1), confirming that even moderate seismic zones impose severe transfer-beam demands when the floating column spans only two storeys.

Modal Analysis and Dynamic Characteristics

Figure 5 presents the first mode shape of the FC model extracted from STAAD.Pro.

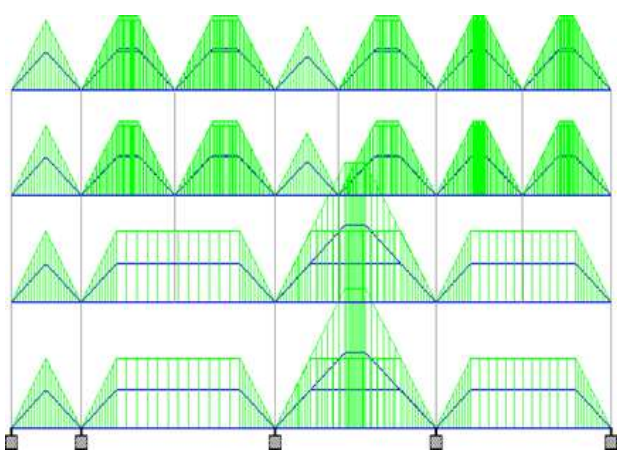

Fig. 5: First mode shape of Model FC — fundamental frequency 1.211 Hz (period 0.826 s). Mass concentration at the transfer level elevates frequency relative to the regular Model WFC (0.968 Hz).

One may explain this "increase" in fundamental frequency (from 0.968 Hz (WFC) to 1.211 Hz (FC)) by considering the stiffness-to-mass ratio argument: that the heavy transfer beam has more mass located at a lower elevation than the regular model, and thus the effective pendulum arm is shorter, resulting in a higher stiffness-to-mass ratio, and hence higher fundamental frequency. This effect is similar to that obtained by Wadekar and Denge [21] for their taller G+7 model, where the upper storey is more flexible to dominate the modal response due to the smaller fraction of the transfer level in the total building height.

The frequencies of the modes 1-3 in the FC model (1.211-1.890 Hz) are converging to that of the WFC model (0.968-1.567 Hz) which confirms that in the required model there are closely spaced modes and hence the necessity to use the combination rule of CQC rather than that of SRSS as per IS 1893 [5].

V. CURRENT TRENDS AND DEVELOPMENTS

Performance-Based Seismic Design (PBSD)

Floating-column buildings are increasingly being designed using a performance-based method that explicitly sets building performance objectives (immediate occupancy, life safety, collapse prevention) at a specified level of hazard. The work done by Garg and Sharma [17] is the most systematic fragility study in the Indian context for which IDA paradigm has been applied, where fragility quantified as loss of collapse capacity due to combination of setback and floating-column irregularities. The methodology produces fragility curves giving the probability of failure to meet a performance limit state for a range of spectral accelerations to identify the risk of failure for design decisions that go beyond the deterministic IS-code approach.

Non-linear Progressive Collapse Analysis

In critical buildings, the recommendations of IS 875 (Part 5): 2015 [16] on robustness have led to the development of progressive collapse analysis as an ancillary design check for floating-column buildings when subjected to notional column removal conditions. Wang et al. [15] showed that the primary mechanism of resistance is the catenary action in the transfer member and that it must be continuously reinforced at or near the location of maximum sagging moment, which is at the bottom. Later Zhang and Zhang [24] simplified DAFs (elastic response 1.8; inelastic response 2.6) to allow for preliminary design without the need to full non-linear dynamic simulation.

Near-Fault and Long-Period Ground Motion Effects

Singh and Agrawal [22] reported that near-fault, pulse-like motions are dangerous to floating-column buildings due to the occurrence of the pulse duration happening to be equal to the elongated fundamental period of the FC model, causing resonance-like amplification with up to 1.8× increase in transfer-beam bending moments compared to the far-field ground motion of the same magnitude. There are important implications for buildings near active faults, such as those in Zone IV and V of the IS 1893 seismic zoning map.

Computational Intelligence in Transfer System Optimisation

Kaveh and Zakian [18] showed the optimization solution of transfer beam geometry and reinforcement of RC frame with floating columns using the harmony-search metaheuristic. Pareto optimal solutions between material cost and seismic performance were obtained. Although the approach is currently very compute-intensive, it is a stepping stone to an IS-code design space that is rapidly optimised using machine-learning surrogate models. The logical extension of floating-column systems is similar genetic algorithm and neural-network approaches which have been successfully applied to regular RC frames [18].

