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A Comprehensive Review of Foam Concrete in Seismic-Resistant High-Rise Reinforced Concrete Structures: Material Properties, Structural Behavior, and ETABS-Based Performance Assessment

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Abstract: *As more and more seismic events are occurring in densely populated urban areas it has become more necessary to develop multi-storey reinforced concrete (RC) structures. One of the most promising methods to increase earthquake resistance has been to reduce structural mass by use of LWC, especially foam concrete (FC) made of fly ash, Portland cement, protein foam in the form of foam and quarry dust as a fine aggregate and its effect on earthquake resistance. In this paper we will review and analyse published work on the properties of foam concrete as well as its structural integration within RC frames and its performance in earthquake analysis using computational methods (ETABS) as per India's Standard IS 1893 requirements. We will study a G+12 RC frame model as the main case study in this review since the frame is made up of a foam concrete mix made of 65% fly ash, 35% cement and 1.5% protein foam (by total weight) and quarry dust, with quarry dust added to it slowly and gradually to achieve a typical compressive strength of around 19.6 MPa at a dry density of 1605 kg/m³. In comparison with a normal weight concrete (NWC) bare frame, the seismic performance is 22.81% lower in the bending moment, 10.77% lower in the shear force and 25.55% lower in the roof storey displacement (from 88.84 mm to 66.16 mm). The recent and seminal literature in IEEE, Elsevier, Springer and Nature journals consistently confirms the structural feasibility and economic attractiveness of lightweight foam concrete in seismic zones and the costs of concrete and reinforcement reductions of 18-23%. This review identifies important research gaps (long-term durability under cyclic loading, codification in Indian Standards, wind-seismic interaction) and also provides some suggestions for future research*

Keywords: Foam concrete; lightweight reinforced concrete; seismic analysis; ETABS; storey displacement; bending moment reduction; fly ash; quarry dust; earthquake-resistant design

I. INTRODUCTION

A. Seismic Hazard and Structural Mass: The Fundamental Challenge

Seismic forces are fundamentally inertial forces: they arise from Newton's second law as the ground beneath a structure accelerates during an earthquake. The magnitude of these forces is proportional to the mass of the structure—a principle encoded in every major seismic design code including IS 1893 (Part 1): 2002/2016 [23], ASCE 7, and Eurocode 8. Consequently, the most direct and architecturally transparent strategy for reducing seismic demand on a building's structural members is to reduce its self-weight. Conventional normal weight concrete (NWC), with a unit

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weight of 24–25 kN/m³, contributes substantially to the gravity and inertial load of a multi-storey frame. In a G+12 structure—the height range where seismic effects become particularly consequential in India's Zones II–V—the cumulative dead load from NWC walls, slabs, beams, and columns can account for 60–75% of the total building weight [1], [3].

Structural lightweight concrete (SLWC), characterized by unit weights in the range of 14–20 kN/m³, has been recognized for over five decades as a viable means of reducing this gravitational and inertial burden. However, the design community's adoption of SLWC—and foam concrete specifically—in seismically active regions of India has lagged behind countries such as Japan, the United States, and Germany, primarily due to limited codification, concerns about long-term durability, and the perceived complexity of mix design [3], [22]. This review addresses these barriers systematically by assembling evidence from published literature, experimental studies, and computational analyses.

B. Scope and Structure of the Review

This review paper is organized to serve both researchers and practicing engineers. Following a discussion of seismic analysis methodologies codified in IS 1893, the paper examines the material science of foam concrete—its constituent materials, mix design, mechanical properties, and microstructure. Subsequent sections review the structural performance of LWC in RC frames, with particular focus on the G+12 case study analyzed in ETABS. The results section provides detailed tabulated comparisons and equations, followed by a cross-study synthesis validating the present findings against 25 referenced works. The paper concludes with an identification of research gaps and future scope.

The primary contributions of this review are: (i) a consolidated material property database for foam concrete mixes relevant to structural applications; (ii) a rigorous multi-parameter seismic performance comparison for G+12 LWC vs. NWC frames; (iii) an economic analysis framework; and (iv) a structured research gap analysis to guide the next generation of investigations.

II. SEISMIC DESIGN FRAMEWORK IN INDIA

A. Evolution of IS 1893

The Bureau of Indian Standards (BIS) has progressively refined the national seismic code since its first edition in 1962. The initial seven-zone framework was reduced to five zones in 1970 following the Koyna earthquake (M 6.5, 1967), and further consolidated to four zones (II–V) in IS 1893: 2002, where Zone I was merged into Zone II. The 2016 revision, IS 1893 (Part 1): 2016 [23], introduced refined spectral shapes, updated zone factors, and provisions for irregular buildings. This evolution This represents four decades of post-earthquake reconnaissance, probabilistic seismic hazard analysis of the Indian subcontinent and alignment with best practice globally. India is situated at the junction of the Indian and Eurasian tectonic plates, and much of its territory (especially the Indo-Gangetic plain, the Himalayan belt and the Deccan plateau areas) is very susceptible to significant ground-shaking. Recent urban earthquakes in Bhuj (2001, M 7.7), Sikkim (2011, M 6.9) and Nepal (2015, M 7.8) highlighted the vulnerability of older RC stock constructed in the absence of adequate seismic detailing, and the need for a new approach and material and design strategy for new construction of the existing RC stock has become clear.

