

# Comparative analysis of performance under seismicity, wind variability, and coastal environments across 16 prominent Indian urban centers: Hybrid tanks versus standard RCC water tanks

Sukanya Saxena\* & Krishna Kant Pathak

Department of Civil Engineering, Indian Institute of Technology (B.H.U), Varanasi 221005, India

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This study has compared Hybrid Tanks and Standard RCC water tanks in 16 prominent cities across India, considering diverse seismic zones, wind speeds, and the influence of coastal and non-coastal variations. The chosen cities have represented a range of seismic zones: Bhopal, Hyderabad, Jaipur, Puducherry (Zone II); Ahmedabad, Vadodara, Lucknow, Chennai (Zone III); Shimla, Alibag, Delhi, Dwaraka (Zone IV); and Mandi, Kohima, Imphal, Guwahati (Zone V). Encompassing all seismic zones and considering wind velocities of 39 m/s, 44 m/s, 47 m/s, and 50 m/s, the study has designed 600 kL Intze water tanks utilizing C++ software programs developed for both tank types. The findings have revealed that seismic base shear has significantly increased as seismic zones have progressed, with rises of approximately 60%, 140%, and 260% in Zones III, IV, and V, respectively, compared to Zone II. Coastal cities have experienced higher wind shear forces, leading to increased costs. Wind forces have often surpassed seismic forces in coastal regions. Tank costs have risen with changing wind speeds and seismic activity zones, particularly in coastal areas, for both Hybrid and Standard RCC tanks. These findings have emphasized the crucial role of considering seismic zones, coastal effects, and wind dynamics in water tank infrastructure design and construction.

Hybrid tanks have outperformed Standard RCC ones with 22–23% cost savings, 28% less concrete (38.6% in body, 12–15% in staging), and 17.5% less steel (13.3% in body, 19.9% in staging). They have shown reduced base shear (up to 5% full, 15% empty tank), 5% less bending moment, 11% less deflection (full), 40.1% less deflection (empty tank), and crack width has been reduced by 63–87%, making them a promising alternative nationwide.

**Keywords:** Coastal structures, Crack width, Ferrocement, Hybrid tanks, Non-coastal structures, Wind speeds deflection

## 1 Introduction

Elevated water tanks are crucial water infrastructures. The construction of RCC water tanks is essential to meet the water needs of communities across the country. Thousands of tanks are being constructed nationwide under various government schemes. However, failures in such scenarios are not uncommon. In India, where seismic zones II, III, IV, and V coexist alongside high-intensity wind occurrences (39-50 m/s), conducting seismic and wind studies across various cities is imperative. Such studies are crucial for understanding the behavior of water tanks under diverse conditions. Alongside controlling leakages, cost economization of water tanks is vital. Assessing seismic and wind studies across different regions, particularly in coastal areas where wind velocities can reach 50-55 m/s, is another critical factor. Certain cities in India are highly

vulnerable to seismic impacts, coupled with frequent occurrences of high-intensity winds. With India's coastal border spanning 7516.6 km, studying the impact of coastal regions on tank design and performance is essential. Therefore, a comprehensive study is needed to address all the mentioned issues, including high costs, leakage-related failures, wind impacts, seismic events, and coastal variations.

To mitigate the high cost and failure due to leakages, Saxena and Pathak<sup>1,2</sup> proposed Hybrid tanks over Standard RCC water tanks and also provided detailed guidelines for the design of Hybrid Tanks. Standard RCC are being constructed of RCC alone leading to huge costs & material wastage. RCC tanks were prone to leakages also. There was a need to look after both the challenges- Leakages and excessive costs leading to the birth of Hybrid tanks. In Hybrid tanks, Ferrocement lining is integrated with RCC tank body, RCC is supposed to bear all the structural loads and Lining is designed to impart impermeability to the structure. It was imperative to

\*Corresponding author  
(E-mail: Sukanyasaxena.rs.civ22@itbhu.ac.in)

assess the suitability of Hybrid tanks in the Indian context to determine their applicability nationwide, considering cost savings, leakage failure, and prioritizing structural feasibility across various seismic zones, climatic and geographical regions & wind turbulence. Validating the usage of Hybrid tanks involves evaluating their performance across various regions in India.

The primary objective of this study is to assess the feasibility of Hybrid tanks compared to Standard RCC tanks across 16 major cities and state capitals in India. This evaluation will encompass various factors such as cost-effectiveness, durability, sustainability & serviceability. By conducting a comparative analysis, the study aims to provide valuable insights into the potential advantages and challenges of implementing Hybrid tanks in different geographical and urban settings across the country.

This study is done to ascertain the feasibility of Hybrid vs Standard RCC tanks in different cities in India. All the cities selected are major cities or metropolitan cities. For this study, 600 kL Intze tanks are chosen. It is designed for construction in 16 Major cities/ State Capital of India to ascertain the behavior and cost-effectiveness of Hybrid tanks over Standard RCC tanks across the country. The selection of these cities was based on their diverse seismic zones and varying wind speeds, facilitating an examination of the feasibility of Hybrid tanks nationwide. The study aims to determine the impact of lateral forces on structures and assess the dominance of wind and seismic forces in these major Indian cities.

Additionally, four cities from coastal regions were chosen to investigate the influence of the Importance factor in cyclonic regions. The study also analyzes the percentage change in cities with similar wind speeds and seismic zones in both coastal and non-coastal regions. Conducting a comparative analysis becomes crucial for evaluating the influence of wind and seismic forces in both full and empty tank scenarios. Additionally, the study delves into the impact of cyclonic (coastal) regions on the design of Intze tanks. Key parameters, including the cost of tanks, tank body, staging, Ferrocement lining in Hybrid tanks, material consumption, seismic base shear, wind force, crack width, deflection, maximum bending moment in columns, and the influence of coastal regions compared to non-coastal areas, are examined to study the cost-effectiveness & structural performance of water tanks.

### 1.1 Literature review and research gaps

In the Indian context, where seismic zones II, III, IV, and V coexist alongside high-intensity occurrences, studying seismic and wind patterns across different cities is crucial to understanding tank behavior under varied conditions. Therefore, the initial focus of the literature review will be on examining the failures of RCC tanks under extreme conditions and remedial measures. Sharma et al.<sup>3</sup> address the seismic margin assessment of such critical structures through pushover analysis, focusing on a 16-meter high, 65 m<sup>3</sup> capacity water tank supported on a circular RCC shaft. The study compares practical modeling approaches utilizing frame and shell elements, evaluating performance points and seismic margins under various reinforcement configurations and shaft cut-out scenarios. Rai<sup>4</sup> performed retrofit studies to address seismic vulnerabilities in elevated water tank supports, highlighting challenges in enhancing ductility and proposing concrete jacketing as a solution, albeit requiring substantial foundation strengthening. Few studies have forecasted climatic conditions, particularly focusing on wind speeds and humidity levels. These studies also highlight the challenges regarding the serviceability and durability of RCC structures constructed in such environments (Subrahmayam et al.<sup>5</sup>; Malik et al.<sup>6</sup>). Few studies have been done to ascertain the optimal staging patterns or the configuration to mitigate the lateral impacts on such structures. Period evaluation and also impact of seismic activity on the water tanks along with the mitigation studies are also done. (Jyothsna et al.<sup>7</sup>; Nirmal et al.<sup>8</sup>; Mitra and Debbarna<sup>9</sup>). All studies have unanimously concluded that to mitigate the effects of seismic activity, it is imperative to minimize the self-weight or loads on structures. It's a standard guideline for critical structures like water tanks to ensure long-term serviceability and maintain a low rate of deterioration. Following studies present the failure of water tank structures. Failure can occur due to seismic activities or cracking due to lack of serviceability & durability of Standard RCC tanks. The studies focus on the seismic failures and vulnerability of elevated water tanks, particularly in earthquake-prone areas. Rai<sup>10</sup> pointed out deficiencies in current Indian design standards for tank supports, exposed by the Bhuj earthquake, advocating for revisions. Mori<sup>11</sup> emphasizes the critical risk posed by the proximity of heritage-listed R/C tanks to railway infrastructure, suggesting

