Chapter 2: Literature review

2.1. Introduction

The literature review Section is divided into four parts, each focusing on specific aspects of RCC tank design and the integration of ferrocement.

1. Comprehensive RCC tank design: Analysis, Standards, Failure, Seismic Assessment, and Soil interaction comprising of:
    a. Analysis and design studies
    b. Soil-structure interaction (SSI) studies
    c. Seismic studies
    d. Failure studies
    e. Cost optimization studies
2. Understanding the properties of ferrocement.
3. Exploring the versatile applications of ferrocement
4. Discussing RCC Structures enhanced by ferrocement integration

The first part, titled "Comprehensive RCC tank design: Analysis, Standards, Failure, Seismic Assessment, and Soil interaction," addresses various critical components. It encompasses studies on cost optimization, analyzing and designing RCC tanks, investigating failure mechanisms, examining soil-structure interaction (SSI), and evaluating seismic behavior. These studies aim to optimize designs, ensure compliance with standards, understand failure modes, assess seismic vulnerability, and analyze the interaction between soil and structure. The second Section focuses on "Understanding the Properties of ferrocement" and aims to elucidate the properties and behavior of ferrocement materials. This part provides a thorough understanding of the material's characteristics, including its strengths, weaknesses, and applications. In the third part, "Exploring the versatile applications of ferrocement," a diverse range of applications for ferrocement beyond RCC tank design is explored. This includes discussions on how ferrocement can be utilized in various engineering and construction projects, showcasing its versatility and potential benefits in different contexts. Lastly, "Discussing RCC Structures enhanced by ferrocement integration" examines the integration of RCC and ferrocement. This part explores how combining these materials can enhance the properties and performance of structures, presenting examples of innovative designs and applications that leverage the strengths of both materials.

2.2. Comprehensive RCC tank design: Analysis, Standards, Failure, Seismic assessment, and Soil interaction

Efforts to optimize the design and construction of reinforced concrete (RCC) tanks have been a focal point in engineering research for many years. The goal is to minimize costs while ensuring the structural integrity and performance of these vital structures. Over several decades, researchers have conducted numerous studies covering various aspects of RCC tank design, including cost optimization, failure analysis, seismic considerations, and soil-structure interaction (SSI) analyses. Through the integration of innovative design concepts, advanced computational techniques, and multidisciplinary methodologies, these studies aim to provide sustainable and economically viable solutions for water storage infrastructure.

The significance of comprehensive RCC tank design studies cannot be overstated. Cost optimization studies ensure that RCC tank construction remains economically viable while meeting project requirements. analysis and design studies lay the foundation for creating structurally sound tanks that adhere to regulatory standards. Insights from failure studies guide the development of preventive measures to mitigate risks. Furthermore, soil-structure interaction and seismic studies are crucial for assessing how RCC tanks respond to seismic events and for refining designs to enhance seismic performance. Integrating these various aspects into RCC tank design processes enables engineers to create infrastructure that not only meets immediate needs but also withstands environmental challenges, contributing to long-term sustainability. Thoroughly examining these factors enables engineers to craft resilient and economically viable RCC tank designs that emphasize safety, structural integrity, and longevity. This comprehensive approach to RCC tank design, as outlined through these studies, is indispensable for ensuring the safety, reliability, and cost-effectiveness of water storage infrastructure, thereby benefiting communities worldwide.

2.2.1. Analysis and design studies

The studies outlined provide comprehensive insights into the analysis and design processes crucial for water tank infrastructure. Beginning with Chau (1992) development of the RCTANK program, which offers detailed recommendations for concrete thickness and reinforcement in liquid retaining structures, the research progresses to Buschmeyer and Esser's (2009) discussion on the implementation of the "watertight Concrete" guideline, emphasizing crack management and prestressing techniques to enhance structural durability. Naveen et al. (2011) contribute valuable insights through a comparative study on various tank types, particularly highlighting the efficiency of Intze tanks in minimizing steel usage. Moving forward, Zych (2016) delves into crack control methods for reinforced concrete tank walls, providing practical solutions for compliance with design standards. Terenzi et al. (2019) shift the focus towards preserving historical tank structures, presenting base isolation strategies aimed at minimizing intervention impact while ensuring structural integrity. Chandana and Surendhar's (2019) evaluation of different tank types using STAAD.PRO software further refines design recommendations, particularly emphasizing seismic and wind loading considerations. Velivela et al. (2020) propose an analytical method to precisely determine tank stiffness under lateral loads, offering valuable insights for structural engineers. Imadabathuni et al. (2021) stress the importance of crack-free tank design, underlining its significance for long-term structural integrity. Jyothsna Sree et al. (2023) delve into the complexities of shaft-type tank staging stiffness analysis, crucial for seismic vulnerability assessment. Gurkalo et al. (2024) contribute novel insights into improving seismic resilience through reinforced concrete slit shaft design. Singh and Tiwari (2024) highlight the criticality of seismic analysis, comparing different staging types to enhance structural resilience. Lastly, Sonawane et al. (2023) provide a comprehensive comparison of design standards, reflecting advancements in construction materials and methodologies. Collectively, these studies significantly advance water tank design and analysis practices, ensuring safety, efficiency, and longevity in infrastructure development.

2.2.2. Seismic studies

The studies on water tanks emphasize the need for updated seismic design standards, revealing that increased seismic coefficients and revised importance and response factors enhance resilience. Analyses of seismic responses highlight vulnerabilities due to stiffness ratios, staging patterns, and fluid-structure interactions. Jain (1991,1995) proposes revising seismic design standards for Indian water tanks, suggesting a potential increase of up to 2.75 times in horizontal seismic coefficients and recommends adopting an importance factor of 1.2 and a response reduction factor of 4.0, replacing the current values of 1.5 and 1.8, respectively and also gave the guidelines and explanatory notes on Indian Standard for seismic design. Dutta (2000) analyzed seismic torsional behavior in water tanks, highlighting vulnerability in systems with smaller torsional-to-lateral stiffness ratios, suggesting a need for design revisions to improve seismic resilience. Jain (2006) provided a critical review of the Indian draft code on earthquake-resistant design of liquid-retaining tanks, discussing its implications in structural engineering. Pandya (2007) conducted a primary evaluation and non-destructive testing of a shaft-supported water tank.

Shakib et al. (2010) evaluated seismic demand for elevated concrete water tanks, focusing on 900 cubic meter structures with heights of 25 to 39 meters. They found increased base shear, overturning moment, displacement, and hydrodynamic pressure by 8% to 32% due to mass increase and staging stiffness decrease. Shakib and Omidinasab (2011) studied the seismic performance of a 900 cubic meter tank under different earthquake records, showing that structural parameters and earthquake characteristics significantly impact system responses. Tiwari and Hora (2015 a) analyzed the interaction between an Intze-type water tank and the ground, comparing non-interaction and interaction approaches to highlight significant response differences.

