

A Case Study: Criteria of Insulated Concrete Foam (ICF) in a Project in Saudi Arabia

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Abstract:- In this paper, the structural and heating performance of Insulated Concrete Form wall panels and conventional reinforced concrete structural systems were examined. Both experimental work and finite element analysis were used to analyse the loading capacity, displacement, and heating efficiency of the two structural designs. Experiments were carried out on five panels of ICF designs having expanded polystyrene of various densities and thicknesses. In addition, a finite element analysis using the ABAQUS program was performed to validate the experimental data. The analysis showed that the ICF 40100 design had a compressive strength of 25.01 MPa, which was over 40% higher than plain concrete, as well as an ultimate load of 17.97 kN. Increased density and thickness of the expanded polystyrene improved load support, minimized crack propagation, and enhanced material ductility. The addition of ferrocement and CFRP increased structural stiffness by 62%, as well as minimized displacement. Heating analysis of the designed villa proved that ICF performed better by cooling the interior temperature by 8°C and shortening the structural creation process by 15%, thereby presenting strong evidence of better energy and economic advantages. The high correlation between experimental and FEA data ensures that the FEA model provides precise estimates. The data thus supports the applicability of ICF as an effective energy-saving technique that provides structural stability against reinforced concrete walls.

Keywords: *Insulated Concrete Form (ICF); Expanded Polystyrene (EPS); Finite Element Analysis (FEA); Structural Performance; Energy Efficiency*

1. Introduction

The growing global population and improving living conditions have amplified the need for high-performance construction materials and sustainable construction methods. The Insulated Concrete Form (ICF) technology is one new-age technology that has come into the limelight, comprising interconnected expanded polystyrene (EPS) blocks filled with concrete. The walls made from the ICF have the advantage over traditional construction methods of better thermal resistance, improved structural capability, soundproofing, longevity, and resistance to disasters (Amer-Yahia & Majidzadeh, 2012; Morcous & Sekpe, 2010). Even though the adoption rate was relatively low during the early 2000s, the construction industry has increasingly been opting for the ICF system for the potential offered by the construction by means of minimised energy demands as well as lifecycle expenditures.

All over the world, construction with ICFs has been extensively utilised in residential buildings, office buildings, institutional buildings, and other structures in the USA, Canada, Japan, and Germany since the 1970s. Although initially greeted with concerns over cost estimated at 5–10% above conventional concrete construction methods, studies have shown that monthly savings in energy consumption and eventual maintenance pay for this premium. In recent years, the passive house concept has underscored the significance of the ICF method. In the past few years, the passive house concept has still heightened the importance of the ICF method. Passive houses feature an airtight construction with excellent insulation for the retention of warmth during the cold months and coolness during the hot months without the need for active cooling/heating systems (Narayanan et al., 2018). By reducing energy leakage, passive design promotes environmental sustainability and operational efficiency. The insulating nature of technology makes the ICF an excellent partner in such designs compatible with global sustainability targets.

The construction industry in Saudi Arabia is undergoing rapid transformation, driven by significant investments in transportation infrastructure and the adoption of sustainable building practices. The service delivery of ICF construction is still underresearched. The warm desert climate, the existing socio-economic conditions, and standard construction methods all present special challenges that need empirical testing. The current study fills this gap by undertaking an overall comparison between Saudi-based ICF construction work and traditional concrete construction. The study addresses the following aspects: (i) structural performance, through finite element modeling and cyclic loading testing to compare stress–strain characteristics, energy absorption, and ultimate loads; (ii) management efficiency during project work, by way of cost, time, and quality evaluations; (iii) energy performance, by way of insulation characteristics and total lifecycle cost savings during service operations; and (iv) human aspects, comprising consumer receptiveness, user contentment, and the resultant cultural adoption barriers.

The aims of this study are thus dual: firstly, to analyse the structural performance and durability of ICF structures under loading simulations with the aid of ABAQUS, and secondly, to compare cost-effectiveness, efficiency, quality, environmental performance, and user acceptance of ICF construction versus traditional concrete work. Through the synthesis of technical, financial, and societal viewpoints, the research endeavours to bring out valuable information that may influence the adoption of ICF construction better among the policy-makers, developers, and construction practitioners.

This paper presents several contributions, including the propagation of technical expertise associated with ICF structures under desert and hot weather conditions, comparative data applicable to the Saudi construction industry, and data-based suggestions for industry players to improve sustainability and efficiency. The work informs, on an expanded level, the enhancement of energy-aware construction practices within the analogous climatic regions by committing to the factors associated with market readiness, prevailing regulation, and cultural acceptance.

2. Literature reviews

Performance of Insulated Concrete Form (ICF) technology has been extensively studied along structural, thermal, economic, and environmental facets. Previous research continuously emphasises ICF's superiority over conventional systems, but context-specific proof for hot climates like Saudi Arabia has been minimal. This section provides a summary of the most applicable prior research under four themes: structural performance, project delivery and cost, energy and thermal efficiency, and environmental and adoption barriers.

2.1 Structural Performance

ICF systems have been tested against various loading conditions, and have been dynamic in behaviour against seismic, blast, and axial compression conditions. Dusicka and Kay (2011) tested ICF grid walls experimentally against cyclic loading, confirming their energy dissipation and drift control behaviour. Hemalatha et al. (2022) and Mohammed et al. (2018) have conducted experimental and shake-table ICF walls to validate their capacity against resonance to seismic resistance, verifying that the walls demonstrated remarkable ductility and stable failure characteristics. In comparison, similar blast research has been conducted by Davis et al. (2012) and Prasittisopin et al. (2022), reaffirming that ICF buildings can meet safety and serviceability demands even under extreme loading conditions. Axial compression behaviour studies further emphasise these results, consistently confirming the structural behaviour of the ICF system. Axial compression studies further validate these observations. Solomon and Hemalatha (2018) and Lopez et al. (2021) reported consistent structural responses up to the point of ultimate strain. In contrast, Qun et al. (2018) examined prefabricated ICF variations to evaluate their performance-enhancing characteristics. SAP2000 and ABAQUS finite element simulations have also been simulated to replicate hysteresis behaviour, stress strain responses, and energy absorption, which have functional predictive capabilities to refine design and optimise structure (Saba Shamim & Khan, 2020; Solomon & Hemalatha, 2020).

2.2 Cost and Project Delivery

Time, cost, and quality are essential considerations in construction, and various studies indicate that ICF provides quantifiable advantages. Pertile et al. (2021) and Nilimaa (2023) reported a construction time savings of 10–15%

based on the interlocking block system combining insulation and structural containment. Armstrongbrands (2024) also notes labour economies due to the less skilled masonry or insulation trade.

Economic analyses have determined that, although ICF building components may increase initial costs by 5–10%, lifecycle energy savings and lower maintenance costs offset these premiums in a few years (Kashan et al., 2023). Durability advantages of resistance to rot, mould, and bugs mean fewer repairs and lower costs in the long run (Solomon & Hemalatha, 2020). Ekrami (2023) demonstrated that standardised assembly also enhances envelope quality, lowering variability in building performance compared to conventional construction. For hot climates where cooling energy demand predominates, these lifecycle cost savings are significant.

2.3 Thermal and Energy Efficiency

Insulation performance still constitutes the paramount strength of ICF systems. Comparison projects have indicated that ICF walls are superior to framed or masonry walls in heating and cooling efficiency (Chasar et al., 2006; Chasar et al., 2002). Deflection, compression strength, and insulation characteristics are highly dependent upon EPS density and thickness (Solomon & Hemalatha, 2017; Woltman et al., 2017). Sound performance is also higher, and Lopes et al. (2022) have reported lower sound transmigration levels compared to masonry systems.

At a building level, lifecycle energy assessments verify ICF's effectiveness. Modelling residential buildings in Dubai, Friess et al. (2012) determined that ICF assemblies decreased annual energy consumption by as much as 30%. Comparative case studies in the Gulf region note dramatic cooling load reductions compared to block masonry walls (Carpino et al., 2019). Worldwide passive house and near-zero energy building (nZEB) precedents further endorse ICF's appropriateness, focusing particularly upon thermal mass and airtightness to minimise peak energy demand and provide occupant comfort (Harkouss et al., 2018). ICF, although confidently deployed in cold climates, has limited evidence to date in hot and dry environments, prompting localised case studies.