VI. CHALLENGES AND LIMITATIONS

Technical Design Challenges

The principal technical challenges in floating-column structural design are summarised below:

- The main technical problems that face the floating column structural design are summarized as follows:

- The shearing of shear force at the transfer beams is 4 times to 6 times that of regular shear beams, which brings about the requirements for details, such as closely spaced stirrups, diagonal reinforcement and corner hairpins, that may be hard to be carried out in the congested construction area around column cages.
- Conventional flexural theory does not apply to deep-beam behaviour, and Transfer beams with a span/dpth ratio < 4 violate the assumption of plane-section behaviour. Theoretically, it is suggested that strut-and-tie modelling as per IS 456: 2000 Annex B should be used but it is seldom used in practice which may result in underestimation of diagonal cracking at serviceability loads as per IS 456: 2000 Annex B [11].
- Torsional coupling: If the floor plan is not symmetric and floating columns are situated off-center, eccentricity between centre of mass and centre of stiffness results in torsional modes which the ESM can't account for; RSM at least with three dimensional modelling is needed [5].
- The high sustained dead load due to the floating column above can cause cracking to non-structural elements at the transfer floor because of long term creep and shrinkage deflection of the transfer beam. Deflection limitations (IS 456: 2000 deflection limits span/350 or 20 mm) can be applied independently of strength limits in the case of transfer-beam sizing [25].
- The sequence for construction of the casting of the transfer beam relative to the floating column influences the residual stress state at the critical section. When building up in a congested urban site, top down construction can cause unplanned differential settlements that are not detected by conventional linear analysis [2].

Code and Regulatory Limitations

IS 1893 (Part 1): 2016 [5] prescribes 1.5× amplification of the design forces for irregular storey of building with floating columns in Zone III and above but does not give any specific guidance for Zone II buildings. Based on the Zone II literature reviewed and analyzed in the present review, the displacement amplification factors ranged from 67 % to 101 % for the buildings, and were within the range of higher-zone buildings, indicating that the Zone II exemption from mandatory RSM might not be sufficient for buildings taller than G+2. IS 456: 2000 [25] does not have a specific chapter devoted to transfer-beam design, and the use of the general deep-beam clauses which are not specifically calibrated to the combined gravity-seismic loading scenario is expected to be problematic.

Research Gaps

The published literature does not address:

- Detailed data for G+9 floating-column buildings are not available; and studies are available for Zone III and IV.
- There are few studies which have pursued non-linear time-history analyses specifically designed for Indian ground motion records [17],[22].
- The interaction of floating-column irregularity and plan irregularity (torsion) due to biaxial seismic loading has not been systematically studied.
- There are no peer-reviewed life-cycle cost analyses that have taken into account the cost premium of the structure versus rental income from column-free floor areas.
- Genuine testing of STAAD.There was no report on the prediction of Pro and ETABS of floating-column buildings under cyclic loading (monotonic or modal loading).
- Machine-learning surrogate models for the rapid design of floating columns which comply to IS codes are still in their infancy and not yet validated with physical test data.

VII. FUTURE RESEARCH DIRECTIONS

Non-linear Time-History Analysis

Most of the current knowledge is based on linear elastic analysis (ESM and RSM). The inelastic deformation capacity, hysteretic energy dissipations and collapse margin ratios of floating-column buildings of various heights (G+2 to G+14) and seismic zones (II to V) must be characterised with a systematic programme of non-linear time-history analysis of a suite of twenty or more IS 1893-compatible ground motion records, including both far-field and near-fault records. This study will yield fragility curves for use in risk-informed design and would be used to calibrate force amplification factors for IS 1893 for Zone II scenario.

Base Isolation and Supplemental Damping

The base isolation systems considered, that is, lead-rubber bearings (LRB), friction pendulum systems (FPS) and triple friction pendulum (TFP) bearings, significantly reduce floor accelerations and interstorey drifts, and potentially limit the seismic demand amplification at the transfer level in floating-column buildings. It would be important to fill the gap in knowledge with a parametric investigation of the structural performance and cost-effectiveness of base-isolated floating-column buildings as compared to conventionally designed buildings in Zones III and IV.

Machine Learning-Assisted Design Optimisation

Building on the harmony-search optimisation of Kaveh and Zakian [18], supervised learning models (gradient boosting regressors, deep neural networks) trained on large databases of IS-code STAAD.Pro analyses could generate surrogate models that could predict the quantities of transfer beams and columns from the high-level inputs (floor count, span, zone, soil type) in real time to facilitate rapid iterative design in professional practice.

Robustness and Residual Capacity

Floating-column buildings should be evaluated according to robustness analyses carried out for progressive collapse following the provisions of IS 875 (Part 5): 2015 [16] analysing remaining capacity after transfer-beam failure. Wang et al. [15] determined catenary action minimal reinforcement requirements that require experimental verification for post-earthquake aftershock cyclic loading.