the potential for severe damage or collapse. Lakhade et al.<sup>12</sup> provide probabilistic drift limits for performance-based design through extensive nonlinear analysis. Jain et al.<sup>13</sup> highlight the importance of enhanced seismic design for elevated reservoirs, considering factors like water depth and brace flexibility. Dilena et al.<sup>14</sup> survey old water tanks in Italy, offering insights for retrofitting. Prakash and Bansal<sup>15</sup> stress the need for pre-disaster mitigation in public structures, using non-destructive tests to assess the structural integrity of an old OHSR in India.

Crack and leakage failures in concrete water tanks are significant issues affecting durability and functionality. Bhadauria<sup>16</sup> highlighted severe deterioration in surveyed water tanks, with a majority showing signs of seepage and reinforcement corrosion. His study correlated tank age with degradation, stressing the need for routine maintenance to extend service life. Bhadauriya<sup>17</sup> emphasized the importance of systematic performance monitoring and field studies to validate laboratory findings, noting that modern concrete structures deteriorate faster due to cracking from rapid hydration. Sangiorgio et al.<sup>18</sup> found leakage as a primary cause of tank deterioration in Spain, further underscoring the need for robust design and maintenance practices. Saeed et al.<sup>19</sup> investigated cracking due to restrained shrinkage and heat of hydration in the arid Arabian Gulf, finding tensile stresses exceeding concrete's capacity. They proposed a repair strategy and guidelines for similar environments. Saxena and Pathak<sup>20,21</sup>. Rodd<sup>22</sup> identified horizontal cracks in on-ground circular concrete tanks in Australia, linking them to leakage and durability issues, and introduced a unified design approach with a practical model to predict bending moments and crack widths. IS standards and standard texts and circulars are used to study the design guidelines of Standard RCC Tanks as well as Seismic Design of Tanks<sup>23-33</sup>.

To address the cost reduction of structures, earlier studies proposed Hybrid tanks as an alternative to RCC tanks. Their study emphasized the need and significance of Hybrid tanks and analyzed the crack reduction characteristics of Hybrid tanks. The study was done primarily focusing on a single Seismic zone i.e. Seismic Zone II. Only a minor investigation was conducted for other zones, calculating base shear only. Wind speed was considered at 39 m/sec, which is the lowest in

non-coastal regions, and coastal effects were not taken into account. However, parameters related to design change significantly in high seismic activity zones, high wind zones, or coastal areas, such as the importance factor of the structure. Therefore, it was imperative to assess the feasibility of Hybrid tanks across the entire country. Additionally, it is essential to assess the percentage of cost savings and determine whether these savings are achievable across different zones and under high wind velocities when Hybrid tanks are compared with Standard RCC tanks. This present study is an extension of the works done on Hybrid Tanks.

### 1.2 Research gaps

Previous studies introduced Hybrid tanks as an innovative alternative to traditional RCC tanks, focusing on the need and benefits of Hybrid tanks over conventional ones and also provided detailed guidelines for the design of Hybrid Tanks. Their research was limited to Seismic Zone II, with only a brief analysis of base shear calculations for other seismic zones. They considered a wind speed of 39 m/sec, the minimum for non-coastal areas, without accounting for coastal influences. However, design parameters change significantly in regions with higher seismic activity, stronger winds, or coastal environments, affecting factors like the importance of the structure.

This limitation highlights the necessity for a more extensive evaluation of Hybrid tanks' feasibility across different seismic zones, wind conditions, and coastal regions throughout the country. Furthermore, there is a need to assess the cost savings potential of Hybrid tanks compared to Standard RCC tanks across various zones and wind velocities.

The current study extends previous studies on Hybrid tanks by providing a comprehensive assessment of Hybrid tanks across diverse geographical and environmental conditions in India. This includes analyzing the impact of different seismic activities, wind speeds, and coastal effects. The study aims to determine the optimal tank design and construction for 16 major cities and state capitals in India, each located in different seismic zones (ranging from Zone II to V) and experiencing wind speeds between 39-50 m/s. Additionally, it evaluates the structural performance and cost-effectiveness of Hybrid tanks compared to Standard RCC tanks, particularly in four coastal cities: Alibag, Puducherry, Dwaraka, and Chennai.

This study aims to validate the effectiveness and feasibility of Hybrid tanks across different seismic zones, wind speeds, and coastal regions in India, ensuring their structural integrity and cost-efficiency compared to Standard RCC tanks. This research gap underscores the need for a thorough investigation into the structural and economic viability of Hybrid tanks across the entire country, addressing the variations in seismic and wind conditions, and coastal impacts to guide infrastructure planning and development.

### 1.3 Objective of the study

The objective of this study is to conduct a thorough comparative analysis of Hybrid Tanks and Standard RCC water tanks in diverse seismic zones and wind speeds across 16 major cities in India. The selected cities represent a broad spectrum of seismic zones, ranging from Zone II to Zone V, and include various wind speeds from 39 m/s to 50 m/s. 600 kL tanks are usually constructed by municipal corporations for communities in India. The study aims to assess the feasibility of 600 kL Hybrid tanks, against Standard RCC water tanks. Key parameters to be examined in the study include the cost of tanks, tank body, staging, Ferrocement lining in Hybrid tanks, material consumption, seismic base shear, wind force, crack width, deflection, maximum bending moment in columns, and the influence of coastal regions compared to non-coastal areas. The study aims to highlight the importance of considering seismic zones, coastal effects, and wind dynamics in water tank infrastructure design and construction. Additionally, the study seeks to demonstrate the robustness and versatility of hybrid tank designs across various geographical and climatic conditions. The study also assesses the structural performance of both tank types and determines their cost-effectiveness across different seismic and wind conditions. The study seeks to provide insights into the potential advantages of hybrid tanks over Standard RCC tanks. Standard RCC tanks are also called Conventional tanks.