2.4 Environmental Impacts and Adoption Challenges

ICF systems also participate in environmental sustainability by minimising energy demand and facilitating LEED certification credits. Eberly (2008) and Reeder (2010) comment that the ICF building can achieve the best 10 points in the LEED's Optimise Energy Performance category. Other credits come from waste reduction, recycled content, and enhanced indoor air quality (Newsham et al., 2009). Case studies validate embodied carbon and lifecycle emission reductions versus conventional building materials (Amiri Fard et al., 2021). Although these advantages, there are several challenges that inhibit widespread use. Front-of-the-money cost premiums can dissuade smaller constructors (Nilimaa, 2023); erratic material supply and shortage of skilled labour make projects uneconomic in some regions (thermohouse, 2024). Installation quality remains a concern too: insufficient sealment around penetrations to provide thermal bridges and lower energy efficiency (Solomon & Hemalatha, 2020). Moisture accumulation in walls remains a threat, particularly in hot climates, if the application of vapour barriers and ventilation does not take place (Mani & Goniewicz, 2023). Improvement in these gaps via education, quality assurance, and regulation helps to scale ICF use in Saudi Arabia.

2.5 Synthesis

The literature shows that ICF systems provide benefits in structural resilience, building efficiency, thermal efficiency, and environmental sustainability, which have long-term cost savings that oftentimes outweigh higher first costs. However, gaps remain in empirical evaluations under hot desert climates, particularly in studies that integrate structural analysis with lifecycle cost, energy efficiency, and user acceptance. These gaps justify the present study's holistic case-based comparison of ICF and traditional concrete systems in Saudi Arabia.

3. Methodology

The proposed research work uses a comparative case study methodology to evaluate the efficiency and viability of an Insulated Concrete Form (ICF) system against conventional reinforced concrete methods in the Saudi Arabian climate. The proposed research methodology includes finite element analysis, project management comparison, and scheduling analysis as presented in Figure 1.

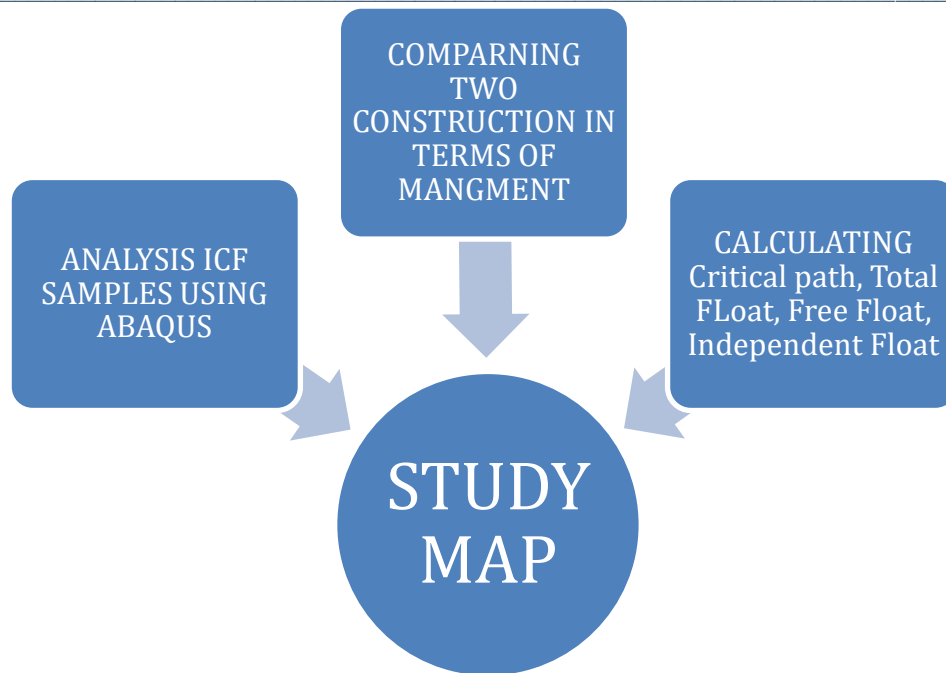


Figure 1. Research design map illustrating the integration of structural analysis, project comparison, and scheduling evaluation.

The ICF specimens undergo simulations and modelling on the structural system of ABAQUS. These simulations entail numerous tests designed to determine stress distributions, strains, failure loads, and the maximum displacement of the specimens due to cycle as well as compression loads. In addition to the usual ICF specimens made as per conventional designs on strengthened shapes like ferrocement and carbon fibre-reinforced polymers, there are various types of ICF specimens included in the simulations to determine the effectiveness of toughness and resilience. The main aim of performing these simulations is to determine the structural integrity of ICF.

The second stage involves comparing two projects that entail the construction of buildings using conventional reinforced concrete and ICF. The two projects were chosen based on set parameters, including floor area, design complexity, and resource accessibility. This comparison helps in finding the efficiency of ICF technology.

The third part of the analysis involves optimizing the construction process schedule. In project management, the critical path, total float time, free float time, and independent float time are very important factors. The third component helps an analyst understand the role of ICF system implementation on the sequencing of events in a project.

These three aspects of methodological approach ensure that the research incorporates both the technical aspect and the viability of ICF construction in Saudi Arabia's climate. The research approach provides a comprehensive framework within which ICF and conventional concrete constructions can be compared in order to provide useful information for experts who may want to implement higher levels of sustainability in Saudi Arabia.

3.1 Finite Element Analysis for Structural Evaluation

The Finite Element Method (FEM) provides a numerical solution that helps in the analysis of complicated structural systems by discretizing them into simpler structural components that can be solved with the help of a model. The FEM approach helps in overcoming complications of the structural system by performing complex calculations that determine stress, displacement, and modes of failure. In the research work, FEM analysis helped analyze and design the Insulated Concrete Form (ICF) structural system by using the ABAQUS system. The FEM analysis helped analyze the ICF structural system by characterizing it as a compound system of expanded polystyrene and the concrete core. The analysis of the structurally complex system aimed at understanding stress-strain rupture properties, displacement capacity, energy absorption capacity, and the ductility ratio of both compressed and cyclic loads. The research work helps determine the stability of the ICF structural system by

understanding its strength and failure modes. The research work incorporates FEM analysis principles to create predictive models that help design the ICF structural system. The FEM analysis helps create a model that validates it as an efficient structurally sound system compared to the conventionally used reinforced concrete walls in Saudi Arabia.

3.2 Case Study Description

The proposed research uses a case study methodology in designing and analyzing single-story villas. The chosen villas act as a demonstration model to analyze the effectiveness of the Insulated Concrete Form Technology in the environmental and socioeconomic context of the area. Hail City's hot and dry climate with large temperature variations and high solar intensities make it a prime location for testing the effectiveness of various building material types on energy efficiency and structural stability. The location of the site of the proposed research has been presented in Figure 2.

The villas have a total constructed area of around 300 square meters as depicted in Figure 3 above. The architectural floor plan includes normal domestic sections such as living rooms, sleeping quarters, kitchen spaces, and service quarters. The design of the plan fits the normal Saudi Arabian design of housing in urban settings for ease of generalization.

This study enables a comparison of the effectiveness of traditional reinforced concrete and ICF construction. The factors that define effectiveness include the duration of the construction process, cost effectiveness, energy efficiency, and environmental factors. The concept of eco-friendly homes in Saudi Arabia may gain new momentum from the concepts synthesized from the practical implementation of the research work.

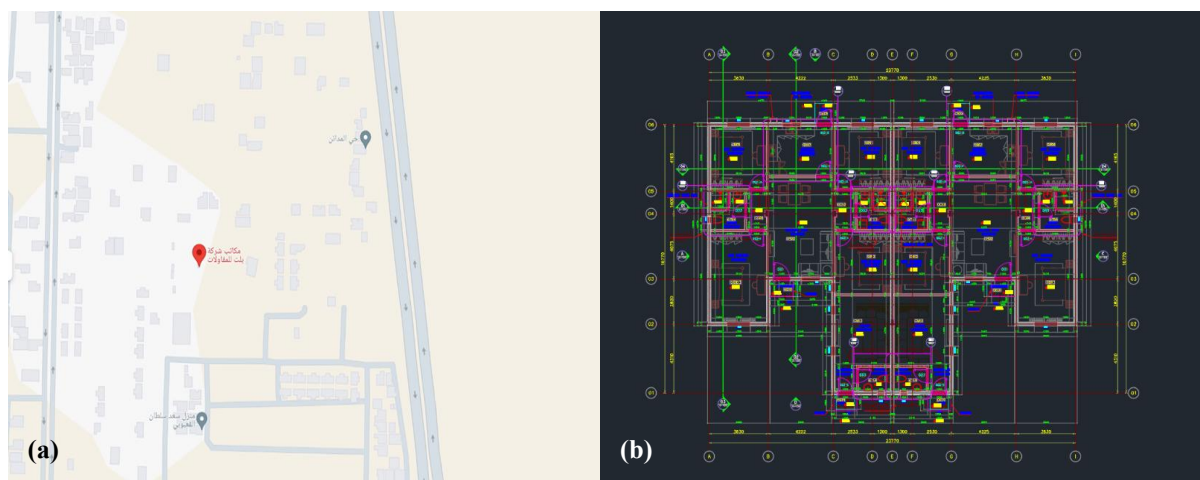


Figure 2. (a) Location of the case study (villa) in Hail City, Saudi Arabia, (b) Architectural plan of the case study villa (300 m² total area).