Shiva and Phanikanth (2015) analyzed earthquake effects on ground-supported liquid storage tanks using both analytical and FEM-based solutions, finding good agreement between methods, which improves the design understanding of these tanks under seismic loads. Roy and Roy (2015) found that bi-directional interaction in R/C elevated water tanks with shaft stagings significantly amplifies the global response, especially when tanks are empty, with ground motion characteristics enhancing interaction effects by up to 30%. Jain et al. (2017) estimated the fundamental time periods of elevated reservoirs. Kildashti et al. (2018) assessed the seismic vulnerability of an anchored liquid storage tank considering fixed and flexible base restraints. Kamyar (2018) explored the seismic performance of fully anchored liquid storage tanks, originally designed to API-650 standards, focusing on the impact of base flexibility on seismic performance. Naidu et al. (2019) examined seismic responses of RC elevated water tanks across seismic zones, evaluating tank behavior under varying conditions and employing IS 1893-1984 and IS 1893-2002 methods. Using STAAD PRO, they assessed seismic forces and responses to recommend design improvements.

Kumbhar et al. (2019) introduced a modified Direct Displacement-Based design (DDBD) approach for reinforced concrete elevated water tanks with frame staging. The study proposed adjustments to the existing DDBD procedure based on nonlinear time history analysis of RC frame staging with various configurations, ensuring post-earthquake functionality. Djelloul et al. (2020) studied the influence of supporting systems on dynamic buckling of elevated water tanks. Tabish et al. (2020) analyzed the seismic safety of Intze tanks for water and chemical storage using single and two-mass models with conventional and finite element methods, finding that masonry infills reduced joint displacement but increased base shear.

Mansour et al. (2021) examined the seismic vulnerability of elevated water tanks with diverse staging patterns, focusing on fluid-structure interaction and identifying significant influences on seismic performance. Balaraju and Manchalwar (2021) studied the blast response of elevated water tank staging with metallic dampers, finding x-plate metallic dampers effective against various blast-induced ground vibrations. Manchalwar and Verghese (2021) explored seismic response reduction in elevated water tank staging using lead rubber bearings (LRB) and X-plate dampers (XPD), observing significant reductions in seismic responses. Jogi and Jayalakshmi (2021) analyzed a 700 m^3 elevated Intze water tank's seismic response using ANSYS, finding convective hydrodynamic pressure exceeded impulsive pressure, with maximum displacements at one-third the liquid level. Kangda (2021) reviewed the finite element modeling of liquid storage tanks in ANSYS. Pranitha and Jayalekshmi (2022) analyzed the sloshing response of water tanks under seismic excitation. Kangda et al. (2022) investigated using pall friction dampers to enhance the seismic performance of elevated water tanks, finding dampers effectively mitigate structural responses, although efficiency decreases with increased staging height.

Tirupathi and Srinivasu (2022) analyzed elevated water tanks with varying capacities in different seismic zones, assessing structural performance under dynamic loads through finite element analysis. Chitte et al. (2022) investigated seismic performance of R.C. elevated water storage tanks, analyzing various "R" factor values from different standards to highlight their influence on structural ductility and strength. Chowdhury (2022) discussed seismic performance variations in R.C. shaft-supported elevated water towers, investigating the impact of changing shaft staging proportions on structural behavior under seismic forces. Nimisha et al. (2022) analyzed liquid tank dynamics under seismic loading, using ANSYS Mechanical APDL, finding significant deviations in impulsive frequency values compared to finite element results.

Saha et al. (2023) studied the free vibration response of composite side walls in liquid retaining tanks, considering fluid-wall interaction and finding frequency values increase with ply angle and tank wall height. Sharma et al. (2023) assessed the seismic margin of an elevated RCC water tank on an RCC circular shaft through pushover analysis, comparing different reinforcement configurations. Mansour and Nazri (2023) examined the impact of seismic design and fluid-structure interaction on frame-supported elevated water tanks, evaluating plastic hinge formation, lateral stiffness, and ductility factor. Kumar et al. (2023) analyzed and designed an Intze water tank for gravity and lateral loads using both manual methods and SAP2000, finding the software efficient and consistent with manual methods. Raghuwanshi and Nikhade (2023) assessed the seismic vulnerability of elevated water tanks, highlighting significant earthquake damage due to design flaws and finding half-filled Intze tanks show higher acceleration, stressing the need for thorough analysis to improve structural resilience. Velivela et al. (2023) proposed a self-adaptive penalty approach for analyzing lateral loads on framed elevated water tank stagings, providing a precise method for designing resilient elevated water tank stagings.

2.2.3. Soil-structure interaction (SSI) studies

Several studies emphasize the critical role of soil-structure interaction (SSI) in assessing the seismic behavior of elevated water tanks. They highlight the necessity for advanced analysis methods and identify key factors, such as soil type and tank configuration, that influence seismic responses, aiming to enhance structural resilience and seismic safety. Livaoglu and Dogangun (2007) investigated foundation embedment and its impact on the seismic behavior of fluid-elevated tank-foundation-soil systems across various soil types. Their finite element analysis in ANSYS revealed significant effects on tank roof displacements, especially in soft soils. Dutta et al. (2009) identified deficiencies in seismic design strategies for R/C elevated tanks with SSI and proposed simplified design procedures. Tiwari and Hora (2015 b) performed a 3D interaction analysis of Intze-type water tanks supported by deformable soil, using ANSYS to evaluate stresses, deflections, and natural frequency under different filling conditions. Chowdhury et al. (2017) explored the seismic response of rectangular liquid retaining structures, proposing a mathematical model to address limitations in existing code-recommended models. Meng et al. (2019) found that SSI reduces impulsive mass displacement, base shear, and moment in soil-supported tanks during earthquakes. Nath and Dutta (2021) analyzed SSI impacts on Intze-type tanks across various soils, using ANSYS models and time history analysis to uncover design discrepancies in seismic-prone regions. Rao et al. (2022) studied the seismic behavior of large elevated water tanks on different foundations, emphasizing SSI effects, especially on soft soils. Jayalakshmi (2022) used ANSYS to show that hard soil conditions generate maximum base shear and moments, while soft soil causes higher displacements, underscoring the importance of SSI. Kumar et al. (2023) examined the influence of SSI on peak seismic responses, noting that soft soil increases overturning moments and higher slenderness ratios reduce them. Shahana and Deepu (2023) assessed seismic vulnerability in baffled elevated water tanks.

2.2.4. Failure studies

The studies focus on the seismic failures and vulnerability of elevated water tanks, particularly in earthquake-prone areas. Rai (2003) points out deficiencies in current Indian design standards for tank supports, exposed by the Bhuj earthquake, advocating for revisions. Mori (2015) 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. Jain et al. (2017) highlight the importance of enhanced seismic design for elevated reservoirs, considering factors like water depth and brace flexibility. Lakhade et al. (2018) provide probabilistic drift limits for performance-based design through extensive nonlinear analysis. Dilena et al. (2021) survey old water tanks in Italy, offering insights for retrofitting. Prakash and Bansal (2021) 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 (2006) 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 (2007) 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. (2013) found leakage as a primary cause of tank deterioration in Spain, further underscoring the need for robust design and maintenance practices. Saeed et al. (2020) 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. Rodd & Castel (2022) 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.