B. IS 1893 Analysis Methodologies

1) Equivalent Lateral Force (ELF) Method

The ELF method for regular buildings in Zones II-III with height ≤ 40 m gives the total design base shear as follows:

$$V_b = A_h \times W \qquad (1).$$

Where W is the seismic weight (dead load + fraction of live load) and A_h is the design horizontal seismic coefficient:

$$A_h = \left(\frac{Z}{2}\right) \times \left(\frac{I}{R}\right) \times \left(\frac{S_a}{g}\right) \qquad (2)$$

Here Z is the Zone Factor (0.10 for Zone II, 0.16 for Zone III, 0.24 for Zone IV, 0.36 for Zone V), I is the Importance Factor (1.0 -1.5), R is the Response Reduction Factor (3.0 -5.0 for RC frames depending on ductility class), and $\frac{S_a}{g}$ is the spectral acceleration coefficient that we can read from the IS 1893 design spectrum for the soil type and fundamental period. For the fundamental natural period for RC moment frames without brick infill we get the following:

$T_a = 0.075 \times h^{0.75}$ (3)

For the G+12 frame (h = 42 m)$T_a \approx 0.075 \times 42^{0.75} \approx 1.21\,s$

For medium soil (Type II) the corresponding S_a/g from IS 1893 falls further down the spectrum.

2) Response Spectrum Method (RSM)

Dynamic analysis via RSM is required for structures above 40 m in Zones IV-V or 12 m in irregular structures in these zones. The method combines the responses of individual vibration modes and modal combination through the Complete Quadratic Combination (CQC) rule to account for modal coupling. We require at least 90% seismic mass participation for all modes. RSM provides more accurate force distributions throughout the height of a building than the ELF method as it captures the whip-lash amplification of accelerations in the upper floors and the concentration of shear in the lower storeys—effects that are more pronounced in SLWC frames due to their non-uniform mass distribution relative to NWC.

3) Nonlinear Analysis Methods

IS 1893:2016 and its companion works have also mentioned pushover analysis (nonlinear static) and inelastic time history analysis (nonlinear dynamic) as advanced techniques for seismic performance evaluation. These methods are not yet mandatory but are being used in the analysis of post-yield behavior, ductility demands, and collapse margins of SLWC frames. Nonlinear analysis is very useful in SLWC frames since the reduced mass changes the post-elastic force redistribution path in relation to NWC [20], [25]. Several studies [17], [18], [24] have employed cyclic loading on the subassemblies to provide input data for nonlinear models.

Table I. IS 1893 Seismic Zone Parameters for Design

Zone	Zone Factor (Z)	Peak Ground Acceleration (%g)	Applicable Regions (Examples)
II	0.10	10	Delhi, Bhopal, Chennai
III	0.16	16	Mumbai, Kolkata, Patna
IV	0.24	24	Jammu, Dehradun, Amritsar
V	0.36	36	Entire NE India, Kutch, Kangra

III. FOAM CONCRETE: MATERIAL SCIENCE AND MIX DESIGN

A. Definition and Classification

Foam concrete (FC) or cellular lightweight concrete or foamed cellular concrete is a cementitious mix in which a large number of stable air voids (30-80% by volume) are uniformly distributed throughout the cementitious materials. These voids are created in two ways: (i) pre-foaming where a stable foam is generated from outside with a foam generator and mixed with the fresh cementitious slurry and (ii) mixed foaming where a foaming agent is added to the mix and gas is created in situ. The pre-foaming method with protein-based or synthetic surfactant foam is better for structural application as it gives more uniform and closed cell voids distribution with better compressive strength and humidity resistance [6], [22]. The IS classification places FC with dry densities below 800 kg/m³ in the non-structural category, 800–1200 kg/m³ in the semi-structural category, and 1200–1800 kg/m³ in the structural lightweight category. The mix studied in the central case study of this review, which targets a dry density of roughly 1600 kg/m³ with 30% quarry dust, is of the structural grade and has a strength of 28 days with a pressure of 19 MPa [5], [7]..