## 2 Materials & Methods

The study's methodology is detailed in the flowchart depicted in Fig. 1, while the member dimensions and material specification used are outlined in Table 1. RCC tanks body is analyzed by the continuity method & designed as per Limit state method. For this study, 600 kL Intze tank are chosen. It is designed for construction in 16 Major cities/ State

Capital of India to ascertain the behavior and cost-effectiveness of Hybrid tanks over Standard RCC tanks. These cities were selected for their diverse seismic zones and varying wind speeds, as outlined in Table 2. The study aims to determine the impact of lateral forces on structures and assess the dominance of wind and seismic forces in these major Indian cities. Additionally, four cities from coastal regions were chosen to investigate the influence of the Importance factor in cyclonic regions. The study also analyzes the percentage change in cities with similar wind speeds and seismic zones in both coastal and non-coastal regions. The Methodological Framework for the Comparative Study is shown in Fig. 1.

### 2.1 Dimensions & specifications of the tank and lining used in the study

Dimensions of the Hybrid and Standard RCC tanks are provided in Table 1. Figure 2 depicts the tank wall of 600 kL Hybrid tanks used in this study. The strain occurring at the interface was of the order 0.0017-0.0018 in all the 16 Hybrid tanks. For 600 kL tanks 15 mm thickness Ferrocement lining is used with 4 layers of square welded mesh of H.B. wires. The lining will be constructed using 1:2:0.45 cement: sand and water ratio.

### 2.2 Wind analysis

Following IS 875:2015 (Part III) guidelines for designing wind speeds, the calculation of Design Wind Speed ( $V_z$ ) involves obtaining the basic wind speed ( $V_b$ ) for a specific site from IS 875:2016. The determination of the design wind speed,  $V_z$ , at a given height ( $z$ ) for a particular structure involves adjusting the basic wind speed. This adjustment considers several factors, including the level of risk, roughness of terrain and structure height, topographical factors, and the Cyclonic factor importance factor. Mathematically, it can be expressed as follows:

$$V_z = V_b \times k_1 \times k_2 \times k_3 \times k_4 \quad \dots (1)$$

$k_1$  = risk coefficient

$k_2$  = terrain roughness factor

$k_3$  = topographical factor

$k_4$  = Cyclonic region importance factor

The west coast of India, particularly Gujarat, is vulnerable to severe cyclones. Analysis of wind speed and structural damage indicates that speeds recorded during cyclonic events often exceed those predicted by the basic wind speed map. The impact of cyclonic storms is most acutely felt in a coastal zone roughly 60 km wide. To bolster the safety of structures

**Comparative Analysis of Performance under Seismicity, Wind Variability, and Coastal**

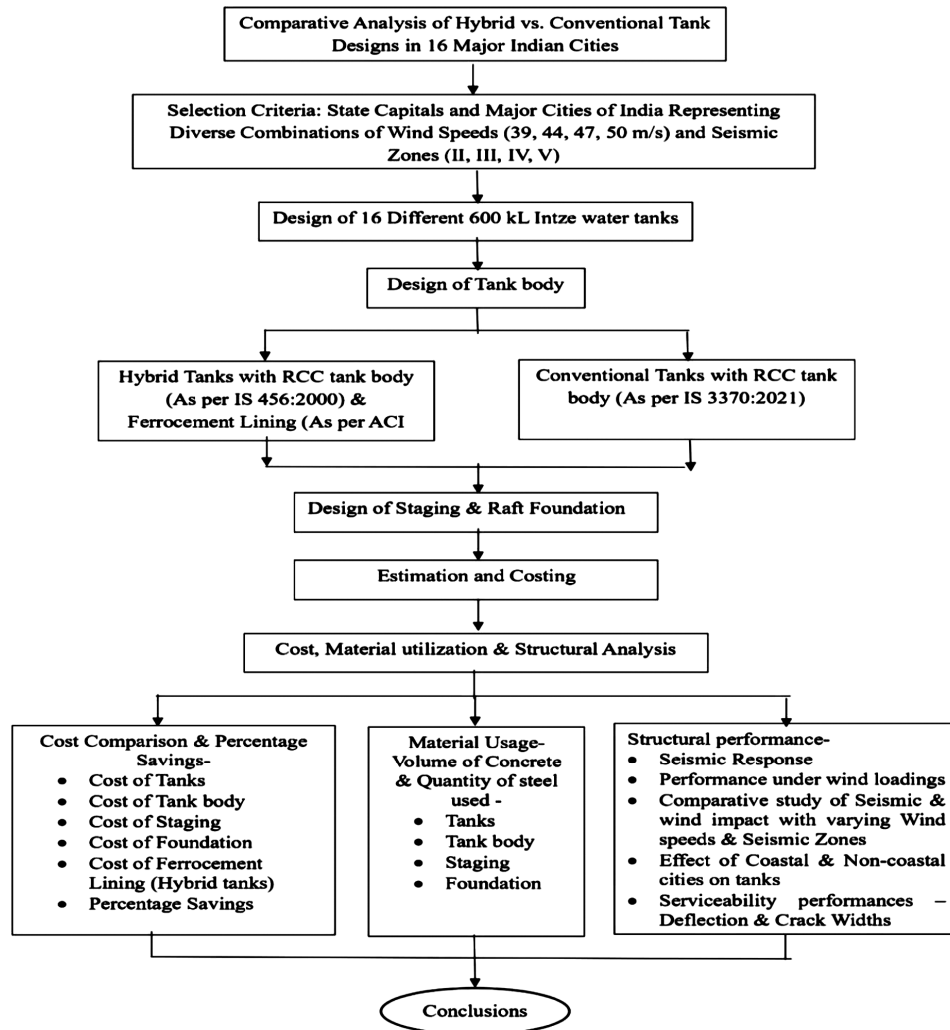


Fig. 1 — Methodological framework for comparative study.

Table 1 — Member cross sections/ thicknesses for hybrid & standard RCC tanks.

Member	Dimensions/Thickness (mm)/Details		
		Hybrid Tank	Standard RCC Tank
Top Dome		80	120
Top Ring Beam		200 x 200	200 x 200
Cylindrical wall	Top	100	200
	Bottom	100	230
Middle Ring Beam		1000 x 120	1000 x 150
Conical Dome	Top	150	330
	Bottom	150	200
Bottom Dome		120	160
Middle Ring Beam		400 x 600	400 x 600
Column	Nos	10	10
	Diameter	400	400
Braces Size		200 x 500	200 x 500
Foundation Beam & Raft Dimensions		Different for all 16 Tanks	
Material used		Concrete mix M 30 & steel Fe 500. 15 mm thick Ferrocement lining of 1:2:0.45Cement- PPC 53 Grade. 1mm dia mesh provided in 4 layers	
Foundation Details		80 kN/m <sup>2</sup> and 1.8 m	

in this region, including both the east coast and Gujarat, specific values of  $k_4$  are assigned based on the structure's importance. Critical infrastructure such as cyclone shelters, hospitals, schools, and communication towers are assigned a value of  $k_4$  set at 1.30, underscoring the imperative for enhanced safety protocols in these cyclone-prone areas.

**2.3 Seismic analysis**

Following IS 1893: 2016 the seismic behavior of the tanks is evaluated. The Response spectrum method is used. The equivalent weight, design horizontal seismic coefficient, and Average response acceleration coefficient of the structure have been calculated, further response time is calculated along with the deflections, and then Base shear is calculated. Mathematical expression for design horizontal seismic coefficient  $A_h$  for a structure -

$$A_H = \frac{Z \times 0.5 \times \frac{S_a}{g}}{[R/I]} \dots (2)$$

Table 2 — Cities with wind speeds and seismic zones.