3.3 Data Collection Methods and Analysis

The data gathering process has attempted to determine the structural characteristics of the ICF using laboratory-made specimens. The specimens were made using standardized procedures and precise measurements of the important factors such as size of the specimens, the concrete compressive strength of the material, and the properties of the Expanded Polystyrene. The data gathered can now be used to analyze the structural characteristics of the ICF.

The dimensions and properties of the specimens used in testing are shown in Table 1. The test specimens were designed so that the influence of EPS thickness and density on the overall performance of the structure could be assessed without maintaining a constant concrete core thickness. The average strength of the concrete mix used in the test (M25) corresponds to the normal structural strength of residential housing. The density of the used EPS ranges from 20 to 40 kg/m³.

Table 1. Dimensions and material properties of ICF specimens (Hemalatha et al., 2022)

Specimens Dimension			Concrete Properties	EPS Material Properties & Thickness		
#	Length (mm)	WIDTH (mm)	Concrete Thickness	Fc	Density (Kg/m ³)	E (Mpa)
1	1000	500	60	M25	20	6.451
2	1000	500	60	M25	20	7.544
3	1000	500	60	M25	40	7.254
4	1000	500	60	M25	40	8.632
5	1000	500	60	M25	-	-

Note: Fc = compressive strength of concrete.

Two main types of experimental work were carried out; these were flexural testing and compression testing. In the flexural testing, data on tensile strength and ductility were collected. In compression testing, the data collected included compressive strength and the corresponding compression behavior. The input data collected from these tests were used in the FEM analysis carried out by the software program ABAQUS.

The approach used for data collection, based on Hemalatha et al. (2022), forms the framework within which the mechanical performances of ICF structures could be studied for various stress states. The approach followed here forms an extension of that work.

In addition, material properties were also defined for ABAQUS by using calibrated parameters that were summarized in Table 2. Concrete was modelled using the Concrete Damaged Plasticity (CDP) model to capture nonlinearity in compression and tension. EPS was treated as an isotropic elastic material, while steel reinforcement, CFRP laminates, and ferrocement overlays were defined using their respective mechanical constants. The configuration and tagging of specimens are summarised in Table 3.

Table 2. Material properties used in the finite-element models

Material	Density (kg/m ³)	E (MPa)	v	fc / fy (MPa)	Notes
Concrete	2400	30,000–36,000	0.20	25	CDP model parameters from tests
EPS	20–40	6–8	0.25	–	Isotropic thermal insulation
Reinforcing steel	7850	200,000	0.30	fy = 500	Bilinear elastic–plastic
CFRP	1600	230,000	0.25	fu = 4100	SikaWrap 300C, 0.167 mm sheet
Ferrocement / bond layer	2100	20,000	0.20	–	COROCRETIN IHL18, 2 mm coating

Table 3. Experimental specimen matrix and configuration.

Tag	EPS thickness (mm)	EPS density (kg/m ³)	Reinforcement	Enhancement	Test type
ICF2050	50	20	Single steel	None	Axial / Flexural
ICF20100	100	20	Single steel	None	Axial / Flexural
ICF4050	50	40	Single steel	None	Axial / Flexural
ICF40100	100	40	Single steel	None	Axial / Flexural
Plain60	—	—	None	Control	Axial / Flexural
ICF2050-F	50	20	Single steel	Ferrocement	Axial / Flexural
ICF2050-C	50	20	Single steel	CFRP	Axial / Flexural

3.4 Experimental Procedures

Two major laboratory tests were conducted on the ICF panels to prove the simulations. These tests include an axial compression test and a four-point flexural test. An MTS servo-hydraulic testing system determined the ultimate load, deformation, and ductility. The bending test used midspan loading of the ICF panel. The displacement of the ICF panel was detected by linear variable differential transformers. Figure 3 (a) shows the test setup of the ICF panels. Figure 3 (b) shows the test boundaries and loads simulated by the analysis used in ABAQUS.

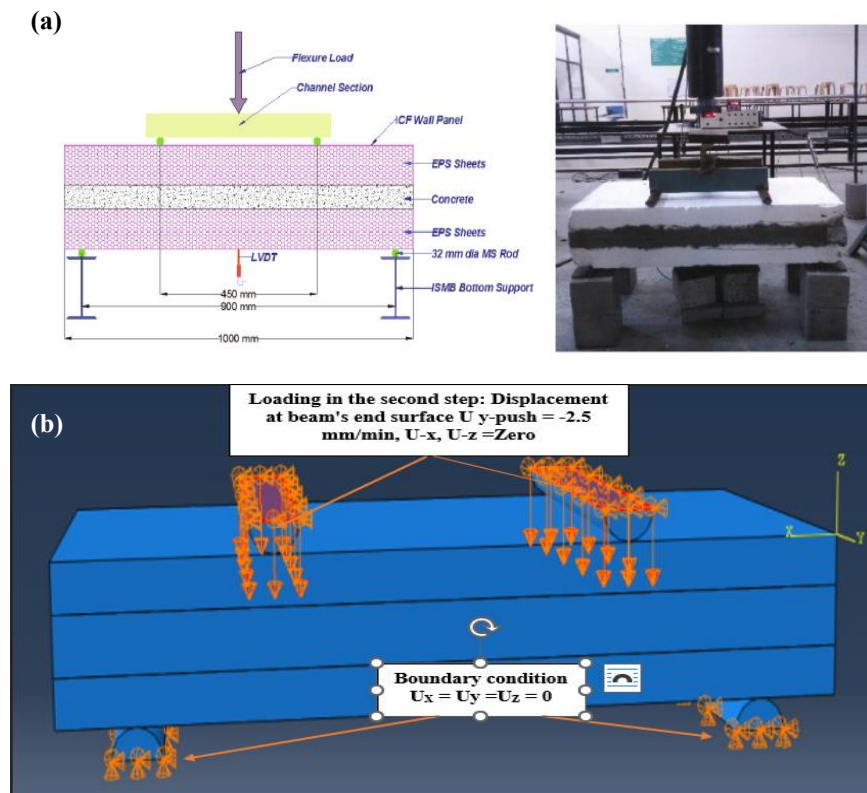


Figure 3. Experimental and numerical setups: (a) laboratory flexural and axial test configurations; (b) simulated boundary conditions and loading in ABAQUS.

3.5 Mathematical Model Used in Abaqus (Model Definition)

The mathematical model used in ABAQUS is grounded in the fundamental principles of solid mechanics and linear static analysis, allowing accurate evaluation of how a structure behaves under different loading conditions. The model discretizes the structure into finite elements, each defined by interconnected nodes, forming a mesh that enables computation of equilibrium equations across the system.

The general equilibrium equation that governs the finite element method is:

$$F = K \times U$$

where F is the nodal force vector, K is the global stiffness matrix, and U is the nodal displacement vector. The stiffness matrix integrates material properties, geometry, and boundary conditions, establishing the fundamental relationship between applied loads and structural response.

The stress tensor (σ) is expressed as:

$$[\sigma] = \begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix}$$

This tensor captures the normal stresses (σ_x, σ_y) and the shear stress (τ_{xy}) at a given point, which are used to determine the internal stress distribution in the material.

The principal stresses (σ_1, σ_2) are derived from the stress tensor and represent the maximum and minimum normal stresses acting on orthogonal planes:

$$\sigma_1 = \frac{\sigma_x + \sigma_y}{2} + \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xy}^2}$$

$$\sigma_2 = \frac{\sigma_x + \sigma_y}{2} - \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xy}^2}$$

The strain tensor (ε) describes the deformation of the material under applied stress and is given as:

$$[\varepsilon] = \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix}$$

The relationship between stress and strain is defined through the constitutive (elastic) matrix D , based on Hooke's Law:

$$[D] = \frac{E}{1 - \nu^2} \begin{bmatrix} 1 & \nu & 0 \\ \nu & 1 & 0 \\ 0 & 0 & \frac{1 - \nu}{2} \end{bmatrix}$$

where E is the modulus of elasticity and ν is Poisson's ratio. This matrix links applied stress and resulting strain, enabling accurate simulation of material behavior under elastic conditions.

These equations collectively form the mathematical framework within ABAQUS for simulating ICF structural performance, predicting stress concentration zones, and identifying potential failure points.

In the axial compression model, the specimen base was fully restrained ($U_x = U_y = U_z = 0$), and an incremental displacement of -0.01 mm/min was applied at the top. For flexural simulation, the specimen ends were fixed, and a vertical displacement of -2.5 mm/min was applied at the midspan to simulate four-point bending. Mesh sensitivity analysis using hexahedral elements was performed to ensure numerical stability and convergence.