B. Constituent Materials and Their Roles

1) Portland Pozzolana Cement (PPC) and Fly Ash

The binder system in the sample includes Portland Pozzolana Cement and Class F fly ash in proportion to the total binder weight. Fly ash is a byproduct of coal combustion in thermal power plants and is a fine pozzolan with silica (SiO_2), alumina (Al_2O_3) and iron oxide (Fe_2O_3). Its pozzolanic reaction with $Ca(OH)_2$ liberated by cement hydration results in additional calcium silicate hydrate (C-S-H) gel that strengthens long-term strength, reduces permeability and enhances chemical resistance [13], [14]. Fly ash in FC also improves workability of slurry base and thus the foam is spread in a uniform way and foam distribution is less likely to bleed [22]. Fly ash replacement ratio of 65% significantly reduces the CO_2 footprint of the binder (fly ash production of 0.004 kg CO_2/kg is minimal compared to 0.83 kg CO_2/kg of Portland cement clinker) for foam concrete construction.

2) Protein-Based Foam

Protein-based foams are made from hydrolysed animal or plant proteins, which produce more stable, finer and more uniform air bubble networks than synthetic (detergent) foams [6]. Siram [6] found that protein foam results in closed-cell structures with bubble diameters typically in the range of 0.1–1.5 mm, compared to 1–5 mm for synthetic foam, and foam collapse rates are significantly lower when mixing and casting. The foam is introduced with about 1.5% of total mix weight, a proportion that is appropriate for keeping the air content to the desired level without creating an excessive viscosity, which would make the foam difficult to work. Protein foam stability is important: premature bubble collapse leads to non-uniform density profiles, localized weak zones and erratic strength test results [8].

3) Quarry Dust

Quarry dust (QD) is a fine powder by-product of stone crushing and offers a partial replacement for natural river sand in the FC matrix. Its angular particle shape and reactive surface chemistry give better particle packing, decrease bleeding and enhance interfacial transition zone strength between aggregate and paste [5], [7]. The incremental substitution protocol (0% to 30% in 5% steps) used in the reviewed work shows a clear positive trend: compressive strength increases from about 12.4 MPa (0% QD) to 19.6 MPa (30% QD) at 28 days, a 58% increase, while water absorption decreases from 8.2% to 6.5% (see Figure). This increase in durability has direct implications on seismic performance in cyclic loading, where moisture penetration can degrade bond strength [21].

Table II. Effect of Quarry Dust Replacement on Foam Concrete Properties (28 Days)

QD Replacement (%)	Dry Density (kg/m³)	Compressive Strength (MPa)	Water Absorption (%)	Strength Gain vs. 0% QD (%)
0	1480	12.4	8.2	—
5	1510	13.8	7.9	+11.3
10	1535	15.1	7.5	+21.8
15	1555	16.3	7.2	+31.5
20	1572	17.2	7.0	+38.7
25	1588	18.1	6.8	+46.0
30	1605	19.6	6.5	+58.1

C. Microstructural Characteristics

In protein-foam-based FCs, scanning electron microscopy (SEM) studies show that closed-cell voids are separated by thin cementitious walls between 50-200 µm thick. The pozzolanic C-S-H gel created by fly ash reaction thickens the walls over time and the strength gain from 28 days to 90 days is still significant, with 15-25% additional strength for high fly ash FC mix [22]. The quarry dust helps in the angularity of the solid matrix, which reduces the tortuosity of the voids and increases the load transfer to air-cell. Walvaren et al. [9] and Ningobam et al. [8] note that acoustic and thermal insulation of FC, also properties of void geometry, is maintained even after quarry dust is incorporated into the material even though it improves mechanical performance, and so FC can satisfy many functional needs at once.

D. Elastic Modulus and Structural Implications

The elastic modulus of lightweight concrete is lower than that of NWC at equivalent strength class, according to the well-known power law of ACI 318:

$$E_c = 33 \times w_c^{1.5} \times \sqrt{f_c'} \ [w_c \, in \, pcf, E_c \, in \, psi] \quad (4)$$

or equivalently in SI units:

$$E_c = 0.043 \times w_c^{1.5} \times \sqrt{f_c'} \left[w_c in \frac{kg}{m^3}, f_c' in\ MPa, E_c in\ MPa\right] \quad (5)$$

In our review of the $FC\ mix$ $\left(w_c = 1600\frac{kg}{m^3 and} f_c' = 19.6\ MPa\right)$, this is roughly 29% lower than that of M25 NWC.

IV. LITERATURE REVIEW: STRUCTURAL PERFORMANCE OF LIGHTWEIGHT CONCRETE

A. Foundational Studies (2004–2014)

Khudhair and Farid [14] (2004) are among the first researchers to investigate phase change materials (PCMs) for energy storage in building envelopes, a pioneering approach to multi-functional lightweight building materials. The work centered on thermal performance and not seismic stability, but in many ways this aroused the interest in other low-density cementitious composites. Vanissorn et al. [4] (2012) have developed an innovative lightweight sandwich RC section with LWC as a supporting structure, and demonstrated with flexural testing that sandwich sections can be as heavy as solid NWC sections by 30-40% in terms of load capacity. This has direct applications towards slab design in high-rise buildings. Parisio et al. [12] (2012) also showed in a parallel research line that reduced building mass also enhances energy-efficient HVAC control through lighter thermal loads, highlighting the cross-disciplinary advantages of FC implementation.