Seismic Zone	Wind Speed			
	39 m/s	44 m/s	47 m/s	50 m/s
II	Bhopal	Hyderabad	Jaipur	Puducherry
III	Ahmedabad	Vadodara	Lucknow	Chennai
IV	Shimla	Alibag	Delhi	Dwaraka
V	Mandi	Kohima	Imphal	Guwahati

- $A_h$ =The design horizontal seismic coefficient
- $Z$ = Zone factor
- $S_a/g$ =Avg response coefficient for acceleration
- $I$ = Factor for importance
- $R$ = Response Reduction factor

Equivalent weight, Stiffness, Period of vibration & further deflection is calculated. For the calculation of Base shear in Full & empty tank conditions,  $A_h$  is multiplied by the Equivalent weight in Full tank and Empty conditions. Design is done using the partial safety factors as specified in IS 456:2000. Further the staging and foundation are designed for the maximum lateral Forces.

**2.4 Software program**

Two distinct C++ software applications have been developed to facilitate the design comparison between Hybrid and Standard RCC approaches. These modular programs encompass Input, Dimensioning, Analysis, and Design stages, with specialized modules tailored for Lining Design (specific to Hybrid design), Staging, Foundation Analysis and Design, Wind and Seismic Analysis, as well as costing and estimation calculations. Designed with a user-centric approach, these applications offer functionalities such as parameter input handling, dimension computations, stress checks, and optimization algorithms in compliance with Indian standard codes. Matrix

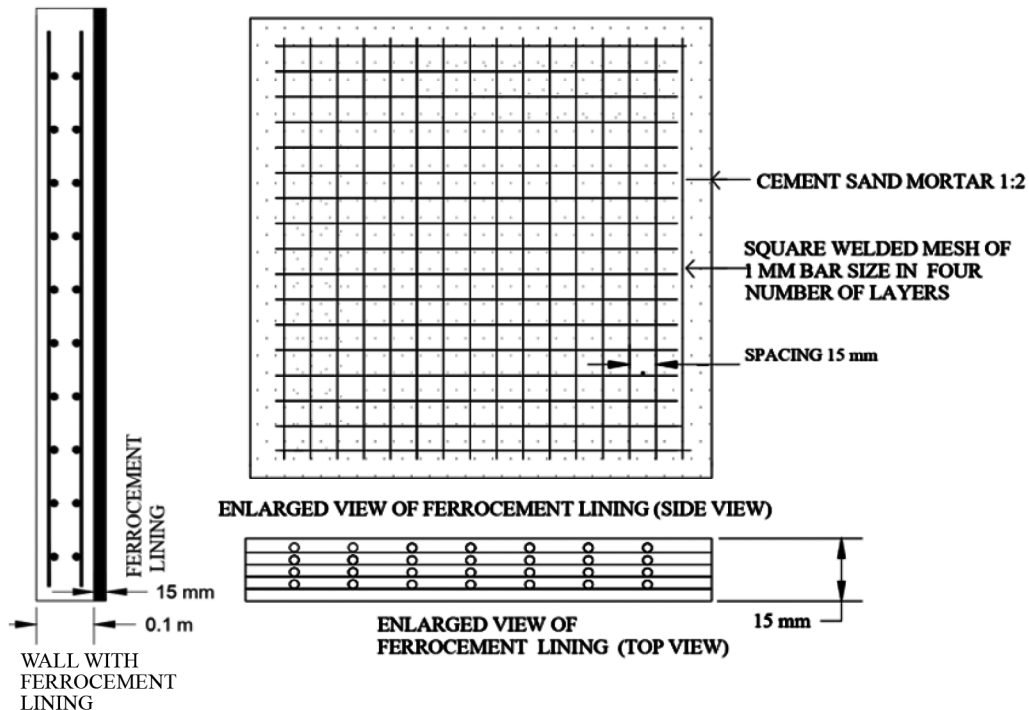


Fig. 2 — Design of hybrid tank wall for 600 kL tank.

methods are employed for structural analysis, ensuring safety criteria are met through iterative or heuristic adjustments. The software provides comprehensive design coverage for various tank components, integrating seismic and wind load calculations, annular raft footing design, and strain compatibility calculations for Ferrocement lining in Hybrid tanks. Furthermore, the software facilitates concrete volume and steel reinforcement calculations, along with cost estimation based on standardized rates, offering flexibility for user input. The software discussed in this context represents a remarkable leap in engineering and structural design. Its novelty lies in its unique application and approach to analyzing water tanks. Traditional methodologies often rely on manual calculations and time-consuming processes, but this software introduces a novel way to expedite the design and analysis of this critical structure.

The C++ software program developed encompasses several features:

#### **2.4.1 Input and assessment**

- This section details the parameters necessary for input into the software, including tank capacity, staging height, soil bearing capacity, foundation depth, seismic zone, location, and terrain category.
- The software autonomously suggests or allows users to input optimal H/D ratios and number of columns
- Calculations are performed to determine the optimal dimensions of various tank members such as cylindrical walls, Conical dome, domes, beams, and their respective diameters and radii.
- Preassigned minimum member cross-sections are incorporated with a heuristic optimization algorithm to enhance structural integrity.
- Additionally, the software includes checks for crack width for elements in contact with water and ensures compliance with relevant Indian standard codes.

#### **2.4.2 Design parameters**

- This section encompasses the key parameters and specifications involved in the design process of the water tank.
- It includes details about the design considerations for various components such as the top dome, ring beams, circular wall, conical, middle ring beams, bottom ring beams, columns, braces, bottom dome, foundation beam, and raft foundation.

- The software computes the dimensions of these components, determines steel reinforcement requirements, and ensures precise tank design.
- Design principles adhered to include IS 3370:2021 for conventional design and IS 456:2000 for hybrid and Limit State design.
- Seismic design considerations are provided for Zone II, III, IV, and V, including seismic response time calculation.
- Thorough wind load calculations according to IS 875:2015 are conducted, accommodating various Indian cities, terrains, and regions.

#### **2.4.3 Software approach and process**

- This section outlines the methodology, approach, and process followed by the software to carry out its functions effectively.
- It describes the algorithm and logic employed by the software to perform tasks such as computing member dimensions, conducting analysis, and optimizing designs.
- Specific geometrical properties are predefined for certain components to ensure consistency and efficiency in the design process.
- The software conducts thorough scrutiny for stress, exposure, and crack width criteria, employing matrix methods of Direct Stiffness method for analysis.
- Iterative modifications are made to ensure all members meet safety criteria throughout the design process.

#### **2.4.4 Estimation and financial analysis**

- This section discusses the features related to estimation and financial analysis provided by the software. The software computes the volume of concrete needed for each structural member, determines steel requirements for various aspects, and calculates steel quantities in tonnes. Rates from specified sources are utilized for costing purposes, with flexibility for users to input state-specific rates.

#### **2.4.5 Software verification**

- This section focuses on the validation process undergone by the software to ensure its accuracy and reliability.
- Preliminary manual pilot tests were conducted before software development, covering various tank capacities, seismic zones, and wind speeds.
- Results from manual designs were cross-verified using the developed software program.