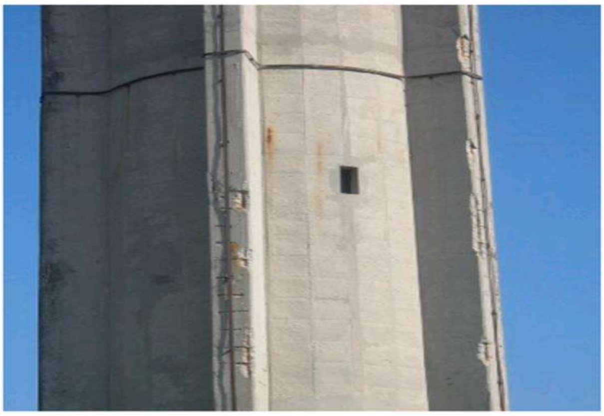

Fig. 2.1: Cover detachment in the shaft ribs.[Dilena et al., 2021]

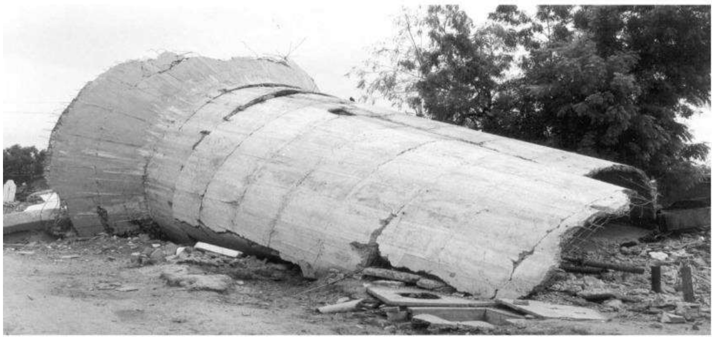

Fig. 2.2: Collapsed 265 kL water tank in Chobari village about 20 km from the epicenter. [Rai, 2003]

Jauhari et al. (2023) assessed the seismic performance and retrofitting of an old URM railway station building in Padang City, Indonesia.

(a) (b)

Fig. 2.3: Collapsed water tank stagings in Manfera village. (b) Damaged water tank staging in Bhachau. [Rai, 2003]

Fig. 2.4: Poor detailing joints at Manfera tank.[Rai, 2003]

Fig. 2.5: Horizontal cracks resulting in corrosion of rebars [Rodd and Castel, 2022]

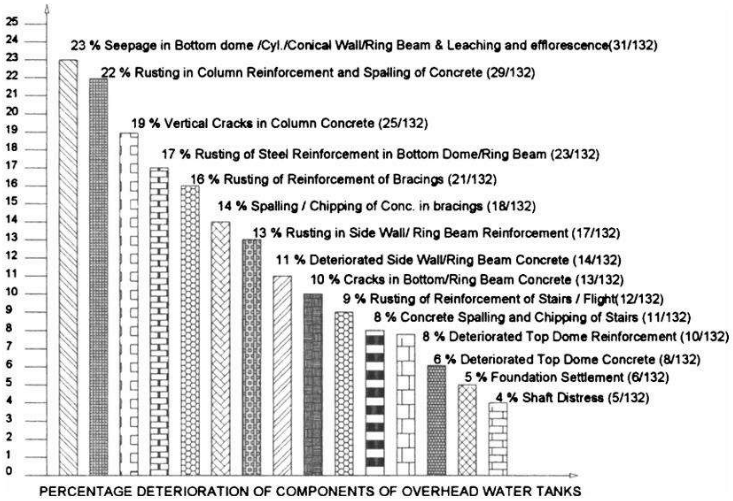

Fig. 2.6: Component-wise Deterioration of water tanks (Survey of 204 water tanks Reveals 132 in Deteriorated Condition)

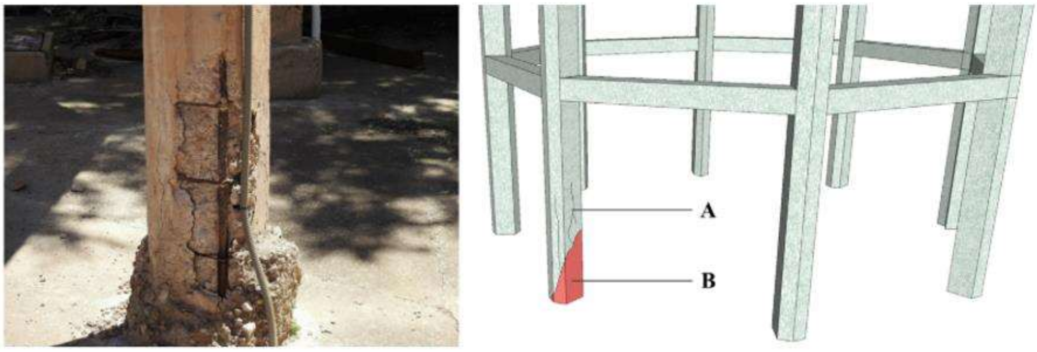

Fig. 2.7: Recurrent damage: Wet areas, cracks & concrete spalling columns near foundation [Sangiorgio et al., 2013]

2.2.5. Cost optimization studies

The quest for cost optimization in the design of reinforced concrete (RCC) tanks has been a persistent endeavor within engineering research. Various studies have investigated different aspects of tank design and construction, aiming to minimize material usage, labor costs, and overall project expenses while maintaining structural integrity and performance. Kameshwara and Raju (1982) optimized the design of Intze tanks on shafts. Choube (1984) and Gambhir (1986) proposed innovative design approaches aimed at reducing construction complexities and material usage. Choube's study compared the cost-effectiveness of traditional Intze tanks with modified versions, offering practical insights into alternative design configurations. Gambhir's novel design concept, replacing cylindrical walls with curved shell petals, demonstrated the potential for disruptive innovations to drive cost optimization in tank construction. Chand et al. (1984) conducted a significant parametric study focusing on optimizing the economical properties of Intze type water towers. Their analysis aimed to identify optimal dimensions for minimum weight design by systematically examining the impact of different design parameters on the quantity of cement concrete required. Saxena et al. (1985, 1987) leveraged nonlinear optimization techniques to streamline the design process of Intze type water tanks, achieving significant reductions in material consumption while adhering to structural requirements. Their studies underscored the importance of adopting advanced computational tools and optimization methodologies to achieve cost-effective designs in RCC tank projects. Thevendran and Thambiratnam (1986) developed a minimum weight design for cylindrical water tanks, while Thevendran and Thambiratnam (1987a) analyzed and designed cylindrical concrete water tanks and (1987b) explored optimal tank shapes. Thevendran and Thambiratnam (1988) extended their work to the minimum weight design of conical concrete water tanks. Similarly, Incorporating advanced computational methods, Tan et al. (1993) explored minimum weight design principles according to British Standards (BS5337), utilizing the finite element method and numerical analysis.