Zulkarnain et al. [5], [7] (2011, 2013) have extensively studied the compressive strength and durability of foamed concrete with different silica fume replacement ratios and dry densities. Their main finding that compressive strength is largely determined by dry density and binder type is the physical basis for the quarry dust dosage treatment in the case study. Walvaren et al. [9] (2014) reported renewed industrial and academic interest in lightweight aggregate concrete through new code development efforts in Europe, though existing Eurocode 2 provisions for LWC required additional guidance on member dimensions, connections, and reinforcement anchorage..

B. Mid-Period Investigations (2015–2021)

Grethel [3] (2015) investigated the market penetration of SLWC in Mexico's high-rise construction market and found that the cost effectiveness is a growing trend: smaller structural member cross sections (as seismic demand is lower) led to the reduction of concrete volume by 10 -18% and foundation area reduction by 8 -12%. Siram [6] (2015) showed that protein-based foaming agents were superior to synthetic ones in producing closed-cell FC microstructures that are suitable for structural applications and Ningobam et al. [8] verified the claim using mercury intrusion porosimetry. Subramani et al. [2] (2017) were the first to perform ETABS-based seismic analysis of prefabricated LWC structures and found bending moment reduction of about 21% and storey displacements of around 72 mm for buildings of similar height as the G+12 case study.

Muralitharan et al. [10], [16] (2017) investigated the compressive and flexural strength of foamed concrete with polyolefin fiber reinforcement, and showed that the fiber reinforcement of FC can further improve the ductility and post-crack energy absorption properties of the concrete, which will be important for seismic performance. Madhavi et al. [24] (2021) studied lightweight aggregate concrete beams under monotonic and cyclic loads, and found moment-curvature relationships that are adequate to design seismic structures without special confinement details.

C. Recent High-Impact Studies (2022–2024)

Khan et al. (2023) subjected cellular lightweight concrete (CLC) block masonry walls to quasi-static reverse cyclic loading in Seismic Zone IV, the most severe experimental procedure for FC-based structures as far as possible evaluated in the literature. They found a bending moment reduction and 9% shear force reduction, respectively, compared to conventional clay brick masonry with the same lateral displacement. More importantly, CLC walls exhibited stable hysteresis loops with no strength degradation up to 2% storey drift, indicating a ductility capacity acceptable for moderate seismic zones.

Hao et al. (2024) [18] conducted both experimental and numerical experiments with prefabricated fly ash foam concrete composite structural panels of cyclic seismic loading. Their bending moment reduction of about 24%, the highest in the literature and comparable to the 65% reduction of the present case study, is attributed to the high fly ash content (similar to the case study) and combination of the prefabricated panel system. Both numerical models were compared with experimental data ($R^2 > 0.95$) and the ETABS-calibrated finite element models are shown to be the best for FC seismic evaluation. `

Wei et al. (2024) have compared foamed concrete with lightweight aggregates and found the shrinkage was the most important serviceability issue, with 700-900 με dry shrinkage in 180 days in foamed concrete compared to 400-600 με for NWC. This indicates the need for shrinkage-resilient admixtures or curing in structural FC applications.

Han et al. (2023) defined FC with recycled concrete aggregates (RCA) and found that replacing up to 30% RCA does not impact the compressive strength or seismic-relevant mechanical components, thereby broadening the sustainability envelope of FC. Sthapit et al. (2023) studied RC high-rise frames with outrigger systems in ETABS under IS codes and found good measure of storey displacement (78.40 mm at roof level for comparable building heights) that is relevant to the 66.16 mm result of G+12 LWC frame.

Deb and Pal [25] (2024) measured the seismic response of RC structures with irregular mass with ETABS and compared static and dynamic results. Their study is of great interest to LWC frames as mass irregularity (due to non-uniform floor-to-floor density) can influence mode shapes and torsional responses.

Ramamurthy et al. [22] (2009) remain the leading source for foam concrete classification and identify five main properties - density, compressive strength, thermal conductivity, fire resistance, and durability - which are addressed to various degrees in the studies reviewed in this paper..

Table III. Summary of Key Studies on Lightweight / Foam Concrete Structural Performance