- Known problems from standard texts were examined using the software for validation.

**2.4.6 Software constraints**

This section outlines the limitations or constraints of the software. Currently, rates are sourced exclusively from specified entities, requiring manual entry for projects outside these regions.

**2.4.7 Performance analysis and exported data**

- The software facilitates a thorough performance analysis of water tank structures, offering insights into various critical aspects:
- Exporting Essential Data and Parameters: Users can export vital data and parameters such as cost estimations, material specifications, and base shear values in both empty and full tank conditions.
- Deflections in Empty and Full Tank Conditions: Analysis and exportation of deflection data allow users to assess structural behavior under varying load conditions.
- Wind Analysis: Comprehensive assessment and exportation of wind-related data, including wind loads, pressure distributions, and induced stresses, aid in
- Cyclonic Analysis: Evaluation and exportation of cyclone-related data, such as wind speeds, pressures, and forces, assist in designing structures resilient to cyclonic conditions.
- Comparative Analysis of Forces: Comparative analysis of seismic, wind, and cyclonic lateral

forces offers insights into their relative contributions to structural response.

- Maximum Bending Moment in Columns: Assessment and exportation of maximum bending moments in columns provide critical information for structural integrity evaluations.

**2.5 Application**

This study comprehensively compares Hybrid Tanks and Standard RCC water tanks across 16 prominent Indian cities, spanning diverse seismic zones and wind speeds. The cities selected cover seismic zones II to V, including coastal and non-coastal variations. Wind velocities ranging from 39 m/s to 50 m/s are considered, ensuring a robust evaluation of tank performance in various environmental condition .Additionally, four cities from coastal regions were chosen to investigate the influence of the Importance factor in cyclonic regions. The cities chosen for this study are mentioned in Table 2.

**3 Results & Discussion**

16 Hybrid and Standard RCCIntze Tanks of 600 kL capacity are designed, Results obtained are as follows-

**3.1 Cost comparison of all the sixteen hybrid & standard RCC tanks**

Figure 3 represents the comparative study as shown below-

The Results are as follows:

- Figure 3 provides clear evidence that Hybrid designs outperform Standard RCC ones in terms of cost-effectiveness across all 16 cities.

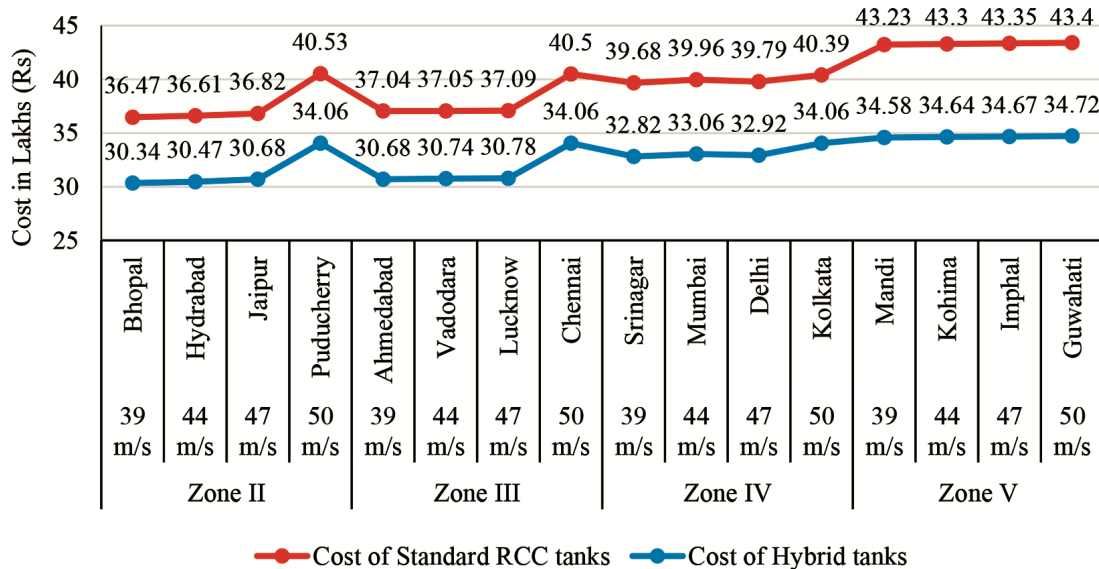


Fig. 3 —Cost comparison of all the sixteen hybrid & standard/conventional RCC tanks.

- The cost of the tanks escalates with variations in wind velocities & Zones of seismic activity.
- The cost of the tanks in Coastal cities is highest in their Zones because of the increase in wind shear forces.
- Cost savings falls within the range of 16-21% in non-coastal cities and increases with an increase in Seismic zones. Coastal cities show a substantial savings of about 16%.
- On average, there is approximately an 18% saving, equating to about one-fifth of the total cost, particularly in material expenses, which is significant.

**3.2 Cost of ferrocement lining**

- Uniform 15 mm lining with steel mesh square welded mesh in four layers is provided in all the water-facing elements of the tank body.
- The cost of ferrocement lining is about 1.5 lakhs Rs which is about 4-5% of the overall cost of the structure.

**3.3 Material utilization**

Quantity of material (Concrete & Steel) used in the Hybrid & Standard RCC tanks are calculated for all the cities and are shown in Fig. 4.