Their study exemplifies the integration of cutting-edge technology and engineering principles to achieve optimal design outcomes, balancing structural performance with cost considerations. Titiksh (2019) delved into the optimization of cylindrical water tanks by varying aspect ratios to determine the most cost-effective height to diameter (H/D) ratio for fixed-capacity overhead water tanks. Siddiqui et al. (2016) contributed valuable insights into optimizing RCC circular water tanks under seismic conditions. By analyzing dynamic responses using sophisticated software tools like STAAD.Pro, the study provided designers with actionable recommendations to enhance the seismic performance of water tank structures without compromising cost efficiency. Furthermore, Patil et.al. (2016), Reddy et al. (2022), and Workeluel (2023) integrated machine learning, comparative analysis, and code evaluations into the design process, expanding the scope of optimization efforts. These studies exemplify a multidisciplinary approach to cost optimization, incorporating advancements in data analytics, computational modeling, and regulatory compliance to deliver sustainable and economically viable solutions for RCC tank infrastructure.

Efforts to optimize staging configurations and enhance structural resilience have been explored by researchers such as Patel and Patel (2012), Khandeshe and Ingle (2015), and Pathak and Mishra (2023). Sathe et al. (2023) analyzed the structural performance of ferrocement panels under low- and high-velocity impact loads. These studies address factors such as lateral earthquake loading, staging types, and bracing systems, contributing to the holistic optimization of RCC tank projects considering both structural and economic considerations.

In summary, the pursuit of cost optimization in RCC tank design encompasses a diverse range of methodologies, including parametric studies, computational modeling, innovative design concepts, and advanced optimization techniques. By integrating these approaches, researchers aim to develop sustainable and economically viable solutions that meet the growing demand for water storage infrastructure while minimizing environmental impact and resource consumption.

2.3. Understanding the properties of ferrocement

Several studies conducted between 1971 and 1981 investigated various aspects of ferrocement, including its tensile behavior, flexural capacity, moment capacity, and cracking behavior. Researchers explored the material's strength under different loading conditions, developed predictive models for elasticity, and examined the influence of reinforcement surface on cracking. studies also delved into the inelastic behavior of ferrocement slabs, analyzed its performance in tension and compression, and proposed design recommendations for structural elements. Additionally, investigations explored the fatigue behavior of ferrocement beams, discussed crack width predictions, and summarized the material's applications and ongoing research efforts.

Nervi (1956) offered foundational insights into the characteristics and potentials of ferro-cement, laying the groundwork for subsequent explorations in this domain. Collen and Kirwan (1959) provided insights into ferrocement characteristics. Claman (1969) correlated material properties with observed plate behavior in ferrocement. Naaman and Shah (1971) investigated the tensile behavior of ferrocement, revealing that its ultimate strength corresponds primarily to the mesh alone, while establishing predictive models for elasticity and exploring the influence of reinforcement surface on cracking behavior. Rao and Gowdar (1971) explored the behavior of ferrocement in flexure, highlighting properties that differentiate it from reinforced concrete through tests on small models. Shah and Key Jr. (1972) explored ferro-cement's impact resistance and tensile strength, suggesting lightweight sand use. Shah and William (1972) studied the impact resistance of ferrocement. Logan & Shah (1973) delved into the moment capacity and cracking behavior of ferrocement in flexure, reporting data on initial cracking, crack widths, and ultimate strength of ferrocement beams, along with proposed design equations compared to conventionally reinforced concrete. Pama et al. (1974) treated ferrocement as a homogeneous composite material, deriving its rigidities and strength in various loading conditions, providing explicit expressions for its moduli and discussing its strength behavior. Johnston & Mowat (1974) conducted tests on ferrocement planks, revealing significant differences in strength and load conformity among various reinforcement systems based on geometry and orientation. Austriaco et al. (1975) investigated the inelastic behavior of ferrocement slabs in bending, deriving moment-curvature relationships analytically and confirming experimental results with theoretical predictions. Johnston & Mattar (1976) explored ferrocement behavior in tension and compression, highlighting the superiority of expanded metal in tension and welded mesh in compression. Balaguru et al. (1977) conducted experiments on ferrocement beams, developing an analytical model to predict load-deflection curves and crack widths, successfully predicting beam behavior up to ultimate. Huq & Pama (1978) analyzed ferrocement behavior in tension, deriving expressions for modulus of elasticity and crack width, providing design recommendations for structural elements. Karim & Joseph (1978) investigated the flexural behavior of ferrocement, exploring factors such as mesh type and reinforcement layout, aiming to assess its potential for long-span roofing applications. Shah and Naaman (1978) studied crack control in ferrocement compared to reinforced concrete, finding advantages in containment structures. Balaguru et al. (1979) studied the fatigue behavior and design of ferrocement beams. Raichvarger and Raphael (1979) investigated sand grading's influence on ferrocement mortar workability. Naaman (1979) discussed crack width predictions in ferrocement, emphasizing their importance for serviceability criteria and suggesting design approaches. Shah (1980) summarized the state of knowledge and applications of ferrocement, highlighting its increasing use and ongoing research efforts. Somayaji and Naaman (1981) investigated stress-strain responses and cracking behavior in ferrocement composites under tensile loading, providing accurate measurements of crack widths and spacings.

In the early 1980s, a comprehensive exploration of ferrocement structures occurred through various studies. Balaguru (1981) provided equations to predict crack widths in ferrocement beams reinforced with wire meshes, derived from mechanics principles and experimental observations.