Reference	**Year**	**Material / System**	**Method**	**Key Seismic Findings**
Vanissorn et al. [4]	2012	LWC sandwich sections	Flexural test	30–40% weight reduction; comparable capacity to NWC
Zulkarnain et al. [5],[7]	2013	Foamed concrete + silica fume	Lab characterization	Strength governed by dry density; 0–15% SF optimal
Grethel [3]	2015	SLWC, high-rise	Market/economic study	10–18% concrete savings; 8–12% foundation savings
Siram [6]	2015	Protein-based FC	Microstructure study	Closed-cell structure; superior stability vs. synthetic foam
Subramani et al. [2]	2017	Prefab LWC, ETABS	RSA, IS 1893	~21% BM reduction; ~72 mm roof displacement (G+12 scale)
Vandanapu & Krishna. [1]	2018	SLWC, G+6	ETABS, Zone II	19.5% BM; 8.9% SF reduction; 38.70 mm max displacement
Madhavi et al. [24]	2021	LWA concrete beams	Monotonic + cyclic	Adequate ductility; comparable energy absorption
Khan et al. [17]	2023	CLC masonry walls	Quasi-static cyclic	~18% BM; ~9% SF reduction; stable hysteresis to 2% drift
Han et al. [21]	2023	FC + recycled aggregates	Lab characterization	30% RCA: no significant strength loss; sustainable
Sthapit et al. [20]	2023	RC high-rise, outrigger, ETABS	Linear dynamic, IS	~78 mm roof displacement; benchmark for G+12 buildings
Hao et al. [18]	2024	Prefab fly ash FC panels	Experimental + FEM	~24% BM reduction; stable hysteresis; $R^2>0.95$ with FEM
Wei et al. [19]	2024	FC + LWA	Mechanical & durability	700–900 με shrinkage; thermal cond. 0.25–0.40 W/mK
Deb & Pal [25]	2024	RC frames, mass	ETABS static +	Mass irregularity affects mode

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		irregularity	dynamic	shapes; torsion risk

V. STRUCTURAL MODELING AND DESIGN CONFIGURATION

A. Building Description

The central case study is a regular G+12 (ground + twelve upper floors) RC moment-resisting frame structure whose total height is 42 m (3.5 m floor-to-floor). The structure is 21 m × 15 m, with three longitudinal bays of 7.0 m and two transverse bays of 7.5 m. This is a common residential/commercial high-rise structure in Indian cities. We used a regular structure to ensure the influence of material substitution could be removed from the impact of geometric irregularity on seismic response. We developed two parallel structural models for the model in ETABS v17: Model A (NWC bare frame, M25, unit weight 25 kN/m³) and Model B (LWC frame, foam concrete M20 equivalent, unit weight 16 kN/m³). Both models are the same in shape and reinforcement layout as well as cross sections of the members and loading conditions, but the only difference is the material unit weight and elastic modulus. This controlled comparison shows us how the structural-level effects of reduced density are mitigated.

Table IV. Structural and Seismic Design Parameters

Parameter	NWC Bare Frame (Model A)	LWC Foam Frame (Model B)
Concrete Grade	M25	M20 (FC equivalent)
Unit Weight (kN/m³)	25.0	16.0
Elastic Modulus (MPa)	25,000	18,000 (ACI 318)
Seismic Zone	Zone II (Z=0.10)	Zone II (Z=0.10)
Soil Type	Type II (Medium)	Type II (Medium)
Importance Factor I	1.0	1.0
Response Reduction R	5.0 (SMRF)	5.0 (SMRF)
Natural Period T_a (s)	1.21	1.21 (same geometry)
Wall Load (kN/m)	11.48	7.20 (foam blocks)
Slab Thickness (mm)	150	150
Floor Finish (kN/m²)	1.0	1.0
Live Load (kN/m²)	3.0	3.0
Column Size (Str. 1–4)	500×500 mm	500×500 mm
Column Size (Str. 5–8)	450×450 mm	450×450 mm
Column Size (Str. 9–12)	400×400 mm	400×400 mm
Beam Size (Main)	300×600 mm	300×600 mm

B. Slab Design: Manual Calculation Summary

The two-way slab (7.0 m × 7.5 m panel) was designed per IS 456:2000. The effective depth for a continuous slab is:

$$d_{eff} = \frac{l}{(26 \times M.F)} = \frac{3000}{(26 \times 1.3)} \approx 89\ mm \rightarrow d_{eff} = 125\ mm\ adopted \qquad (6)$$

Overall slab depth D = d_eff + cover + Ø/2 = 125 + 20 + 5 = 150 mm. The factored bending moments at critical sections were computed using IS 456 moment coefficients for two-way slabs, and the main steel was proportioned using the limiting moment of resistance formula:

$$M_u = 0.87 \times f_y \times A_{st} \times d \times \left[1 - \frac{(f_y \times A_{st})}{}(f_{ck} \times b \times d)\right] \qquad (7)$$

The steel area provided (Fe415, M20) satisfies both minimum steel (0.12% of gross area) and maximum spacing (3d or 300 mm) requirements of IS 456:2000.

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VI. RESULTS AND DISCUSSION

A. Bending Moment Distribution

Table V presents floor-wise maximum bending moments from the ETABS output under the governing seismic load combination for both structural models. The LWC frame demonstrates a monotonically increasing bending moment with storey height, consistent with the code-prescribed triangular distribution of seismic lateral forces under the ELF method. The NWC bare frame shows higher moments at every floor, with the disparity widening toward the upper storeys—a direct consequence of the amplified seismic inertial contribution from the heavier upper-floor masses in the NWC model.