Results shows that-

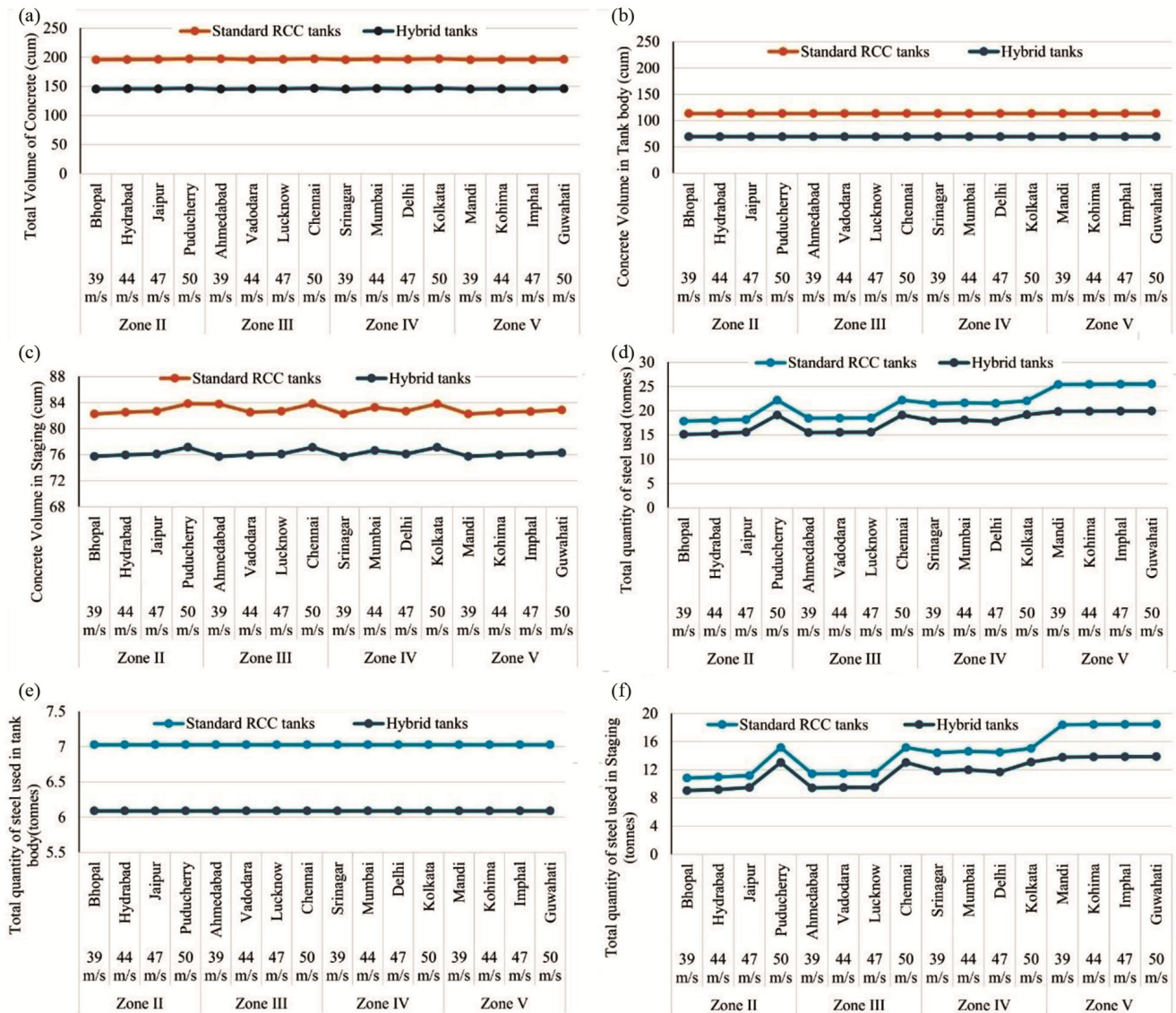


Fig. 4 — (a) Total volume of concrete used in tanks, (b) Total volume of concrete used in tank body, (c) Total volume of concrete used in staging, (d) Total quantity of steel used in tanks, (e) Quantity of steel used in tank body and (f) Quantity of teel used in staging.

- Concrete usage in the body of a Hybrid tank is approximately 38% lesser than Standard RCC tanks.
- The staging of Hybrid tanks requires about 7-8% less concrete than in Standard RCC tanks.
- Hybrid tanks, in total, use about 25% less Concrete compared to Standard RCC tanks.
- Steel usage in the body of Hybrid tanks is approximately 17% less than in Standard RCC tanks.
- The staging of Hybrid tanks requires only about 13% of the steel quantity than Standard RCC tanks.
- Hybrid tanks, in total, use about 15% less steel compared to Standard RCC tanks.
- The volume of steel & concrete in the tank body is uniform, whether it's a Hybrid or Standard RCC tank, across all 16 cities.
- The volume of concrete utilized in staging increases in seismic zones and is higher in coastal cities.
- Steel usage in tanks rises with seismic zone increments and is higher in coastal cities compared to non-coastal ones in the same seismic zone.
- Notably, the Hybrid tanks need less concrete and steel than Standard RCC designs across all tanks.
- Steel and concrete are prime materials, with their amounts crucial in determining overall tank costs.
- This underscores the Hybrid design's effectiveness in achieving substantial material savings across different tank capacities.
- Percentage savings in materials rise with a rise in the water-carrying capacity of tanks.

**3.4 Deflection and crack widths**

The average deflection of all 16 tanks are shown in Fig. 5. The results are as follows:

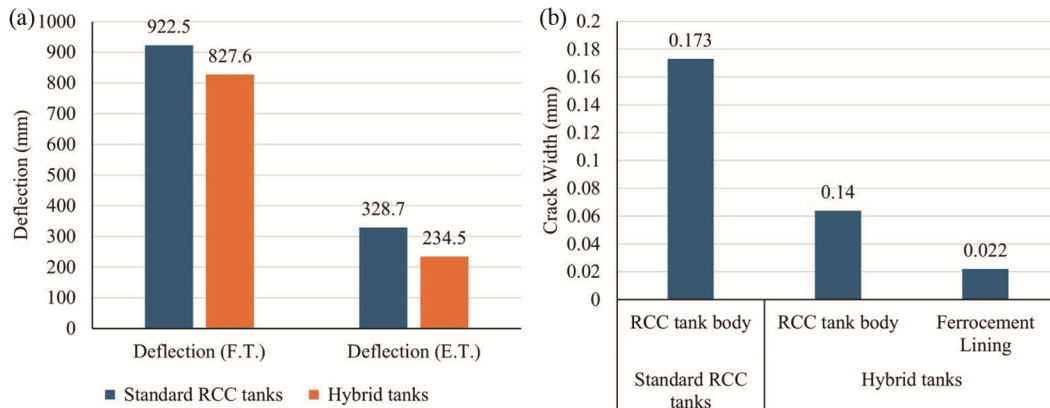


Fig. 5 — (a) Deflection and (b) Crack width for hybrid and standard RCC tanks.

**3.4.1. Deflection**

- The deflection in Standard RCC tanks typically ranges around 922.5 mm when full and 328.7 mm when empty, showing consistent patterns across various tanks with a variation of approximately 2-3%.
- In hybrid tanks, the values differ, with deflection measuring around 827.6 mm when full and 234.5 mm when empty.
- The findings reveal that the Hybrid design tank consistently exhibits lower deflection levels in both full and empty tank states. Specifically, deflection is approximately 10-11% lower when the tank is full. In the empty tank state, deflection sees a significant reduction, ranging from 27% to 28%, compared to Standard RCC methods. Hybrid tanks demonstrate superior performance in seismic events compared to Standard RCC tanks. This decrease is credited to the reduction in self weight of the RCC tank body in the hybrid design.

**3.4.2. Crack width**

- Average crack width of 0.173 mm is obtained in the Standard RCC tanks
- Within the RCC tank body Hybrid tank, a 0.14 mm crack width is found and 0.022mm in the lining of these tanks.
- The crack width of the Hybrid tank RCC body is approximately 19.08% less than that of the Standard RCC tank body.
- The crack width of the Hybrid tank is approximately 87.28% less than that of the Standard RCC tank body.
- The crack width of the Standard RCC tank remains comfortably below the IS 3370:2021 limit of 0.2 mm. Meanwhile, crack width

calculations for both RCC and Lining sections of Hybrid tanks were conducted, yielding results below the ACI standard of 0.05 mm.

- Hybrid tanks offer enhanced structural integrity, ensuring better long-term serviceability compared to Standard RCC tanks, thanks to their superior control over crack width and Deflections.

**3.5 Structural performance under wind and seismic loadings**

Structural performance, encompassing response to wind and seismic forces, assessment of bending moment at the base of columns, and evaluation of the

impact of major lateral forces, is thoroughly examined for all 16 cities in both Full and Empty tank conditions. Additionally, the performance of tanks under wind loads is meticulously studied in coastal and non-coastal cities. Results are shown in Fig. 6.