Hybrid Structural Systems

This approach of steel outrigger trusses, post-tensioned concrete bands, or composite steel-concrete transfer girders with otherwise conventional RC floating-column frames is an under-explored design strategy, which could simultaneously alleviate the deep-beam design problem, increase ductility (steel energy dissipation) and reduce the overall building height. Comparative studies of similar hybrid systems to traditional RC transfer beams are warranted.

VIII. CONCLUSION

Summary of Findings

This review has compiled 30-year long research for floating column structural system in reinforced-concrete high-rise buildings. The critical analysis of published experimental, analytical and computational investigations leads to the following key conclusions:

1. For all lateral displacement, floating columns will generally amplify the displacement at the transfer level, up to 45% to 110% greater than equivalent regular frame columns. The 101.1% increase for G+2 Zone II is the maximum one reported in the Indian low-to-moderate seismicity literature: this is the figure to be used in the present study.
2. **Force concentration:** Maximum bending moments of the Transfer columns are 200-362% higher and maximum axial forces are 133-161% higher than those of regular frame columns. Transfer-beam bending moments are 4-7 times the equivalent regular-beam moments, and shear forces are 3-5 times as high, thus emphasizing the importance of the transfer-member design within the structural system.
3. **Modal characteristics:** Low-rise FC buildings' fundamental frequencies tend to increase when there is mass redistribution at the transfer level and thus the frequencies of the modes move close together, requiring combination of CQC. Near-fault ground motions take advantage of the long period of tall FC buildings to cause resonance type amplification.
4. **Cost premium:** Floating-column construction always costs 14-20% more than regular frames, due to the added cost of concrete and reinforcing steel, which are increased by 35-40% and 15-20%, respectively. Such a premium can be realized commercially within 3-5 years based on the difference between the rent for column-free floor space.
5. **Code adequacy:** The mandatory RSM and 1.5× force amplification requirements of IS 1893 for Zones III and above are in general consistent

with the literature; however, the exception for Zone II looks inadequate for buildings above G+2. The lack of specific guidance on transfer beams in IS 456 is still a practical constraint.

Key Recommendations

The following recommendations, based on the results of this review, are targeted at practicing engineers, researchers and code bodies:

R1. Considering the well documented higher-mode amplification in literature [1] and [5] for all floating-column buildings in Zones II and above, it is recommended to make mandatory RSM: Response Spectrum Method for all these buildings without considering the height.

R2. For a/d < 4, transfer beams should be designed by strut and tie modelling as per IS 456 Annex B and stress concentration at the re-entrant corner of the beam and column should be taken care by providing corner confinement reinforcement [11] [13].

R3. Progressive Collapse Detailing: Transfer beams and slabs should have continuous bottom reinforcement (lap length ≥ 1.5ld at mid-span) to ensure catenary robustness against progressive collapse in the event of notional column loss [15], [16].

R4. Extension of 1.5× force amplification provision to Zone II buildings with floating columns; a special code chapter for design of transfer-beam and transfer-slab structures in high-rise buildings.

R5. For floating-column buildings in Zone II, the published database is limited and the following research priorities should be addressed: non-linear time-history analysis, fragility curves based on IDA, and design optimisation using machine learning techniques.

REFERENCES

1. E. V. Valmundsson and J. M. Nau, "Seismic response of building frames with vertical structural irregularities," Journal of Structural Engineering, ASCE, vol. 123, no. 1, pp. 30-41, Jan. 1997.
2. T. Paulay and M. J. N. Priestley, Seismic Design of Reinforced Concrete and Masonry Buildings. New York, NY: Wiley, 1992.
3. S. R. Damodarasamy and S. Kavitha, Basics of Structural Dynamics and Aseismic Design. New Delhi: PHI Learning, 2009.
4. S. Mhatre and P. Jain, "Structural behaviour of RC buildings with floating columns in different seismic zones of India," International Journal of Civil Engineering and Technology, vol. 8, no. 4, pp. 1634-1643, Apr. 2017.
5. Bureau of Indian Standards, IS 1893 (Part 1): 2016 — Criteria for Earthquake Resistant Design of Structures, Part 1: General Provisions and Buildings. New Delhi: BIS, 2016.
6. S. K. Jain and W. R. Lettis, Eds., Bhuj, India Earthquake of January 26, 2001 Reconnaissance Report. Earthquake Spectra Supplement Vol. 18, Oakland, CA: EERI, 2002.
7. K. Goda et al., "The 2015 Gorkha Nepal earthquake: insights from earthquake damage survey," Frontiers in Built Environment, vol. 1, art. 8, 2015.
8. K. H. Kwan and T. C. Liauw, "Reinforced concrete buildings with transfer structures in high seismic zones," ACI Structural Journal, vol. 91, no. 6, pp. 661-667, Nov.-Dec. 1994.
9. R. Park and T. Paulay, Reinforced Concrete Structures. New York, NY: Wiley, 1975.
10. R. K. L. Su, A. M. Chandler, M. N. Sheikh, and N. T. K. Lam, "Influence of non-structural components on lateral stiffness of tall buildings," Structural Design of Tall and Special Buildings, vol. 14, no. 2, pp. 143-164, 2005.
11. K. H. Tan, S. T. Tong, and C. Y. Tang, "Indirect strut-and-tie model for deep beams and pile caps," ACI Structural Journal, vol. 98, no. 2, pp. 169-178, Mar.-Apr. 2001.
12. R. K. L. Su, S. M. Cheng, and A. Chow, "Experimental study on RC transfer beams under combined gravity and lateral loading," Engineering Structures, vol. 174, pp. 284-298, Nov. 2018.
13. X. Huang, Y. Gong, and C. Cheng, "Three-dimensional finite element analysis of transfer beams in high-rise buildings," Journal of