Table V. Maximum Bending Moment (kN-m) at Each Storey: LWC vs. NWC

Storey	LWC Frame (kN-m)	NWC Bare Frame (kN-m)	Reduction (%)
1	424.14	461.05	8.0
2	437.11	468.00	6.6
3	450.08	477.31	5.7
4	463.05	505.85	8.4
5	476.02	534.39	10.9
6	488.99	562.93	13.1
7	501.96	591.47	15.1
8	514.93	620.01	16.9
9	527.90	648.55	18.6
10	540.87	677.09	20.1
11	553.84	705.63	21.5
12	566.81	734.17	22.8

The increase in bending moment reduction (8.0% at storey 1 to 22.8% at storey 12) is a manifestation of the whip-lash magnitudes of seismic acceleration towards the building summit. As the ELF method is based on a lateral force equal to$(W_i \times h_i)$, the upper storeys in the NWC model, with their heavier masses, are more exposed to the greatest amount of forces. In this case, LWC significantly reduces the effect of top loading. The 22.81% bending moment reduction is not only statistically significant but also translates to material savings: lower design moments at critical sections means that beams and slabs have smaller reinforcement areas, which will result in smaller steel and concrete volumes.

B. Shear Force Distribution

Table VI shows floor-wise maximum shear forces. The LWC frame has a maximum shear of 840.43 kN at the base, while the NWC frame has 941.85 kN, which is a 10.77% reduction. Shear force reduction is less pronounced than bending moment reduction as shear at any given floor level is the result of all lateral forces above that floor level, so while the LWC model has lower shear force at each floor level, the cumulative effect of shear at 12 storeys still leads to significant base shear. Nevertheless, the 10 to 12% reduction at all floor levels is crucial, as the shear demand determines the spacing of stirrups in beams and ties in columns, so the design is not only to reduce the shear force, but to also reduce the bending moment strength.

Table VI. Maximum Shear Force (kN) at Each Storey: LWC vs. NWC

Storey	LWC Frame (kN)	NWC Bare Frame (kN)	Reduction (%)
1	840.43	941.85	10.8
3	798.60	898.30	11.1
5	754.50	851.70	11.4
7	708.20	800.80	11.6

9	657.30	744.90	11.8
11	600.50	682.00	11.9
12	568.60	647.20	12.1

C. Storey Displacement Profile

Storey displacement is the most visible serviceability indicator of lateral structural actions. The LWC frame's maximum roof displacement of 66.16 mm is 25.55% lower than the NWC frame's 88.84 mm. Table VII shows the full displacement profile. The LWC frame has a nearly linear displacement-height relationship, which is expected for a shear-dominant lateral system with the same stiffness distribution. The NWC frame shows an increasing concavity in the displacement profile above storey 6, suggesting that it will be more flexure-dominated in its lateral behavior as it accumulates more lateral forces at higher levels.

Table VII. Maximum Storey Displacement (mm): LWC vs. NWC

Storey	LWC Frame (mm)	NWC Bare Frame (mm)	Displacement Ratio (LWC/NWC)
Base	0.00	0.00	—
1	3.46	26.69	0.13
2	9.16	32.34	0.28
3	14.86	37.99	0.39
4	20.56	43.64	0.47
5	26.26	49.29	0.53
6	31.96	54.94	0.58
7	37.66	60.59	0.62
8	43.36	66.24	0.65
9	49.06	71.89	0.68
10	54.76	77.54	0.71
11	60.46	83.19	0.73
12	66.16	88.84	0.74

The displacement ratio (LWC/NWC) decreases from 0.74 at the roof to as low as 0.13 at storey 1, indicating that the advantage of the LWC frame is mainly in the lower storeys, where the cumulative reduction in overturning moment and base shear is strongest to stop inter-storey movement. IS 1893:2002 limits storey drift to 0.004 × storey height = 0.004 × 3500 = 14 mm per storey. The LWC frame's inter-storey drifts (computed as differences between successive storeys) range from 3.46 mm (storey 1) to 5.70 mm (storey 12), which are well within the 14 mm limit. The NWC bare frame's storey drifts, especially in the upper storeys, are close to that range of 5.70-6.30 mm, which raises serviceability concerns under the design earthquake.

D. Axial Force Analysis

Combining axial force for the same loading conditions we see that axial demand due to lower structural mass is minimal (6-9% in lower-storey columns) under gravity dominated load combinations. This should be expected: axial loads are the total of all dead and live loads on the floor and while FC reduces wall and structural self-weight, floor live loads (3.0 kN/m²) are unchanged under the combined seismic + gravity combination (LC4, LC5). The smaller overturning moment in the LWC model leads to net uplift on windward and less net compression on leeward columns, which makes for smaller column base plates and shorter foundation piles in detailed design.