Results show that-

- Seismic forces increase with the increase in seismic zones.
- Across different seismic zones, the seismic base shear for Standard RCC tanks varies as follows: In Zone II, it is 151.28 kN for F.T. condition and

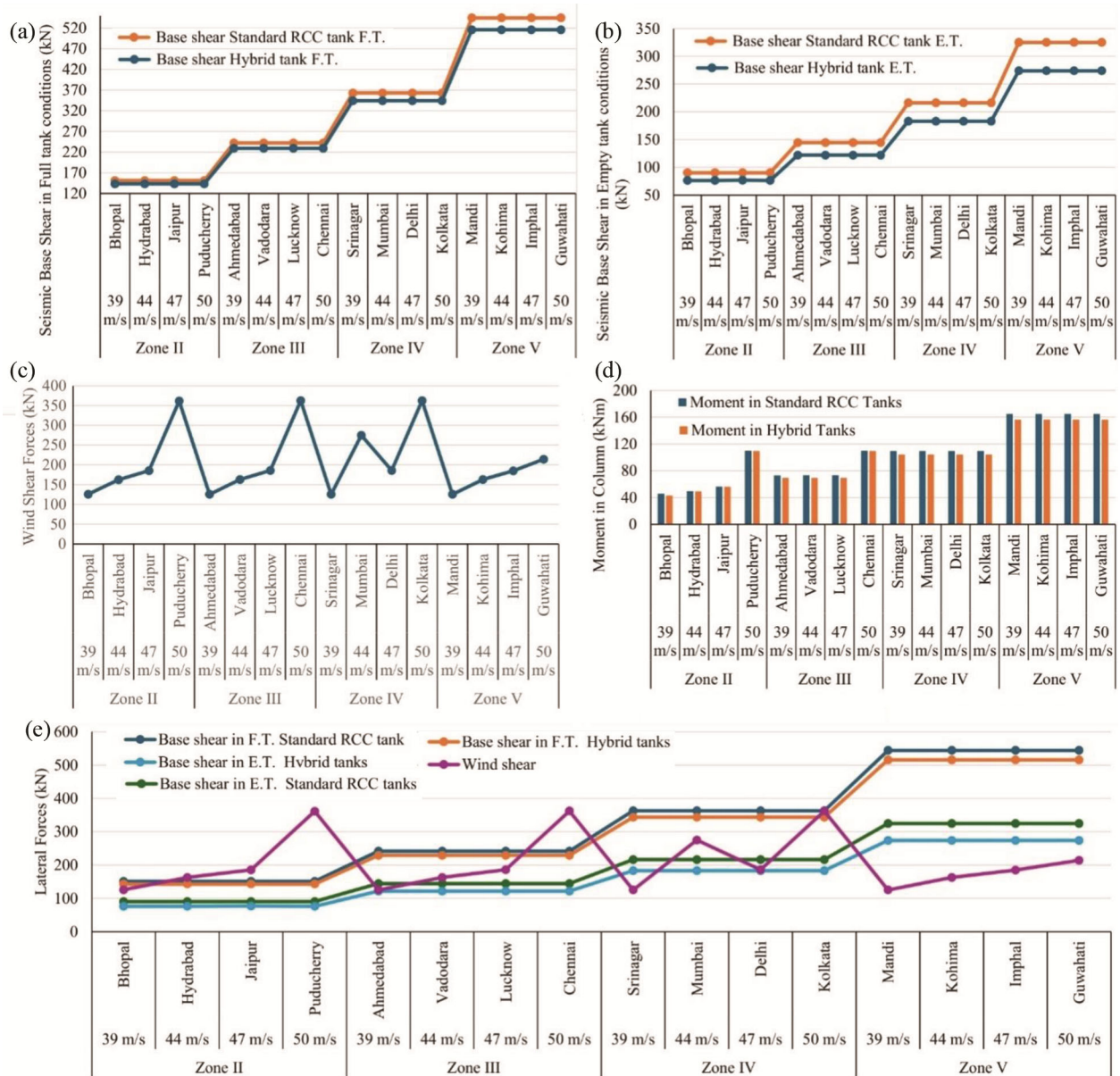


Fig. 6 — (a)Seismic base shear in F.T. conditions, (b)Seismic base shear in E.T. conditions, (c) Wind shear forces acting on tanks in 16 cities, (d) Bending moment in columns and (e) Comparative analysis of base shear forces & wind shear forces in full & empty tank conditions across 16 cities.

90.31 kN for E.T. condition. In Zone III, it is 242 kN for F.T. condition and 144.5 kN for E.T. condition. In Zone IV, it is 363 kN for F.T. condition and 216.4 kN for E.T. condition. In Zone V, it is 544.6 kN for F.T. condition and 325.1 kN for E.T. condition.

- For Hybrid tanks, across different seismic zones, the seismic base shear varies as follows: In Zone II, it is 143.3 kN for F.T. condition and 76.29 kN for E.T. condition. In Zone III, it is 229.3 kN for full tank condition and 122 kN for E.T. condition. In Zone IV, it is 344 kN for full tank condition and 183 kN for E.T. condition. In Zone V, it is 516 kN for full tank condition and 274 kN for E.T. condition.
- Difference in Seismic base shear increases with an increase in the seismic zone between hybrid & Standard RCC tanks.
- In Zone III, seismic base shear increases by approximately 60% for both Standard RCC and Hybrid tanks compared to Zone II, while in Zone IV, there's a notable spike with seismic base shear surging by roughly 140% for both tank types. Moving to Zone V, the increase is even more significant, with seismic base shear soaring by approximately 260% for both Standard RCC and Hybrid tanks compared to Zone II.
- The percentage savings for Hybrid tanks compared to Standard RCC tanks across different seismic zones range approximately between 5.24% to 5.27% for full tank conditions and 15.46% to 15.70% for empty tank conditions.
- Wind forces acting on the tanks are similar in both type of tanks because height of tank body, height of staging and dimensions are kept same in all the tanks.
- The magnitude of wind forces escalates as wind speeds increase, with values ranging from 125.68 kN in cities experiencing winds at 39 m/s, 162.5 kN at 44 m/s, 185.4 kN at 47 m/s, and 214.5 kN at 50 m/s in non-coastal cities.
- Wind shear forces peak in coastal regions. In cities such as Alibag, where the wind speed is 44 m/s, the wind shear forces reach 275 kN. In cities like Puducherry in Zone II, Chennai in Zone III, and Dwaraka in Zone IV, where the wind speed is 50 m/s, the highest wind forces are experienced, reaching 361.2 kN.
- The maximum moment in the column, as depicted in Fig.6, is contingent upon the highest lateral forces stemming from either wind shear forces or seismic forces. The moment tends to be nearly the same or lower in Hybrid tanks when compared to Standard RCC tanks.
- The bending moment in the column spans from 43.6 kN to 156.3 kN across different cities.
- The disparity in moments amplifies with the escalation of Seismic Zones.
- Figure 6 shows a comparative study of Seismic base shear & wind forces across all the cities.
- In Seismic Zone II, wind forces prevail over seismic base shear in empty tank conditions. However, in full tank conditions, cities such as Bhopal (wind speed 39 m/s) exhibit wind forces that are lower than seismic base shear, whereas cities like Hyderabad (44 m/s), Jaipur (47 m/s), and Puducherry (50 m/s), wind forces exceed seismic base shear.
- In Zone III, wind forces are generally lower than seismic base shear for full tank conditions, except for Chennai, a coastal city experiencing wind speeds of 50 m/s. However, in empty tank scenarios, wind forces are either comparable to or higher than seismic base shear for all cities in the zone.
- In Zone IV, wind forces are generally lower than seismic base shear for full tank conditions, except for Dwaraka, a coastal city experiencing wind speeds of 50 m/s. For Dwaraka, wind shear forces exceed seismic base shear in hybrid tanks and are equivalent in Standard RCC tanks. In empty tank scenarios, wind forces are lower than seismic base shear for all cities in the zone, except for coastal cities like Alibag with a wind speed of 44 m/s, and Dwaraka with a wind speed of 50 m/s.
- In Zone V Seismic base shear is higher than wind forces in both Full and empty tank conditions.
- Hybrid tanks consistently exhibit lower seismic base shear across all seismic zones compared to Standard RCC tanks.
- Percentage savings range between approximately 5.24% to 5.27% for full tank conditions and 15.46% to 15.70% for empty tank conditions.
- Hybrid tanks maintain similar or lower moments in columns compared to Standard RCC tanks, ensuring structural integrity under seismic forces.
- Both hybrid and Standard RCC tanks exhibit similar wind forces, ensuring structural stability.
- In coastal areas, hybrid tanks demonstrate superior performance, with wind shear forces