Ravindrarajah and Tam (1984) explored techniques for enhancing watertightness and durability of ferrocement in water-retaining structures, employing very-low-permeability mortar and superplasticizer for workability. Neelamegam et al. (1984 a) studied the flexural behavior of polymer-ferrocements, emphasizing the significant improvement with increased reinforcement surface area. Somayaji and Shah (1984) scrutinized the tensile response of ferrocement composites under various parameters, demonstrating satisfactory agreement between theoretical predictions and experimental data. Neelamegam et al. (1984 b) examined the deformational behavior and durability of polymer-impregnated ferrocement compared to traditional ferrocement, highlighting significant improvements. Trikha et al. (1984 b) studied corrosion in ferrocement structures. Mansur and Paramasivam (1985) explored the behavior of ferrocement under combined bending and axial loads. Walraven and Spierenburg (1985) analyzed ferrocement reinforced with chicken wire mesh, showing satisfactory predictability through theory-experiment comparisons. These studies collectively enriched the understanding of ferrocement's mechanical properties and diversified its potential applications. Bennett et al. (1985) studied the fatigue characteristics of ferrocement in flexure, highlighting its performance under repeated loading conditions. Naaman and McCarthy (1985) examined the efficiency of ferrocement reinforced with hexagonal mesh. Naaman (1986) introduced computerized evaluation and design aids for flexural design. Rao and Rao (1986) investigated stress-strain behavior and Poisson's ratio of ferrocement under axial compression, deriving equations for strength prediction. Thang and Pama (1986) demonstrated the mechanical benefits of pre-tensioning in ferrocement elements, especially in improving first crack strength. Mansur and Paramasivam (1986) proposed a method to predict the ultimate moment capacity of ferrocement in flexure, supported by experimental validation. Mansur and Ong (1987) delved into shear strength analysis in ferrocement beams reinforced with welded wire mesh, providing empirical equations for predicting diagonal cracking strength. Nanni and Zollo (1987) focused on tension behavior of ferrocement reinforcement, aiming to enhance structural design and quality control. Batson et al. (1988) provide comprehensive technical guidance on ferrocement design, construction, and repair, aiming to enhance its utilization in terrestrial structures. Ramli (1988) investigated the fatigue strength of ferrocement in marine environments, emphasizing the material's resilience to continuous exposure to seawater. Mansur (1988) explored the ultimate load behavior of ferrocement with varying member thickness, supporting the 'rigid-plastic' concept for strength analysis. Walkus (1988) investigated the behavior of ferrocement elements under long-term tension, comparing deformations under short-term and long-term loads. Ganesan and Murugiah (1988) introduced a method to predict crack spacing and width in ferrocement members under tension, offering improved accuracy compared to existing equations. Alexander (1989) discussed durability factors of ferrocement, highlighting its superior resistance attributed to material composition and construction techniques. Ong and Paramasivam (1990) examined cracking behavior under restrained shrinkage conditions.

Several notable studies have contributed to our understanding of ferrocement across various domains. In Hawlader et al.'s (1990) exploration of ferrocement's thermal behavior, they observed that lower sand-cement ratios increased thermal conductivity while reducing thermal inertia. Al-Rifaie and Trikha (1990) investigated hexagonal mesh arrangement effects on two-way ferrocement slabs, proposing efficiency-enhancing arrangements and theoretical models for determining the first crack load. Meanwhile, Swamy and Shaheen (1990) delved into thin ferrocement plate tensile behavior, revealing potential for high-strength, crack-resistant sheets despite inconsistent cracking behavior across mesh geometries. Tatsa (1991) proposed a limit states design method for ferrocement components in bending, addressing strength and serviceability considerations. Singh and Xiong (1991) critiqued crack-width prediction models for ferrocement, asserting the dominance of steel stress as the primary design criterion for most structural applications. Nedwell and Nakassa (1999) explored high-performance ferrocement using stainless steel mesh and high-strength mortar. In the realm of ferrocement, a diverse array of research endeavors has contributed to our understanding and utilization of this versatile material.

Walkus and Gackowski (1992) investigated the mathematical determination of critical cracking force in the tension zone of ferrocement, emphasizing the formation of "structural microcracks" perpendicular to tensile force during concrete setting and hardening. Rao's (1992) analysis of ferrocement compression behavior highlighted the material's alteration towards near elasto-plasticity due to reinforcement, with implications for structural design. Mansur et al. (1994) examined single-hole bolted joints in ferrocement, proposing a method to calculate joint ultimate strength based on various parameters, with theoretical predictions aligning well with test results. Kaushik et al. (1994) examined ferrocement plate buckling, deriving strengths and failure modes under varying conditions. Khanzadi and Ramesht (1996) examined tension behavior in ferrocement, assessing the impact of reinforcement arrangement, specimen thickness, and mortar cover on crack formation and strength. Recent advancements by Skudra (1995), Pankaj et al. (2002), and Naaman (2000) presents "Ferrocement and Laminated Cementitious Composites," offering practical design guidelines and examples for ensuring good serviceability. Masood et al. (2003) contributed to our understanding of ferrocement's performance in diverse environmental conditions, shedding light on flexural strength variations and material behavior in different settings. Collectively, these studies illustrate the multidimensional nature of ferrocement research, from fundamental explorations to practical applications, driving forward our knowledge and utilization of this versatile material. Kumar and Rao (2005) delved into the behavior of ferrocement under biaxial tension-tension stress conditions, focusing on hollow cylindrical specimens. Their study proposed an interaction curve to estimate ferrocement strength in such conditions, while also elucidating the relationship between octahedral normal and shear stress. Kumar and Rao (2005) further refine our understanding, offering predictive models and insights into ferrocement's mechanical behavior under diverse loading conditions. In parallel, Naaman (2006) furthered this discourse by discussing recent advancements in ferrocement technology, emphasizing innovations in reinforcement materials and improvements in strength and durability.

Mansur et al. (2008) studied ferrocement corrosion durability, finding deeper concrete cover and mineral admixtures provided superior protection. Wafa and Fukuzawa (2010) compared stainless steel and fiberglass meshes in ferrocement, noting stainless steel's enhanced bending characteristics. Vinay et al. (2012)

examined ferrocement elements under bending, showing increased reinforcement volume fractions-controlled crack width and improved strength.

On a more contemporary note, Naaman (2012) provided a comprehensive overview of the evolution of ferrocement and thin cement-based composites, highlighting advancements in reinforcement materials, cement matrix properties, and future challenges and prospects. Morozov and Pucharenko (2013) explored nuclear reactor shells made of heavy ferrocement. Kaish et al. (2018) provide a comprehensive review of ferrocement composites for strengthening concrete columns, emphasizing their effectiveness in repairing structures and identifying research gaps. Hanif et al. (2019) investigated the flexural fatigue behavior of lightweight ferrocement through experimental testing and numerical modeling. AbdulRahman et al. (2020) investigated the mechanical performance of folded ferrocement elements under different aging periods and hot climates. Nivate et al. (2023) studied the durability parameters of ferrocement. Rao and Desayi (2023) conducted a probabilistic analysis of the ultimate strength of ferrocement elements in axial tension. Ceravolo et al. (2023) conducted an experimental durability analysis of historical ferrocement. Ali et al. (2024) explored the enhancement of ferrocement mortar's mechanical properties by incorporating waste plastic fibers. Cardoso et al. (2024) delved into the innovative realm of biocementation, exploring its potential in sealing cracks within concrete water storage tanks. Their study, employing Sporosarcina pasteurii bacteria, showcased promising results in reducing water flow rates in cracks of varying widths, though underscored the necessity for further investigations into material durability, particularly concerning larger crack widths.

Research on ferrocement spanning several decades has provided valuable insights into its mechanical properties and behavior under various loading conditions. studies conducted between 1971 and 1981 explored aspects such as tensile behavior, flexural capacity, moment capacity, and cracking behavior. These investigations aimed to understand ferrocement's strength under different loading scenarios and develop predictive models for elasticity while examining the influence of reinforcement surface on cracking. Moreover, research delved into the material's inelastic behavior in slabs, analyzed its performance in tension and compression, and proposed design recommendations for structural elements. Investigations also explored the fatigue behavior of ferrocement beams, discussed crack width predictions, and summarized its applications and ongoing research efforts.