The primary parameters considered in the experimental and numerical analysis were ultimate load-carrying capacity, stress-strain relationship, ductility ratio, energy absorption capacity, and deflection. Comparing the control ICF specimens with those reinforced with CFRP or ferrocement enabled the determination of the effectiveness of various reinforcement techniques. The agreement of the numerical and experimental data confirmed the model's ability to simulate practical structural performances. The validated ICF system model has

been used in a full-scale villa structure comparison, which included a conventional ribbed slab system. The conventional ribbed slab structure utilises concrete ribs supporting lightweight blocks.

In contrast, the ICF structure uses expanded polystyrene forms and a wire mesh. The heat flow analysis showed better insulation in the ICF structure, with an average internal temperature of 27.7°C, compared to 37.9°C for the solid slab structure and 30.7°C for the ribbed structure. The higher temperature of the ICF structure indicates better heat retention.

Furthermore, the ICF deck slab had the lowest total dead load weight of 6.19 kN/m² in comparison to 9.2 kN/m² for the solid slab and 8.8 kN/m² for the ribbed slab. The lower weight of the structure goes a long way in reducing foundation loads and improving energy efficiency.

Risk management for the villa construction was performed according to standard design-safety principles. Risks were categorized under people, process, and product domains, encompassing issues such as design accuracy, buildability, and site safety. The measures included competency verification of the design competencies of the design team, assessment of the stability of excavations and frame structures, and early integration of the civil and MEP works. The risk register ensured that conflicts and challenges of construction were mitigated.

The above methodological approach combines laboratory testing, finite element analysis, and design evaluation of cases for arriving at an integrated assessment of ICF solutions in the context of residential buildings. The integration of analysis and testing provides robust evidence on the load-carrying capacity and economic viability of ICS solutions for hot climates like that of Saudi Arabia. The findings of the above methodology form the basis of the analysis in the forthcoming sections.

4. Results

The following section discusses the research findings by integrating simulation and empirical results to analyze, the effectiveness of the ICF structure compared to the conventional concrete structure. The findings of the analysis have been presented in four categories: first, the structural analysis of the two types of structures using finite element analysis with the ABAQUS simulation technique. Second, based on the project's cost, time, and quality parameters, third, based on case studies of villas in Saudi Arabia and fourth, based on risk management.

The report discusses structural characteristics, such as stress, strain, displacement, and failure load, to determine the mechanical efficiency of ICF panels. To better understand the subject area, the report also compares conventional and ICF-based structural systems with respect to energy efficiency and sustainability measures. The above analysis provides an overall insight into ICF technology as a technically feasible solution for Saudi Arabia's growing construction industry and for meeting the principles of sustainable construction.

4.1 Finite Element Analysis Results and Discussion

The work of this section involves discussing the results of the finite element analysis that has been carried out using the program ABAQUS. The analysis will cover the flexural response of ICF wall panels as well as the improved types that use ferrocement and CFRP. The analysis of these components primarily used the factors of maximal displacement.

4.1.1 Displacement Analysis

The FEA contour plot result, as depicted in Figure 4 (a), illustrates the displacement of the ICF wall section due to an increase in the flexural load. The central part of the section had the most significant displacement, denoted by the red area, while the edges were relatively restrained. The above observation validates that it behaves like a bending structure.

The comparison of displacement outcomes for all specimens is presented in Table 4. Excellent agreement between laboratory testing and simulation using the ABAQUS program can be observed. The average error margin of 3% validated the accuracy of the simulated model. The most significant displacement of approximately 43 mm for the ICF40100 sample occurred due to its thicker 100 mm EPS core layer and higher density of 40 kg/m³. The lowest value of displacement of around 9 mm was measured for the Plain60 sample. The introduction of both

ferrocement and CFRP increases the stiffness of the ICF panels by up to 29% and 50%, respectively. The most significant benefit of displacement is reduced by CFRP, due to its better tensile strength and adhesion.

Table 4. Comparison of laboratory and finite element displacement results for ordinary and enhanced ICF wall panels.

Specimen	Laboratory Disp. (mm)	FEA Disp. (mm)	Error (%)	With Ferrocement (mm)	Reduction (%)	With CFRP (mm)	Reduction vs. Ordinary (%)
ICF2050 (1)	29.35	29.10	0.86	25	16	20	45
ICF20100 (2)	34.61	33.00	4.88	29	17	25	36
ICF4050 (3)	35.52	34.90	1.78	31	13.5	26	35
ICF40100 (4)	43.73	43.00	1.70	38	13.1	31	39
Plain60 (5)	9.27	9.10	1.87	7	29	6	50

4.1.2 Load Deflection Behavior

The load-deflection curves of various ICF models are given in Figure 4 (b)–(h). These graphs present the performance of ordinary ICF, ICF + ferrocement, and ICF + CFRP for various specimen models (ICF2050, ICF20100, ICF4050, ICF40100, and Plain60). All models showed initial linear-elastic regions, followed by softening due to microcracking.

The CFRP-strengthened panels always had the largest ultimate load capacity and the smallest deflection values, followed by ferrocement-strengthened panels. The stander ICF had the lowest ultimate load capacity and the most significant deflection at yield. The ICF40100 sample had the highest strength-ductility ratio due to its EPS layer's greater thickness. This increased the energy-absorbing capacity. These findings were consistent with those presented in Hemalatha et al. (2022), as discussed below.

From the combined experimental and numerical analysis, it has been confirmed that the ABAQUS model correctly simulated the structural response of ICF wall panels, with a displacement error of less than 3%. The panels with a higher EPS density (40 kg/m³) and a thicker thickness (100 mm) performed better in both deformation capacity and energy absorption. The role of reinforcement was highly significant in these tests. The ferrocement used reduced displacement by 13-29%, while CFRP showed a higher value of 35-50%. Based on these findings, it can be given that the structural efficiency of panels reinforced with CFRP ICF stands at the top position in comparison to ferrocement reinforced ICF panels, normal ICF panels, as well as standard concrete panels. These findings prove that enhanced housing solutions based on ICF with CFRP reinforcement have been made possible by Vision 2030.