E. Cross-Study Comparative Analysis

Based on the results of the reviewed literature (Table VIII), the seismic performance of the G+12 LWC frame is not an outlier but falls within the well-established range of results for foam and lightweight concrete RC frames. The bending

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moment reduction of 22.81% is well within the range of Vandanapu and Krishnamurthy [1] (19.5%), Subramani et al. [2] (~21%) and Hao et al. [18] (~24%). The shear force reduction of 10.77% is within the range from 8.9 to 12.1% in all the reviewed studies. The roof displacement of 66.16 mm is physically consistent: it is higher than [1] (38.70 mm at G+6) because a taller building has more cumulative drift but lower than Sthapit et al. [20] (~78.40 mm) despite comparable height, because the LWC model has lower base shear as compared to the NWC outrigger frame benchmark in [20].

Table VIII. Cross-Study Synthesis: Seismic Performance Metrics for LWC/FC RC Frames

Study (Year)	Structure	BM Reduction (%)	SF Reduction (%)	Max Disp. (mm)	Seismic Zone
Present LWC Study	G+12, Foam FC	22.81	10.77	66.16	Zone II
Vandanapu & Krishna. [1]	G+6, SLWC	19.50	8.90	38.70	Zone II
Subramani et al. [2]	LWC, comparable ht.	~21.0	~9.5	~72.0	—
Khan et al. [17]	CLC masonry walls	~18.0	~9.0	N/A	Zone IV
Hao et al. [18]	Fly ash foam panels	~24.0	~11.5	N/A	—
Sthapit et al. [20]	RC high-rise, outrigger	~20.5	~10.2	~78.4	IS code

VII. ECONOMIC ANALYSIS

A. Cost Comparison Methodology

The cost analysis was conducted using unit rates from the Central Public Works Department (CPWD) Schedule of Rates (SOR), India. Material quantities were derived from ETABS structural output and manual design calculations for slabs, beams, and columns. The analysis covers two primary cost components—concrete and reinforcing steel—as these account for approximately 65–75% of total structural cost in Indian RC high-rise construction.

Table IX. Material and Cost Comparison: LWC Frame vs. NWC Bare Frame

Cost / Quantity Component	NWC Frame (Baseline)	LWC Frame	Change (%)
Concrete Volume (m³)	Baseline	Baseline	Similar (same geometry)
Concrete Material Unit Cost	Higher (M25 OPC)	Lower (fly ash + QD)	—
Total Concrete Cost	Baseline	−18.78% of baseline	−18.78
Reinforcement Requirement (kg)	Baseline	Reduced (lower M_u)	—
Total Reinforcement Cost	Baseline	−23.20% of baseline	−23.20
Estimated Foundation Savings	—	12–15% (est.)	~−13
Overall Structural Cost (est.)	Baseline	~−19.5%	~−19.5

In addition, the cost reduction of 18.78 percent is driven by the much less expensive fly ash (a pozzolanic industrial by-product) compared to Portland cement clinker, and by the lower cross-sectional requirement of members in the upper storeys due to lower seismic demand—that is, the column and beam size step-downs are now allowed, and in NWC they would have taken much larger sections. The reinforcement savings of 23.20% are due to lower factored moments at critical beam and column sections and therefore an area of longitudinal steel at each floor level is lower (18–26%) depending on the height of the storey.

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The cost savings in the foundation are also due to lower column base reactions in the LWC frame, of course, so that the load is lower on the footings and also the pile caps are less rocked. For rocky or hard soils (IS 1893 soil Type I) the savings are small, but for soft soils (Type III) where load loads are impacted by the seismic demand, they are more than 20%. In summary, the structural cost reduction of 19.5% is a good economic case for FC adoption, and more than sufficient to make up for the associated cost in foam concrete production compared to regular concrete.

VIII. RESEARCH GAPS AND CRITICAL ASSESSMENT

A. Long-Term Durability Under Seismic Cycling

The most important gap in the literature discussed here is the lack of long-term experimental data on the durability of FC structural members under repeated seismic cycling. While Khan et al. [17] and Hao et al. [18] provide cyclic load data for FC-based walls and panels, to date no study has examined a whole RC frame with FC members through multiple earthquake sequences in the service life of a structure (currently 50-100 years). There is some work on the effects of fatigue, progressive micro-cracking and moisture ingress through micro-cracks on the strength and stiffness of FC frames. The shortfalls of this will be particularly visible in India's coastal areas (Mumbai, Chennai, Visakhapatnam) where chloride-induced reinforcement corrosion and seismic loading could act together to accelerate structural degradation.

B. Codification Deficiencies

Despite the much-discussed literature reviewed here, IS 1893 and IS 456:2000 do not yet provide explicit provisions for the design of FC structural members. The draft IS 17452 is concerned with production and classification of FC but doesn’t cover structural design guidelines for seismic zones. ACI 318-19, Eurocode 2 and FIB Model Code 2010 all contain lightweight concrete-specific provisions for shear design, anchorage and minimum reinforcement which are quite different from their NWC equivalents. Indian structural engineers designing FC frames need to rely on foreign codes or engineering judgment and this creates liability uncertainty and discourages adoption. Research to develop the experimental database for IS codification of FC in seismic design should be performed.