Building Structures, vol. 38, no. 5, pp. 56-65, May 2017.
14. Bureau of Indian Standards, IS 13920: 2016 — Ductile Design and Detailing of Reinforced Concrete Structures Subjected to Seismic Forces. New Delhi: BIS, 2016.
15. X. Wang, L. Zhang, and Y. Li, "Progressive collapse analysis of high-rise buildings with transfer plate structures," Journal of Performance of Constructed Facilities, ASCE, vol. 33, no. 3, art. 04019024, Jun. 2019.
16. Bureau of Indian Standards, IS 875 (Part 5): 2015 — Design Loads: Special Loads and Load Combinations. New Delhi: BIS, 2015.
17. N. Garg and R. Sharma, "IDA-based fragility assessment of RC buildings with combined setback and floating column irregularities," Structures, vol. 29, pp. 2014-2028, Feb. 2021.
18. Kaveh and P. Zakian, "Optimal seismic design of RC frames with floating columns using enhanced meta-heuristic algorithms," Engineering with Computers, vol. 36, no. 3, pp. 1081-1099, Jul. 2020.
19. P. P. Chandurkar and P. S. Pajgade, "Seismic analysis of RCC building with and without shear wall," International Journal of Modern Engineering Research, vol. 3, no. 3, pp. 1805-1810, 2013.
20. Mundada and S. Sawdatkar, "Comparative seismic analysis of multistory building with and without floating column," International Journal of Current Engineering and Technology, vol. 4, no. 5, pp. 3395-3400, 2014.
21. S. Wadekar and S. Denge, "Seismic analysis of RC building with floating columns," International Journal of Engineering Research and Technology, vol. 5, no. 3, pp. 77-81, 2016.
22. P. Singh and V. Agrawal, "Seismic behaviour of RC buildings with floating columns under near-fault ground motions," Journal of Earthquake Engineering, vol. 26, no. 8, pp. 4203-4224, 2022.
23. R. Patel and C. Khokhar, "Comparative study of RC building with floating column using STAAD.Pro and ETABS," International Journal of Engineering Research and Technology, vol. 5, no. 1, pp. 112-117, Jan. 2016.
24. Y. Zhang and W. Zhang, "Dynamic amplification factors for transfer beams in progressive collapse scenarios," Engineering Failure Analysis, vol. 101, pp. 267-281, Jul. 2019.
25. Bureau of Indian Standards, IS 456: 2000 — Plain and Reinforced Concrete — Code of Practice, 4th rev. New Delhi: BIS, 2000.
26. K. Chopra, Dynamics of Structures: Theory and Applications to Earthquake Engineering, 5th ed. Hoboken, NJ: Pearson, 2020.
27. Bentley Systems, STAAD.Pro V8i SELECTseries 5: Technical Reference Manual. Exton, PA: Bentley Systems Inc., 2014.
28. Bureau of Indian Standards, IS 875 (Part 1 and Part 2): 1987 — Code of Practice for Design Loads for Buildings and Structures. New Delhi: BIS, 1987.
29. Bureau of Indian Standards, IS 875 (Part 3): 2015 — Design Loads: Wind Loads. New Delhi: BIS, 2015.
30. Bhosale, R. Davis, and P. Sarkar, "Vertical irregularity of buildings: regularity index versus seismic risk," ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, vol. 3, no. 3, art. 04017001, Sep. 2017.
31. G. Magliulo, C. Petrone, V. Capozzi, G. Maddaloni, P. Lopez, and G. Manfredi, "Seismic performance evaluation of RC buildings with infills and pilotis through non-linear dynamic analyses," Engineering Structures, vol. 56, pp. 1729-1743, Nov. 2013.