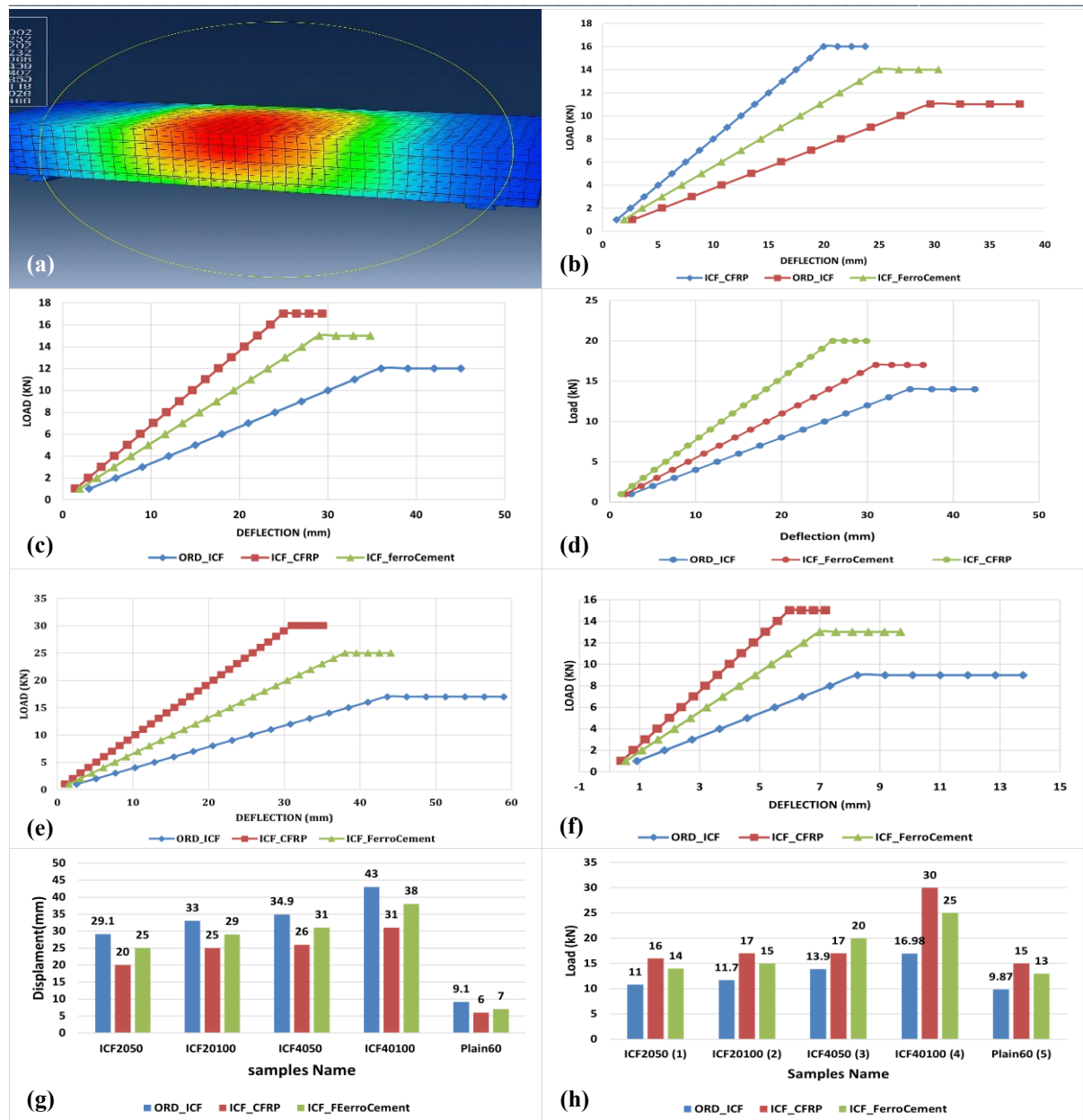


Figure 4. Flexural performance of ICF panels: (a) FEA deformation contour showing maximum displacement; (b–f) Load–deflection curves for (b) ICF2050, (c) ICF20100, (d) ICF4050, (e) ICF40100, (f) Plain60; (g) Combined comparison of overall displacement; (h) Comparison of ultimate load between ordinary and enhanced ICF panels.

4.1.3 Assessment of Flexural Stress Performance in ICF Wall Panels

The data presented in Table 5 shows the values of the maximal flexural stress as derived from both laboratory testing and finite element analysis of the Insulated Concrete Form wall specimens. The data shows that there is a high level of consistency in both laboratory testing and finite element analysis data. The error level in both laboratory testing and finite element analysis data being below 7% confirms that the ABAQUS model is accurate and valid.

Among all the specimens, the panel that showed the largest stress capacity was ICF40100 with 9.55 MPa in simulation and 8.99 MPa in laboratory testing. The improved stress capacity of ICF40100 can be attributed to its higher Expanded Polystyrene density of 40 kg/m³ as well as 100mm of higher insulation. The Plain60 had the

lowest Maximum Stress of approximately 5 MPa, due to the low energy-absorbing capacity of the uninsulated concrete panels.

The addition of the reinforced material led to improvements in mechanical performances. The ferrocement technique used reduced peak stress by 11% to 66% relative to ordinary ICF walls. This is attributed to the functionality of the embedded mesh within the ferrocement that acts as a stress bridge within the material. Similarly, carbon-fibre-reinforced polymer (CFRP) layers achieved even greater reductions, between 40% and 63%, due to their high tensile modulus and excellent adhesion, which enhanced stiffness and limited deformation underload.

In summary, it may be observed that ICF panels reinforced with CFRP had the most beneficial stress response properties, followed by ferrocement-reinforced panels, and lastly by unaltered ICF panels. At the same time, normal concrete panels had the least capacity to resist bending stress. From these findings, it may thus be deduced that the integration of lightweight combinatory reinforcement components within ICF structure designs significantly increases rigidity as well as toughness without influencing overall efficiency. Therefore, reinforced ICF structure designs may indeed constitute an efficient solution to improve the structural integrity of housing structures existing in hot climate zones without exceeding costs.

Table 5. Comparison of laboratory and finite element stress results for ordinary and enhanced ICF wall panels.

Specimen	Laboratory Stress (MPa)	FEA Stress (MPa)	Error (%)	With Ferrocement (MPa)	Reduction (%)	With CFRP (MPa)	Reduction (%)
ICF2050 (1)	5.565	5.425	2.58	4.00	39	3.50	59
ICF20100 (2)	6.555	6.14	6.75	5.10	29	4.00	63
ICF4050 (3)	7.405	6.91	7.16	4.20	76	5.00	40
ICF40100 (4)	8.985	9.55	6.28	8.00	11	6.00	48
Plain60 (5)	5.215	5.10	2.25	3.00	66	3.00	57

4.1.4 Ultimate Load Evaluation

The result of ultimate loads obtained from laboratory testing and FEA shows that there exists a strong relationship between the material configuration and flexural load capacity. The comparison of ultimate loads from laboratory testing and FEA in Table 6 and Figure 5 show the comprehensive comparison of ultimate loads of ordinary ICF panels and panels strengthened by ferrocement and CFRP. The strong agreement of ultimate loads from laboratory testing and FEA within the error margin of 2.9% to 12.1% indicates that the model used in ABAQUS is accurate.

Table 6. Comparison of laboratory and finite-element ultimate-load results for ordinary and enhanced ICF wall panels

Specimen	Laboratory Load (kN)	FEA Load (kN)	Error (%)	With Ferrocement (kN)	Increase (%)	With CFRP (kN)	Increase (%)
ICF2050 (1)	11.13	10.82	2.88	14	26	16	30
ICF20100 (2)	13.11	11.70	12.10	15	14	17	23
ICF4050 (3)	14.81	13.90	6.54	17	15	20	26
ICF40100 (4)	17.97	16.98	5.83	25	39	30	67
Plain60 (5)	10.43	9.87	5.67	13	25	15	44

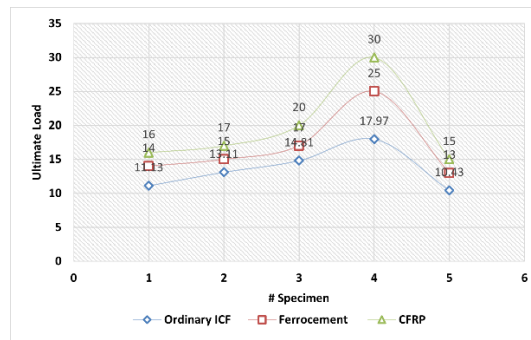


Figure 5. Ultimate-load comparison for ordinary, ferrocement-reinforced, and CFRP-reinforced ICF panels.

The findings have confirmed that an increase in the density and thickness of the EPS significantly increases the flexural strength. The ICF40100 had the highest ultimate load-carrying capacity of 17.97 kN as per experimentation and 16.98 kN in FEA analysis due to the advantages of having higher density (40 kg/m³) and higher thickness (100mm) of the EPS. In contrast, the plain concrete panel (Plain60) showed the lowest capacity (10.43 kN), illustrating the limited ductility and stress-absorption ability of non-insulated concrete.

The ultimate load capacity of the ICF panels reinforced by ferrocement showed an increase of 14% to 39%. However, the addition of CFRP showed higher improvements of 23% to 67%. The ferrocement mesh helped restrain crack propagation and enhanced the distribution of stresses across the panel, whereas the CFRP reinforcement provided higher stiffness and delayed the onset of failure due to its superior tensile modulus and strong bonding characteristics.

Overall, panels strengthened with CFRP exhibited the greatest structural efficiency, followed by those reinforced with ferrocement, ordinary ICF panels, and finally plain concrete panels, which demonstrated the lowest capacity. These results validate the predictive accuracy of the finite element model and confirm that optimizing EPS properties in conjunction with suitable composite reinforcements can significantly improve load-bearing performance and structural resilience, contributing to the development of lightweight, durable, and energy-efficient wall systems.

4.1.5 Compressive Stress Evaluation

The compressive stress results obtained from both laboratory experiments and FEA demonstrate consistent behaviour across all Insulated Concrete Form (ICF) specimens. The comparison of the simulated and experimental maximum compressive stress of regular ICF panels, as well as those reinforced both by ferrocement and CFRP material, is presented in the form of a consolidated table in Table 7. The simulated model's accuracy in comparison with the experimental values, within an error margin of 3%-10%, validates its effectiveness as shown in Figure 6.

Table 7. Comparison of laboratory and finite element compressive stress results for ordinary and enhanced ICF wall panels.

Specimen	Laboratory Stress (MPa)	FEA Stress (MPa)	Error (%)	With Ferrocement (MPa)	Reduction (%)	With CFRP (MPa)	Reduction (%)
ICF2050 (1)	18.642	17.00	9.65	14	33	12	50
ICF20100 (2)	21.030	20.40	3.09	16	31	14	50
ICF4050 (3)	22.844	21.14	8.06	17	29	14	57
ICF40100 (4)	25.972	25.01	3.84	21	19	16	61
Plain60 (5)	17.564	18.70	6.07	13	31	9	47

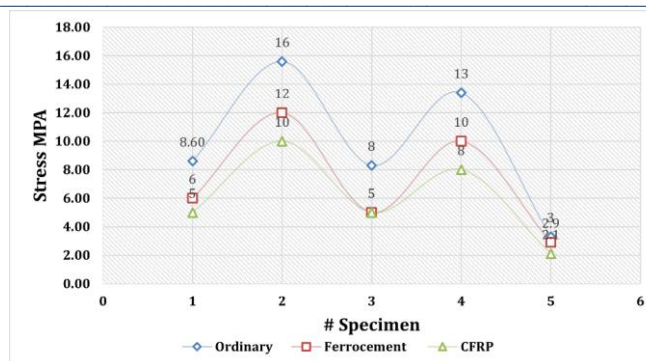


Figure 6. Maximum compressive stress of ordinary, ferrocement-reinforced, and CFRP-reinforced ICF panels.