C. Wind-Seismic Interaction

All the studies reviewed here assess seismic performance in isolation. However, in tall buildings (G+12 and above) in cyclone-prone coastal zones or high altitude regions of India, wind loading can equal or exceed seismic loading in governing lateral design. Because FC's lower mass does not in any way reduce seismic demand (as it depends on exposed area and drag coefficient, rather than mass), wind loading becomes more important for LWC frames. The optimal structural system (moment frame, shear wall, or dual system) for FC high rise in a wind-dominant zone should be investigated in a different way using IS 875 (Part 3) and IS 1893.

D. Nonlinear and Performance-Based Assessment

The ETABS based studies reviewed here are mostly linear elastic or equivalent static. Nonlinear static (pushover) and nonlinear dynamic (time history) analysis would show the post yield behavior, collapse mechanism and performance level (Immediate Occupancy, Life Safety, Collapse Prevention per FEMA 356) of FC frames. The reduced elastic modulus of FC changes the post peak branch of the moment-curvature equation in a way that might enhance ductility, which was suggested by Madhavi et al. [24] at the member level, but not at the system (frame) level.

E. P-Δ (Second-Order) Effects

We are using ETABS with linear analysis which does not fully reflect the geometric nonlinearity (P-Δ effects) in tall frames. For slender structures with significant lateral displacement, for example the LWC frame's roof displacement of 66.16 mm is approximately 0.16% of the total height of the frame, the P-Δ effect can increase effective moments and displacements by 5-15%, depending on the gravity load. SAP2000's geometric nonlinearity module or ETABS's P-Δ option should be activated in future studies to quantify this effect for FC frames.

IX. CONCLUSION AND FUTURE SCOPE

A. Conclusions

We have synthesized 25 references from the field of material science, structural studies, computational studies and economic analysis to show foam concrete's potential and challenges in earthquake-resistant high-rise RC construction. From this paper we can conclude that:

1. Material Viability: Foam concrete mixes containing 65% fly ash, 35% cement, 1.5% protein foam and 30% quarry dust perform consistently at structural grade ($f\_c \approx 19.6$ MPa and $\rho \approx 1605$ kg/m³) and above the IS 17452 level for structural lightweight concrete and a 58% strength improvement is achieved due to quarry dust optimization.

2. Seismic Performance: When NWC is replaced with LWC in a G+12 RC moment frame, all the seismic response parameters are improved - 22.81% bending moment reduction, 10.77% shear force reduction and 25.55% storey displacement reduction. These improvements will be more pronounced in the upper storeys where whip-lash seismic amplification is not as strong and all response parameters within IS 1893 serviceability & safety limits are still met.

3. Cross-Study Validation: Finally, these findings are in line with and bounded by Vandanapu and Krishnamurthy [1] (19.5% BM reduction), Hao et al. [18] (24% BM reduction) and Sthapit et al. [20] (78 mm displacement for similar height NWC frames) and confirm the reliability of ETABS-based IS 1893 methodology for FC frame assessment.

4. Economic Attractiveness: LWC frame has a cost-effective reduction of about 18.78% in concrete material cost and 23.20% in reinforcement cost compared to the NWC baseline, leading to an overall structural cost reduction of about 19.5% and is economically transformative in multi-storey residential and commercial construction.

5. Research Gaps: There remains a lot of research gaps on long-term cyclic durability, IS codification, wind-seismic interaction for coastal zones and nonlinear performance assessment and this gap is important to make FC a normative component of seismic design in India.

B. Future Scope

Extension of seismic analysis to G+20 and above configurations to investigate P-Δ effects, coupled wall-frame interaction, and mass irregularity sensitivity in supertall LWC buildings.

Integration of IS 875 (Part 3) wind loading with IS 1893 seismic loading in a combined lateral design framework for FC high-rises in coastal and high-altitude seismic zones.

Nonlinear pushover and time history analyses using SAP2000 or OpenSees with experimentally validated FC constitutive models to characterize collapse margins and performance levels per FEMA 356 / IS 16700.

Long-duration experimental cycling of FC beam-column subassemblies under seismic protocols (ACI 374.1) to generate ductility and energy dissipation data for code calibration.

Development of shrinkage-compensating admixture protocols for high fly ash FC to address the elevated drying shrinkage (700–900 με) identified in Wei et al. [19] as the primary serviceability concern.

Targeted experimental and analytical research program to provide the data basis for codification of FC in IS 456 and IS 1893 seismic design provisions, aligned with ACI 318-19 and Eurocode 2 LWC clauses.

Life-cycle cost analysis incorporating production energy, thermal insulation savings, maintenance costs, and end-of-life recyclability to establish the full sustainability value proposition of FC for Indian green building rating systems (GRIHA, LEED India).

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