Furthermore, studies in the early 1980s provided a comprehensive exploration of ferrocement structures. Subsequent research addressed enhancing ferrocement's watertightness and durability in water-retaining structures by employing low-permeability mortar and superplasticizers. Investigations into polymer-impregnated ferrocement highlighted improvements in flexural behavior and durability compared to traditional ferrocement. Additionally, studies examined ferrocement behavior under combined bending and axial loads, analyzed shear strength in beams, and explored crack control methods. These endeavors collectively enriched our understanding of ferrocement's mechanical properties, diversified its potential applications, and contributed to its ongoing development and utilization in engineering and construction domains.

2.4. Exploring the versatile applications of ferrocement

This Section delves into the extensive range of applications where ferrocement has found utility and effectiveness. From its inception, ferrocement has emerged as a versatile engineering material with diverse uses spanning multiple disciplines. Early investigations laid the groundwork for understanding ferrocement's properties and its potential applications. Subsequent studies further elucidated its suitability and effectiveness in various structural and construction contexts. From waterproofing solutions to innovative housing designs, and from marine vessels to rural irrigation infrastructure, ferrocement has demonstrated its adaptability and resilience. Each study in this collection contributes to our comprehensive understanding of ferrocement's applications, shedding light on its unique properties and highlighting its advantages in different scenarios.

Shah (1970) contributed to early examinations of ferro-cement as a novel engineering material, setting the stage for its diverse applications across various disciplines. These studies, alongside earlier works by pioneers like Thomas (1971) and Shah and Key (1971), have collectively expanded the horizons of ferrocement applications, from naval construction to nuclear reactor shell creation. Brauer (1973) explored the application of ferrocement in boat and craft construction. Naaman and Shah (1976) evaluated ferrocement's efficacy in various structural applications, offering valuable insights into its suitability and effectiveness in specific contexts. Guerra et al. (1978) investigated the cracking and leakage behavior of ferrocement cylindrical tanks, highlighting their performance under various loading conditions. Naaman (1979) outlined performance criteria for ferrocement structures. Shah (1979) provided tentative recommendations for constructing ferrocement tanks. Sharma (1979, 1980) explores ferrocement's unique role in waterproofing, providing practical construction notes and comparisons with conventional methods. Subrahmanyam et al. (1980) examined thin ferrocement ribbon roofs for long spans, with analysis confirming their structural viability. DasGupta et al. (1980) explored constructing a ferrocement hyperbolic paraboloid shell, reporting on its behavior under vertical loads. Paramasivam et al. (1981) investigated the fatigue behavior of ferrocement slabs, experimenting with different reinforcement volume fractions and comparing experimental results with theoretical stress computations. Kaushik et al. (1982) delved into the ultimate strength behavior of ferrocement beams, particularly focusing on the impact of mesh reinforcement on ductility and cracking. Kaushik et al. (1983) further explored the behavior of ferrocement structural elements in buildings, providing experimental results and proposing expressions for serviceability limits. Alexander and Atcheson (1983) document the construction of a 180 ft (55 m) long fuel oil tanker in Jakarta, emphasizing the innovative use of prestressing, high-tensile wire reinforcement, and wire-fiber mortar to enhance ferrocement's properties for marine applications. Meanwhile, Tieyu et al. (1984) discuss the design and construction of ferrocement U-aqueducts for rural irrigation, highlighting their lightweight, durable, and cost-effective nature. Sharma et al. (1984) demonstrate the use of ferrocement for repairing leaky water tanks, showcasing its impermeability and easy application. Trikha et al. (1984 a) presented experimental results on ferrocement grid roof/flooring units, discussing the effects of mesh-mortar parameters on flexural behavior. Elangovan and Kumar (1984) studied the behavior of a ferrocement funicular shell roof under uniform loads, evaluating its suitability for low-cost housing. Paramasivam and Mansur (1985) investigated common joints in ferrocement construction, shedding light on their tensile and flexural behavior, including insights into cracking characteristics, ductility, and ultimate strength. Desayi and Ganesan (1986 a, 1986 b) explored the fracture behavior of ferrocement beams using different approaches, revealing dependencies on notch depth and mesh reinforcement percentages. Reinhom and Prawel (1986) assessed ferrocement's role in enhancing the dynamic behavior of shaking tables, while Mansur and Ong (1986) provided additional data on composite slabs reinforced with ferrocement decks, emphasizing their structural integrity under heavy loads. Naaman (1989) explores integrating high-tech solutions in ferrocement housing, proposing standardized panel configurations for various structural elements. Paramasivam and Fwa (1990) explored the potential of thin ferrocement overlays for resurfacing concrete pavements, indicating promising rehabilitation prospects. These studies contributed to advancing our knowledge and application of ferrocement in various structural contexts. Hernandez's (1993) meticulous study on low-cost ferrocement water tanks showcased innovative design strategies, such as utilizing the hyperboloid of revolution for enhanced structural integrity. Finally, Fahmy et al. (1995) suggested using ferrocement for thin radial gates in irrigation works, emphasizing its strength and energy absorption compared to steel gates, along with optimal design parameters. Ali et al. (2020) investigated the flexural behavior of one-way ferrocement slabs with fibrous cementitious matrices. Patel & Kute (2021) predicted wall pressures and stresses in cylindrical ferrocement silos. Rajendran (2021) assessed the corrosion of ferrocement elements with nano geopolymer for marine applications. Paul and Mathew (2021) reviewed ferro-geopolymer as a sustainable construction material. Abed et al. (2022) explored sustainable ferrocement mortar incorporating different waste materials and curing methods. El-Sayed et al. (2023) studied the behavior of ferrocement water pipes as an alternative to steel pipes. Chen et al. (2023) investigated the integration of concrete fabrication techniques into ferrocement, focusing on shape-making of cement mixtures. Lim et al. (2023) investigated the strength properties of lightweight foamed ferrocement blocks and beams. Minde et al. (2023) reviewed ferrocement as a sustainable construction material in the Indian context. Ahmed et al. (2024) investigated the static load behavior of ferrocement slabs reinforced with recycled tire steel wire, highlighting its structural performance and sustainability potential. Shinde et al. (2024 a) investigated the bond behavior of ferrocement with different wire mesh specifications, while Shinde et al. (2024 b) examined the flexural characteristics of ferrocement plates.

The diverse applications discussed in this Section underscore the versatility of ferrocement in various engineering domains. studies have explored its use in marine vessels, rural irrigation infrastructure, structural elements in buildings, and even as waterproofing solutions. Pioneering investigations laid the foundation for understanding ferrocement's properties, while subsequent research expanded its applications and highlighted innovative design strategies. Together, these studies contribute to a comprehensive understanding of ferrocement's utility and effectiveness across different structural contexts, suggesting promising prospects for future advancements and applications.