The ICF40100 specimen achieved the highest compressive strength (25.97 MPa experimentally; 25.01 MPa in FEA), confirming the positive influence of higher EPS density (40 kg/m³) and thickness (100 mm) on load resistance. In contrast, Plain60 and ICF2050 recorded the lowest stress values, indicating the limited performance of plain concrete and low-density EPS panels.

The result shows that as the density of the EPS increased, the compressive strength improved. The addition of ferrocement or CFRP affected the stress pattern in the panels. The value of compressive stress reduced by 19%-33% and 47%-61% for ferrocement and CFRP addition. These values express the change from brittle to composite failure.

The accuracy of FEA output by ABAQUS and laboratory data confirms that it can serve as an accurate predictive model in compression analysis. High density ICF panels were observed to possess higher compression strengths and better energy efficiency capabilities that ensure and reinforce the effectiveness of these panels as structural walls.

4.1.6 Maximum Displacement when Compressing

The analysis of maximal displacement of ICF wall panels during compression loads had been helpful in comprehending the process of deformation. The data presented in Table 8 combines the experimental and FEM results for both normal and strengthened wall panels with an error margin of less than 9%, thus testing the accuracy of the model in the program ABAQUS.

Table 8. Comparison of laboratory and finite element displacement results for ordinary and enhanced ICF wall panels under compression.

Specimen	Laboratory Disp. (mm)	FEA Disp. (mm)	Error (%)	With Ferrocement (mm)	Reduction (%)	With CFRP (mm)	Reduction (%)
ICF2050 (1)	8.634	7.95	8.6	6.0	33	5.0	60
ICF20100 (2)	15.656	15.10	3.68	12.0	25	10.0	50
ICF4050 (3)	8.355	7.96	5.02	5.0	33	5.0	60
ICF40100 (4)	13.477	13.90	3.13	10.0	30	8.0	62
Plain60 (5)	3.320	3.60	8.43	2.9	39	2.1	50

Within the specimens as shown in Figure 7 (b), ICF20100 had the largest displacement value of 15.66 mm from the experimentation process and 15.10 mm from FEA analysis. This confirms that ICF20100 had better displacement capabilities owing to the ideal orientation of the EPS material with moderate density of 20 kg/m³ and higher thickness of 100mm. In contrast, Plain60 had the lowest displacement of 3.32mm.

The increase in the thickness of the EPS matrix contributed considerably to the improvement of the deformation capacity. The addition of ferrocement and CFRP contributed to the reduction in displacement of 25%-39% and 50%-62%, respectively. The result indicates improved stiffness and a change towards controlled failure. Deformation control of the CFRP panels indicated enhanced efficiency owing to improved bonding.

The precise similarity in both simulated and experimental results confirms that the model applied in compression-driven deformation analysis within the simulations of ABAQUS is precise. The overall findings have confirmed that ICF panels with optimized properties of EPS have better qualities of ductility and resilience than the conventionally used concrete structural system.

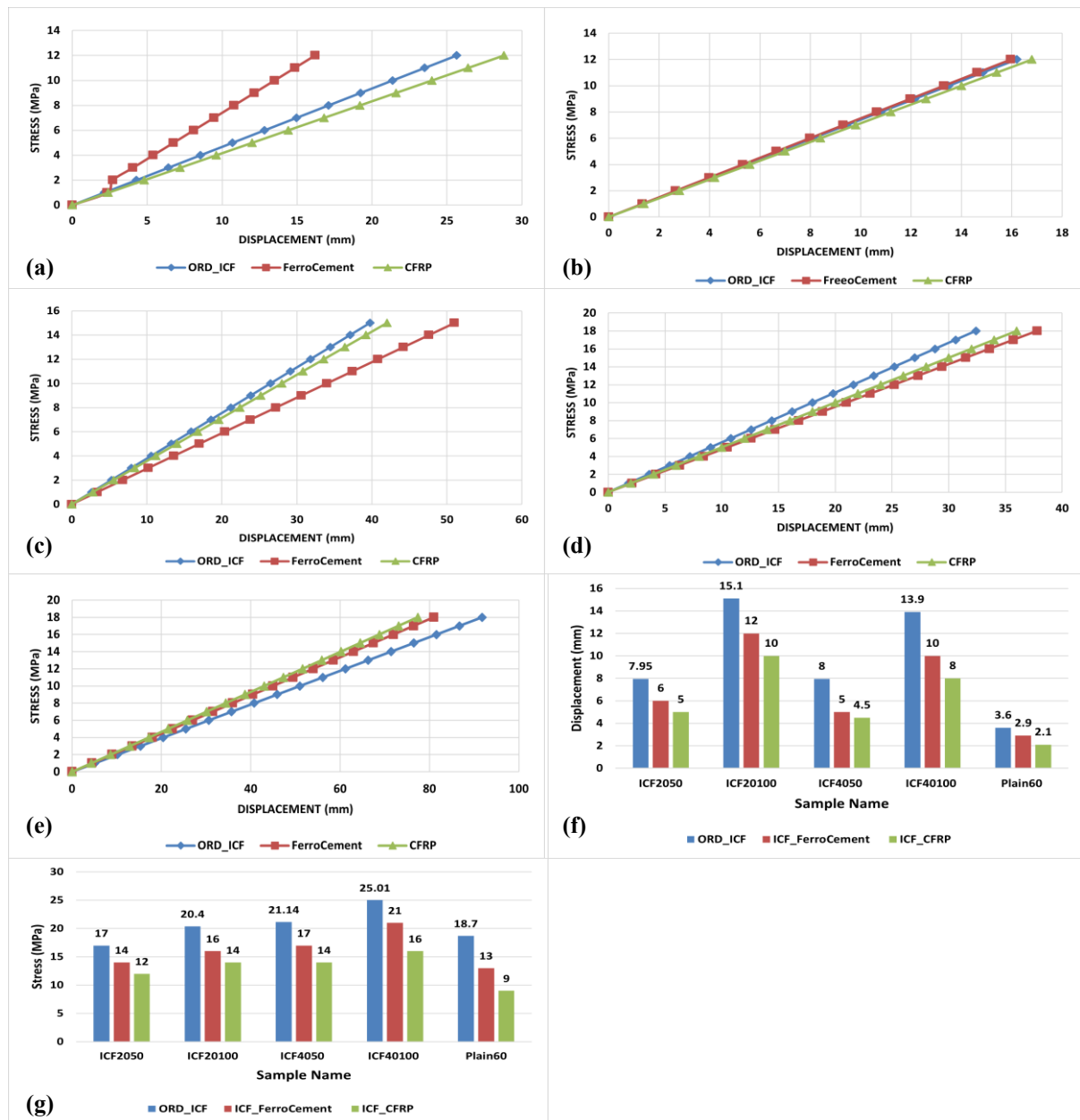


Figure 7. Compression performance of ICF wall panels: (a–e) Stress–displacement curves for (a) ICF2050, (b) ICF20100, (c) ICF4050, (d) ICF40100, and (e) Plain60; (f) Comparison of maximum displacement between ordinary and enhanced ICF panels; (g) Comparison of compressive stress for ordinary and enhanced ICF panels (ferrocement and CFRP)

4.2 Comparative Analysis: ICF vs. Traditional Construction

In this section, a comparison of the total cost distribution of the Insulated Concrete Form system against that of the reinforced concrete system based on two villas located within Hail City in Saudi Arabia has been presented. The findings of the comparison reflect the advantage of the ICF system. Figure 8 of this presentation compares the total cost distributions of both the reinforced concrete system and the ICF system.