exceeding seismic base shear in Standard RCC tanks but remaining optimized in hybrid tanks.

#### 4 Conclusion

- Across all the 16 cities Hybrid designs are cost-effective than Standard RCC tanks with cost savings of 16-21% in non-coastal cities and increases with an increase in Seismic zones. Coastal cities show a substantial savings of about 16%.
- The cost of the both type of tanks rises with the rise in the velocity of wind or the seismic zones.
- The cost of the tanks in Coastal cities is highest in their Zones because of the increase in wind shear forces.
- For a 600 kL tank the Ferrocement lining accounts for roughly 4-5% of the entire cost which is minimal and results in a 0.022 mm crack width which is substantially less as that of traditional tanks.
- Hybrid tanks achieve a 25% reduction in total concrete usage compared to Standard RCC tanks, with approximately 38% less concrete in the body and around 7-8% less concrete required for staging.
- Hybrid tanks utilize approximately 15% less steel overall compared to Standard RCC tanks, with around 17% less steel in the body and about 13% of the steel quantity required for staging compared to Standard RCC tanks.
- The volume of steel and concrete in tank bodies remains consistent across all 16 cities for both Hybrid and Standard RCC tanks, while concrete usage in staging increases in seismic zones and coastal cities, and steel usage increases in seismic zones and coastal cities compared to non-coastal cities within the same seismic zone.
- Seismic forces increase with the increase in seismic zones. The difference in Seismic base shear increases with an increase in the seismic zone between hybrid & Standard RCC tanks.
- Across different seismic zones, the seismic base shear for Standard RCC tanks varies as follows: In Zone II, it is 151.28 kN for the F.T. condition and 90.31 kN for the E.T. condition. In Zone III, it is 242 kN for the F.T. condition and 144.5 kN for the E.T. condition. In Zone IV, it is 363 kN for the F.T. condition and 216.4 kN for the E.T. condition. In Zone V, it is 544.6 kN for the F.T. condition and 325.1 kN for the E.T. condition.
- For Hybrid tanks, across different seismic zones, the seismic base shear varies as follows: In Zone II, it is 143.3 kN for the F.T. condition and 76.29 kN for the E.T. condition. In Zone III, it is 229.3 kN for the F.T. condition and 122 kN for the E.T. condition. In Zone IV, it is 344 kN for the F.T. condition and 183 kN for the E.T. condition. In Zone V, it is 516 kN for the F.T. condition and 274 kN for the E.T. condition.
- In Zone III, seismic base shear increases by approximately 60% for both Standard RCC and Hybrid tanks compared to Zone II, while in Zone IV, there's a notable spike with seismic base shear surging by roughly 140% for both tank types. Moving to Zone V, the increase is even more significant, with seismic base shear soaring by approximately 260% for both Standard RCC and Hybrid tanks compared to Zone II.
- The percentage savings for Hybrid tanks compared to Standard RCC tanks across different seismic zones range approximately between 5.24% to 5.27% for F.T. conditions and 15.46% to 15.70% for E.T. conditions.
- Wind forces acting on the tanks are similar in both Hybrid and Standard RCC tanks because height and dimensions are kept the same in all the tanks.
- The magnitude of wind forces escalates as wind speeds increase, with values ranging from 125.68 kN in cities experiencing winds at 39 m/s, 162.5 kN at 44 m/s, 185.4 kN at 47 m/s, and 214.5 kN at 50 m/s in non-coastal cities.
- Wind shear forces peak in coastal regions. In cities such as Alibag, where the wind speed is 44 m/s, the wind shear forces reach 275 kN. In cities like Puducherry in Zone II, Chennai in Zone III, and Dwaraka in Zone IV, where the wind speed is 50 m/s, the highest wind forces are experienced, reaching 361.2 kN.
- In Seismic Zone II, wind forces prevail over seismic base shear in E.T. conditions. However, in F.T. conditions, cities such as Bhopal exhibit wind forces that are lower than seismic base shear, whereas for cities like Hyderabad, Jaipur, and Puducherry wind forces exceed seismic base shear.
- In Zone III, wind forces are generally lower than seismic base shear for F.T. conditions, except for Chennai, a coastal city. However, in E.T. scenarios, wind forces are either comparable

to or higher than seismic base shear for all cities in the zone.

- In Zone IV, wind forces are generally lower than seismic base shear for F.T. conditions, except for Dwaraka. In E.T. scenarios, wind forces are lower than seismic base shear for all cities in the zone, except for coastal cities like Alibag and Dwaraka.
- In Zone V Seismic base shear is higher than wind forces in both Full and E.T. conditions.
- Hybrid tanks consistently exhibit lower seismic base shear across all seismic zones compared to Standard RCC tanks.
- The maximum moment in the column is contingent upon the highest lateral forces stemming from either wind shear forces or seismic forces. The moment tends to be nearly the same or lower in Hybrid tanks when compared to Standard RCC tanks. The disparity in moments amplifies with the escalation of Seismic Zones.
- In coastal areas, hybrid tanks demonstrate superior performance, with wind shear forces exceeding seismic base shear in Standard RCC tanks but remaining optimized in hybrid tanks.
- The deflection is 10% - 11% lower in the F.T. and 27% to 28%, in the E.T. condition in comparison to the Standard RCC approach.
- The crack width of the Hybrid tank RCC body is approximately 19.08% less than that of the Standard RCC tank body.
- The crack width of the Hybrid tank Ferrocement lining is approximately 87.28% less than that of the Standard RCC tank body.
- Hybrid tanks offer enhanced structural integrity, ensuring better long-term serviceability compared to Standard RCC tanks, thanks to their superior control over crack width and Deflections.

### Conflict of Interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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