2.5. RCC Structures enhanced by ferrocement integration

Ferrocement integration into reinforced concrete structures has been the subject of numerous studies over several decades, aiming to enhance structural performance and address specific engineering challenges. These investigations have explored various applications of ferrocement, ranging from composite beams and slabs to column reinforcement and seismic retrofitting. The integration of ferrocement has shown promising results in terms of improving load-bearing capacity, ductility, crack resistance, and energy absorption, offering potential solutions for enhancing the resilience and durability of reinforced concrete constructions. Kahn et al. (1975) conducted tests on ferrocement-steel plate composite beams, revealing doubled strength compared to reinforced concrete, albeit with reduced ductility. Mansur et al. (1984) investigated one-way concrete slabs reinforced with ferrocement decking, noting minimal influence on structural behavior by deck profiles. Rosenthal and Bljuger (1985) studied composite beams, observing distinctive crack patterns due to ferrocement encasing. Fahmy et al. (2005) explored ferrocement laminates as permanent forms for reinforced concrete beams, highlighting advantages in strength, crack resistance, ductility, and energy absorption. Shaheen et al. (2014) assessed ferrocement domes reinforced with composite materials, offering insights for dome construction, while Shaheen et al. (2020, 2021) developed lightweight ferrocement sandwich panels for walls, demonstrating high strength, crack resistance, and energy absorption. Jayaprakash et al. (2021) proposed an analytical model for predicting ultimate moment carrying capacity based on bending tests conducted on ferrocement laminates. Evbuomwan (2022) examined the behavior of RC beams enhanced with polymer-modified ferrocement. Obaid and Jaafer (2022) conducted an experimental investigation on ferrocement sandwich composite jack arch slabs. Rajguru and Patkar (2022) examined the torsional behavior of RC beams strengthened with ferrocement. Unni and Sengupta (2022) strengthened RC beams for shear using concrete jackets, while Aules et al. (2022) studied ferrocement and CFRP strengthening of short concrete columns. Soundararajan et al. (2022) explored sustainable retrofitting and moment evaluation of damaged RC beams using ferrocement composites. Megarsa and Kenea (2022) numerically investigated the shear performance of RC beams with ferrocement composites. Sinha and Talukdar (2023) explored the repair of web-opened RC beams using ferrocement laminates with alkali-activated mortar, demonstrating improved structural performance. Gowri and Balachandu (2023) reviewed the structural properties of concrete with ferrocement. Ghogare and Kondraivendhan (2023) tested RC specimens reinforced with Ferro-CM and Ferro-GPM composites under axial loads, showing enhanced strength with thicker wraps, especially with Ferro-GPM. Rathinam and Kanagarajan (2023) studied the flexural behavior of ferrocement slabs using foamed concrete. Sen et al. (2023) investigated lateral strengthening of masonry infilled RC buildings using ferrocement, identifying failure mechanisms and proposing a strength evaluation method. Alzabidi et al. (2023) conducted an experimental study on RC beams under torsional loading, demonstrating significant enhancements in load-carrying capacity with ferrocement-based rehabilitation techniques, particularly with dual-layer wire mesh wrapping. Shaheen et al. (2023) studied ferrocement beams with lightweight cores filled with expanded polystyrene and lightweight aerated autoclaved brick wastes, reinforced with welded steel mesh, revealing substantial enhancements in ultimate load, deflection, and ductility. Mahmood et al. (2023) introduced prefabricated ferrocement jackets for repairing and strengthening sub-standard concrete columns, demonstrating improved load-bearing capacity, reduced deflection, and enhanced ductility. Bindurani et al. (2023) compared ferrocement with two variants of fibre-reinforced polymer (FRP) in strengthening beam-column joints, finding ferrocement outperforming GFRP and performing similarly to CFRP, suggesting cost-effective strengthening. Pecka et al. (2023) investigated reinforced-concrete column reinforcement, finding significant resistance boosts with longitudinal reinforcement and minimal impact of ferrocement wrapping on concrete strength. Hameed and Jaafer (2023) reviewed studies on reinforcing RC beams with ferrocement, indicating its viability for retrofitting and strengthening RC structures due to its efficacy in enhancing load ratios compared to controls. Shaheen and Mahmoud (2022, 2023) examined RC channel slabs reinforced with ferrocement, noting a 24% strength increase with welded steel mesh compared to expanded steel mesh. Lenticchia et al. (2023)

analyzed Pier Luigi Nervi's Hall C at Torino Esposizioni, proposing conservation guidelines through historical documentation and non-destructive testing. Basir et al. (2023) examined the flexural performance of reinforced concrete beams retrofitted with ferrocement wire mesh. Eltaly et al. (2023) investigated lightweight ferrocement box columns, demonstrating a 35% enhancement in ultimate load compared to conventional concrete. Sankar and Shoba Rajkumar (2023) explored retrofitting RC square columns with improved ferrocement jacketing, while Ismail et al. (2023) studied the effectiveness of ferrocement layers in retrofitting adobe brick houses against earthquake loads. Kannan et al. (2023) experimentally investigated the flexural behavior of ferrocement composite slabs. Krishna et al. (2024) evaluated the performance of axially loaded high-strength ferrocement-confined fiber-reinforced concrete columns, assessing their structural efficiency and load-bearing capacity. Joyklad et al. (2024) investigated the structural behavior of RC one-way slabs strengthened with ferrocement and FRP composites, revealing significant enhancements in peak load, ultimate deflection, and dissipated energy. Pérez-Pinedo et al. (2024) conducted an experimental study on seismic strengthening of partially grouted reinforced masonry walls using ferrocement coating and Basalt Textile Reinforced Mortar layer, observing increased stiffness and lateral capacity. Abdallah et al. (2024) explored the strengthening of RC beams with inadequate lap splice length using cast-in-situ and anchored precast ECC ferrocement layers, achieving significant enhancements in cracking and ultimate stages. Emara et al. (2024) investigated the enhancement of cantilevered RC beams with inadequate lap spliced reinforcement using sustainable reinforced ECC layers, observing improved structural behavior and energy absorption capacity. Gopal and Shobarajkumar (2024) conducted a comparative study on the structural behavior of ferrocement wall panels, highlighting their advantages such as quick construction, customizable shapes, low cost, and soundproofing insulation. Živković et al. (2024) investigated ferrocement-strengthened RC beams, observing up to a 21.4% increase in bearing capacity with four types of ferrocement strips. Roy et al. (2024) compared HSFRC, ferrocement, and GFRP jacketing for strengthening RC columns exposed to high temperatures, with GFRP jacketing showing superior strength restoration.

Behera et al. (2022, 2023, 2024) explored torque and twist responses of concrete beams with 'U' ferrocement wrap, predicting torsional parameters efficiently and demonstrating significant enhancements in torque and twist over under-reinforced Sections. In conclusion, the comprehensive body of research on RCC structures enhanced by ferrocement integration underscores the versatility and effectiveness of this composite material in addressing diverse structural requirements. From increasing load-carrying capacity to improving seismic resilience and reducing deflection, the findings from these studies highlight the significant benefits of incorporating ferrocement into reinforced concrete systems. As the field continues to evolve, further exploration and implementation of ferrocement integration hold promise for advancing the performance and sustainability of concrete structures in various engineering applications.