THE COMPARISON BETWEEN ICF & TRADITIONAL SYSTEM OF CONSTRUCTION (4 BED ROOM)													
Sr.	Description of Items	Units	Unit Price For ICF			Unit Price For Traditional			ICF System		Traditional System		Remarks
			Material	Sub-contractor	Total	Material	Sub-contractor	Total	ICF Qty	Amount	Traditional Qty	Amount	
1	CONCRETE WORK												
1.1	Raft Foundation	M3	220.00	0.00	220.00	220.00	450.00	670.00	57.70	12,694.00	57.70	38,659.00	
1.2	Raft Foundation Blinding	M3	220.00	0.00	220.00	220.00	50.00	270.00	16.27	3,579.40	16.27	4,392.90	
1.3	Columns	M3	220.00	0.00	220.00	220.00	500.00	720.00	1.49	327.80	9.67	6,962.40	
1.4	ICF Boundary Walls	M3	220.00	800.00	1,020.00	0.00	0.00	0.00	31.76	32,395.20	0.00	0.00	
1.5	B-Deck Slab (ICF)	M3	220.00	800.00	1,020.00	0.00	0.00	0.00	24.73	25,774.60	0.00	0.00	
1.6	Traditional Slab	M3	0.00	0.00	0.00	220.00	500.00	720.00	0.00	0.00	54.86	39,499.20	
1.7	Unifol Beam above door & Windows	M3	220.00	0.00	220.00	220.00	2,500.00	2,720.00	1.43	314.60	3.40	9,248.00	
1.8	Grade Beams	M3	220.00	0.00	220.00	220.00	500.00	720.00	11.08	2,437.60	15.92	11,462.40	
1.9	Main Beams	M3	220.00	0.00	220.00	220.00	500.00	720.00	6.77	1,489.40	14.65	10,548.00	
TOTAL CONCRETE (M3)								0.00	↓ 151.23 m3	78,462.60	↑ 172.47 m3	120,771.90	
2	STEEL REINFORCEMENT												
2.1	Raft Foundation	Ton	2,700.00		2,700.00	2,700.00		2,700.00	4.84	13,068.00	5.79	15,633.00	
2.2	Columns	Ton	2,700.00		2,700.00	2,700.00		2,700.00	0.53	1,431.00	2.45	6,615.00	
2.3	Boundary Walls	Ton	2,700.00		2,700.00	2,700.00		2,700.00	3.38	9,126.00	0.00	0.00	
2.4	B-Deck Slab (ICF)	Ton	2,700.00		2,700.00	2,700.00		2,700.00	1.56	4,212.00	0.00	0.00	
2.5	Traditional Slab	Ton	2,700.00		2,700.00	2,700.00		2,700.00	0.00	0.00	4.98	13,446.00	
2.6	Unifol Beam above door & Windows	Ton	2,700.00		2,700.00	2,700.00		2,700.00	0.13	351.00	0.33	891.00	
2.7	Grade Beams	Ton	2,700.00		2,700.00	2,700.00		2,700.00	0.82	2,214.00	2.25	6,075.00	
2.8	Main Beams	Ton	2,700.00		2,700.00	2,700.00		2,700.00	0.84	2,268.00	1.78	4,806.00	
2.9	Rib Beams	Ton	2,700.00		2,700.00	2,700.00		2,700.00	2.28	6,156.00	0.00	0.00	
TOTAL STEEL (MT)									↓ 14.38 Tonne	38,826.00	↑ 17.58 Tonne	47,466.00	
3	BLOCK WORK												
3.1	Internal & External Blocks	M2	30.80	25.00	55.80	30.80	25.00	55.80	431.00	24,049.80	618.00	34,464.40	
TOTAL BLOCK (M2)									↓ 431.00 m2	24,049.80	↑ 618.00 m2	34,464.40	
4	INSULATION WORK												
4.1	Insulation for walls	M2	45.50		45.50	45.50	20.00	65.50	489.00	22,249.50	250.00	16,375.00	Sub-contractor Not Applied On ICF System Considered in the ICF Walls Concrete
4.2	Insulation for Slab	M2	91.00		91.00	82.00	0.00	82.00	274.00	24,934.00	250.00	20,500.00	
TOTAL INSULATION (M2)									↑ 763.00 m2	47,183.50	↓ 500.00 m2	36,875.00	
Total Amount In SAR									↓ 188,521.90 (SAR)		↑ 239,597.30 (SAR)		
Saving Amount Between Both System										51,075.40 (SAR)			
Total Saving Percentage %										21%			

Figure 8. Cost comparison between the traditional system and the ICF system for walls and slabs in the case study villas (villa 1 and villa 2)

4.2.1 Materials and Cost Breakdown

The ICF structure needed 151.23 m³ of concrete (total cost 78,462.60 SAR) as opposed to 172.47 m³ of concrete that needs to be used in the conventional structure (total cost 120,771.90 SAR), which showed a decrease of 12.3%. This saving comes from the use of the EPS core that decreases the amount of both concrete and carbon used.

As far as steel reinforcement is concerned, the ICF structure used 14.38 tonnes of steel reinforcement (cost: 38,826 SAR) as against 17.58 tonnes of steel reinforcement (cost: 47,466 SAR) of the conventional system, registering a decrease of 18.2%. The weight redistribution along with energy-absorbing properties of the core help in reducing steel reinforcement. In total, the total cost of constructing the ICF system (188,521.90 SAR) is 21% lower than that of the conventional system (239,597.30), thus justifying the cost effectiveness of an ICF.

4.2.2 Insulation Efficiency

Although the ICF system used 763 m² of insulation (cost = 47,183.50 SAR) compared to 500 m² in the traditional system (36,875.00 SAR), its enhanced thermal resistance fully justifies the higher cost. Continuous EPS layers significantly reduce thermal bridging and heat transfer, improving indoor comfort and achieving long-term energy savings (Ekrami, 2023; Ekrami et al., 2015).

The functions of insulation as offered by ICF components also play a significant role in improving energy efficiency by contributing towards saving on operational costs by meeting the objectives of Sustainable Construction.

4.2.3 Construction Efficiency and Sustainability

The comparison made between the two case study villas once again manifests the advantages of the Insulated Concrete Form system in terms of scheduling and functionality. The ICF system project (Villa 1) was finished in 50 working days as opposed to that of the conventional system (Villa 2) for 63 working days, thus manifesting an overall saving of 15%. The factors contributing to efficient execution of the project work primarily include the modularity of ICF panels. Activity A1230 (MEP. Works Slabs) in the ICF system showed very rapid execution of work due to ease of coordination. The use of EPS components and very low waste generation on site also made the system's workflow smooth. The views of Hemalata et al. (2022) and Rajagopalan et al. (2010) bear testimony that ICF system work provides very remunerative advantages of reduced execution and increased economy due to efficient resource allocation. The use of very light weight components of the EPS system thus reduces the cost of site transport and handling as it decreases labor costs on site.

As presented in Table 10 below, the ICF project realized a 15% reduction in total duration and 21% reduction in cost. This shows the efficiency of the system.

Table 10. Comparison of project schedule and performance between traditional and ICF construction systems

Project Parameter	Traditional Construction (Villa 2)	ICF Construction (Villa 1)	Improvement / Observation
Total Project Duration (working days)	63 days	50 days	15% faster completion with ICF system
Formwork Installation	Labour-intensive; multi-stage wooden formwork	Modular EPS blocks act as permanent formwork	Eliminates formwork removal; reduces labour time
Concrete Pouring	Sequential by element	Continuous pour due to integrated formwork	Reduced downtime between stages
Reinforcement (A1220)	Manual placement; dense rebar arrangement	Simplified alignment in uniform ICF cavities	Improved safety and speed
MEP Work (A1230)	Slow progress; coordination delays	Built-in conduit channels in ICF blocks	Faster installation; better integration
Finishing and Insulation	Multiple stages (plaster and insulation)	EPS surface provides built-in insulation	Reduced finishing time and material waste
Labour Requirement	High crew size; multi-trade teams	Smaller crew via modular assembly	25 % labour demand
Material Handling	Heavy transport of formwork and blocks	Lightweight EPS panels	Lower logistics cost and risk
Waste Generation	High (formwork and off-cuts)	Minimal; EPS recyclable	Improved site sustainability
Total Cost (SAR)	239 ,597.30	188 ,521.90	21 % overall cost reduction

The comparison of both the scheduling and cost data illustrates the advantages that the ICF system offers. The efficiency of the ICF system due to its modularity and minimized material handling not only reduced the project cost and schedule but also led to an improved sustainability of the process by reducing waste and energy expenditure during the project. The efficiencies derived from working with an ICF system at an overall level in Villa 1 prove that an ICF system offers economic as well as environmental advantages. The efficiencies from the ICF system do not end at the project level but offer advantages at the operational level as discussed within the next section.

4.2.4 Energy Efficiency

The analysis showed that ICF-built structures had an average temperature of 20°C inside, while conventionally constructed buildings made of concrete had an average temperature of 28.3°C. This measures the effectiveness of the expanded polystyrene core used within the ICF structure. The reduced conductivity of expanded polystyrene reduces heat flow. The cooling load reduces by as much as 30%, as presented by Hemalatha et al. (2022) and Carpino et al. (2019).