In the effort to reduce RCC water tank costs, global initiatives have explored various strategies, such as nonlinear optimization, parametric studies, and computational techniques like machine learning and numerical methods. Research highlights that Indian standards offer a particularly cost-effective approach to water tank design compared to global standards. Additionally, there have been investigations into modifying staging configurations to minimize structural costs. However, challenges persist, especially regarding leakage issues, which remain a significant concern in water tank construction. Despite adhering to stringent material utilization standards, instances of leakage often necessitate costly post-construction maintenance and repairs.

To address both cost and leakage concerns, ferrocement lining emerges as a promising alternative. Studies indicate that ferrocement exhibits remarkable resistance to tension, compression, bending, molding, and possesses impressive waterproofing capabilities. Furthermore, research suggests a harmonious and unified behavior between ferrocement and RCC. By embracing ferrocement lining, stakeholders can potentially overcome the limitations of traditional RCC tank construction, ensuring both cost-efficiency and long-term structural integrity in water storage infrastructure.

2.6. Research gaps

RCC water tanks are essential but come with economic challenges due to substantial material consumption. As per the latest Indian standards, water tanks are primarily designed based on two criteria, determined by the steel stress limits—either 130 N/mm^2 or up to the characteristic strength of steel limiting the crack width up to 0.2 mm. criteria II is more cost-effective compared to criteria I, but it still results in a bulky design, with the material being underutilized.

Global initiatives have sought to mitigate RCC water tank costs through diverse approaches, including nonlinear optimization, parametric studies, and weight reduction via computational techniques like machine learning, or numerical methods. Research indicates that Indian standards are highly cost-effective for designing water tanks as compared to global standards. Other studies have explored altering staging configurations to decrease structural costs. Additionally, few study has been conducted to assess leakage issues in multiple water tanks. studies employing machine learning or numeric methods with RCC alone have shown limited cost reduction.

Despite these efforts, material utilization falls short of allowable stress levels, and strict limitations persist due to leakage concerns—a predominant issue in water tanks. Even after these stringent limits leakage in tanks post-construction is a persistent issue, necessitating expensive maintenance and time-consuming repairs.

There was a need for alternatives which can address both leakage and cost concerns. For leakage concerns ferrocement lining emerges as a promising alternative. Studies suggest that ferrocement is an outstanding choice for lining, primarily because of its exceptional resistance to tension, compression, bending, molding, and its impressive waterproofing capabilities. Research indicates a cohesive and unitary behavior between ferrocement and RCC.

To address the challenges of leakage and cost associated with conventional tanks, this study has introduced an integrated methodology for Hybrid design, incorporating ferrocement lining in elevated RCC Intze water tanks. This represents an uncharted avenue holding significant promise for substantial reductions in overall structural costs, all while adhering to crucial allowable stress standards in hybrid design. Additionally, this study seeks to assess and compare the structural performance and cost-effectiveness of conventional tanks designed with HWT, aiming to establish the preferred choice for tank design and construction.

2.7. Scope and objective

CWT are often bulky and costly due to minimum dimension requirements, exposure, and limiting stress criteria. They are also prone to leakage, leading to expensive repairs, retrofits, and even abandonment after construction. To address these challenges, this study introduces novel "**Hybrid water tanks**," which are RCC (Reinforced Cement Concrete) water tanks integrated with ferrocement lining. This innovative design, combining ferrocement lining with RCC structures, is pioneering and represents the first integration of ferrocement lining as a crucial component, acting as a barrier between the RCC and water. The RCC tank body is designed to bear all structural loads according to IS 456:2000 (Reaffirmed 2021), unlike CWT designed as per IS 3370:2021. The ferrocement lining, designed as per American Concrete Institute Standards, imparts impermeability to the structure.

The objective of this research is to develop a comprehensive methodology for Hybrid design, focusing on the integration of ferrocement lining with the RCC tank body. This study emphasizes the hybrid design methodology, including details, equations, and technicalities of the design procedure for the entire tank, which comprises the RCC tank body, lining, and substructure. Additionally, the study conducts a comparative analysis with Conventional RCC tanks to establish the cost efficiency and structural superiority of HWT over standard RCC ones.

The study specifically focuses on the design of Hybrid Intze water tanks and Hybrid Circular water tanks as Intze and Circular RCC water tanks are among the most constructed types across the country. It includes a comparative analysis of these Hybrid designs with CWT based on the design criteria specified in IS 3370:2021 to assess the cost-effectiveness and structural performance of Hybrid versus conventional tanks. Furthermore, the study validates the designs of these tanks in 16 major Indian cities, considering different seismic zones and wind speed conditions.

To facilitate the design process, software programs were developed in C++ for both Intze and Circular tank types, for both Hybrid and Conventional tank designs. These programs incorporate heuristic optimization, continuity-based analysis, and the limit state design method.

This study marks a significant advancement in water tank structure design, providing detailed guidelines and procedures for developing HWT. The outcomes highlight the innovative nature of this initiative, presenting a novel strategy for achieving cost savings while promoting sustainable development principles.

This study aims to explore and advance the design, analysis, and comparative evaluation of HWTs, encompassing both Intze and circular types. Major objectives are as follows:

1. Develop detailed design guidelines, principles and equations for HWTs, covering both Intze and Circular designs.
2. Create specialized software programs for Analyzing, design and Cost Estimation of Hybrid Intze and Hybrid Circular tanks.
3. Create specialized software programs for Analyzing, design and Cost Estimation of Conventional Intze and Circular tanks (Both type I and type II) for performing the comparative study with Hybrid counterparts.
4. Validate the developed software programs to ensure accuracy and reliability in simulating tank design and performance.
5. Conduct comparative studies of Hybrid versus Conventional (type I and type II) Intze tanks. For this 200 kL(Low), 600 kL(Medium) and 1000 kL (High) Capacity tanks are chosen so as to assess the cost-effectiveness, structural integrity, and performance under seismic and wind loads. A further study has been done to evaluate the cost differences between Conventional type I and type II tanks.
6. Perform a parametric study of elevated Hybrid Circular tanks to explore design variations and optimize performance.
7. Conduct comparative studies of Hybrid versus Conventional (type I and type II) Circular tanks using 100 kL, 150 kL, 200 kL, 250 kL and 300 kL tanks, assessing cost-effectiveness, structural integrity, and performance under seismic and wind loads.
8. Conduct a comprehensive analysis of 600 kL Hybrid Intze versus Conventional Intze water tanks across 16 major Indian urban centers to evaluate economic and structural advantages

9. Conduct a comprehensive analysis of 150 kL Hybrid Circular versus Conventional Circular water tanks across 16 major Indian urban centers to evaluate economic and structural advantages

In conclusion, this research aims to provide valuable insights into the performance and economic feasibility of HWTs compared to conventional RCC structures. By integrating detailed design guidelines, robust software programs, and rigorous comparative analyses, this study seeks to inform and enhance decision-making in urban water infrastructure development across India.