The ICF system also helps stabilize indoor temperatures. This aspect of stable temperatures increases comfort levels and decreases the dependence on mechanical air conditioning. Stable temperatures ensure long-term energy efficiency and environmental sustainability that measure up to the LEED principles of sustainability. The ICF system thus helps decrease operational costs while supporting Saudi Vision 2030 goals of energy efficiency in the area of sustainable buildings.

4.2.5 Time and Cost Efficiency

The comparative project analysis showed that it is achievable to save 15 % of the construction duration and 21 % of the total cost by using ICF as compared to the conventional construction technique. The modularity of ICF with prefabricated panels made from expanded polystyrene helps avoid the complexity of formwork and enables quick assembling. At the same time, the integrated design approach helps minimize rework and MEPS coordination. All these factors led to low manpower needs, quick project execution, and improved quality.

These results support Hemalatha et al. (2022) and Pertile et al. (2021), who stressed that ICF technology helps to increase the effectiveness of project implementation by minimizing the use of material and complexity of implementation. The integration of increased ductility properties, high energy efficiency, and cost-effective advantages makes ICF technology an efficient solution for sustainable development in rapidly developing and hot climates such as in Saudi Arabia.

In summary, the comparative analysis confirms that the ICF system is a more effective alternative to conventionally constructed concrete. The improvements it provides within the structural functionality of buildings include energy efficiency, cost saving, and eco-friendliness. Additionally, the capacity of ferrocement or CFRP reinforcement to improve the mechanical properties of ICFs makes it an ideal alternative for high-performance eco-friendly buildings.

4.2.6 Structural Performance

The structural performance analysis confirmed the superiority of the mechanical property of the Insulated Concrete Form system over that of the conventional concrete structure. The laboratory test and FEM analysis confirmed the better load-carrying capacity and durability of ICF panels against bending and compression.

In bending tests, ICF40100 had the highest ultimate load of 17.97 kN that significantly exceeded the normal concrete control test value of 10.43 kN. The higher density of 40 kg/m³ of Expanded Polystyrene (EPS) and larger sections of 100mm contributed immensely to higher rigidity and strength. In compression tests also, ICF40100 possessed the highest peak stress of 25.01 MPa, as against 18.7 MPa of the regular test subject. The effectiveness of higher density and 100mm thickness of Expanded Polystyrene further contributed to increased rigidity and resilience.

The load-deflection curves indicated that ICF panels were more ductile than conventional concrete. The latter failed instantly in a brittle manner. The test specimens like ICF2050 and ICF40100 showed a linear reduction in

load as a function of displacement. This implied that ICF panels were stiffer as well as had a higher capacity for energy absorption. The addition of the EPS interface minimized the stiffness contrast of ICF panels. Hence, there were relatively fewer surface cracks. The above-discussed trend agreed with the conclusions of Hemalatha et al. (2022) and Solomon & Latha (2017), who claimed that ICF panels had better ductility and control of surface cracks due to actuated cementing force of the combination of ICF and the cementing force of EPS. Computer simulations presented by Ukanwa et al. (2015) confirmed these characteristics.

The ICF system thus possesses a definitive structural advantage in that it has an increased load-carrying capacity along with an increased ability to withstand cracking and a tendency towards predictive failure behaviors. All these factors contribute towards improved durability as well as reduced costs of maintenance, an important factor in sustainable design.

4.2.7 Thermal and Structural Integration

The temperature testing conducted in the villas in the studied cases proved to be additional evidence for superior structure and environmental characteristics for ICF components. Under identical conditions, a temperature of 20° C was maintained in the villa built using ICF components in comparison to a temperature of 28.3° C in a conventionally built villa that has a concrete slab. The lower conductivity of EPS reduced heat flow in the slab and thus controlled the temperature inside. The same findings were observed by Carpino et al. (2019) and Hemalatha et al. (2022), who found that ICF structures led to 20–30 % reduced cooling energy consumption in tropical climates. The dual property of ICF components to serve as both structurally strong and heat-insulated components further validates the advantages of ICF components.

4.2.8 Dead-Load Efficiency

The comparison between dead loads showed that ICF slabs have a significantly lower weight than solid and ribbed slabs. The self-weight of ICF was determined to be 6.19 kN/m² in comparison to 8.8 kN/m² for a ribbed slab and 9.2 kN/m² for a solid one—an important decrease of over 30%. The efficiency in structure weight has reduced loading on foundations and represents a lower seismic force for lighter buildings. The mentioned above is in agreement with Solomon et al. (2022) and Mačková & Spišáková (2015) in pointing out ICF structure efficiency regarding material usage.

4.2.9 Risk and Reliability Assessment

The risk comparison study emphasized the adaptive and stable characteristics of ICF technology. The key risks in this project, including the accuracy of design-stage modeling, handling EPS material, and coordination of MEP works, were adequately mitigated via finite-element simulation techniques in a building information model. The imperatives of quality control in casting works and protective ones related to the vapor barrier were key in ensuring that structure and insulating strength were not adversely compromised. The ICF building technique demonstrated reduced vulnerability to risk when considered against conventional building methods.

Collectively, the findings demonstrate that ICF construction delivers measurable improvements in strength, ductility, thermal stability, weight efficiency, and risk control, establishing it as a high-performance alternative for modern, sustainability-driven construction.

4.3 Summary of Case-Study Outcomes

The combined results of mechanical testing, simulation, and actual project experience have confirmed that ICF is a more efficient structure, superior in thermal performance, and cost-effective when compared to traditional concrete structure building. The ICF panels showed higher ultimate loads and compressive strengths and less displacement and cracking and demonstrated excellent comparison between lab and FEA. The optimally performing sample (ICF40100) has demonstrated a positive effect of enhanced EPS density and thickness.

The thermal analysis confirmed that ICF wall and floor construction can reduce indoor temperatures and even out the daily variation in temperatures. The cooling energy demand can be reduced by as much as 30%. The project cost and duration information suggested that there could be a cost saving of 21% and a reduction in project duration of 15% when ICF systems are used.

The risk-register evaluation demonstrated that most challenges were transitional linked to contractor unfamiliarity and were effectively resolved through training and coordination. Once established, the ICF workflow yielded fewer delays, lower rework, and greater consistency in quality.

In summary, this case study proves that ICF building works in harmony with all four aspects of infrastructure development: structural development, energy efficiency, cost effectiveness, and risk management. The synergy between building mechanics and sustainability in ICF makes it a comprehensive solution for sustainable development in building. The application of this innovative technology in hot and dry countries like Saudi Arabia can largely help in ensuring that Saudi Arabia meets its sustainable development goals in its Vision 2030.

5. Conclusion

In this study, the feasibility and performance of Insulated Concrete Form (ICF) technology in comparison to traditional concrete techniques are evaluated. The performance is analysed through lab tests and simulation tests, as well as through a real-case scenario in Saudi Arabia. The results have ascertained that ICF is a better and more sustainable technique in structure development as well as in its costing. Structurally speaking, ICF panels were more resilient under stress, had less deflection, and were more resilient against cracking under both bending and compression forces. The introduction of concrete strength and EPS materials has made it more robust and energy-efficient under stress. Apart from this benefit, Carbon Fibre-Reinforced Polymer rods have also been added to ensure more strength and flexibility. In a thermal context, ICF systems were able to retain an average indoor temperature level of 20°C in comparison to a level of 28°C in a traditional structure. Consequently, this contributed to a reduction in cooling inputs of close to 30%. On an economic perspective, ICF proved to have reduced project timelines of about 15% and total project costs that were lower by a margin of about 21%, mainly attributable to greater economies of scale and lower labour costs.

In conclusion, the ICF building is a holistic solution that integrates mechanical strength, thermal performance, and cost-effectiveness. The reduction in material usage, energy required, and project duration makes it well-aligned with Saudi Vision 2030 and worldwide goals for a more sustainable and high-performance building.

6. Recommendations

Therefore, future work needs to broaden its scope in ICF research to include a range of climates and loading conditions. In addition, there is a need to develop policies to adopt ICF in building codes. Moreover, advancing computational optimization and ML techniques to better define material properties and structural parameters will improve their performance. Therefore, to transition from a novel to a scalable, sustainable technique for building and development, there is a need to develop life-cycle assessments.

7. Limitations

While these findings validate the advantages of ICF technology, the study was limited to single-storey villas and short-term cost analysis. Broader investigations should include multi-storey or commercial applications, long-term durability assessments, and full life-cycle economic and environmental evaluations to determine carbon footprint, recyclability, and maintenance costs.

Data availability

The data supporting this study are available from the corresponding author upon reasonable request.

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Author contributions

Abdullah Freag Hasanain: conceptualization, methodology, experimental investigation, finite element analysis, data curation, writing original draft preparation. Sameh Youssef Mahfouz Yassin: supervision, validation, writing review and editing, project administration, and final approval of the manuscript.

Competing interests

The authors declare no competing interests.