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Structural Behavior of Hollow Rubberized Ferrocement Beams Reinforced with Glass Fiber Reinforced Polymer

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ABSTRACT

This study investigates the Structural behavior of hollow rubberized ferrocement beams reinforced solely with Glass Fiber Reinforced Polymer (GFRP) bars. The experimental program involved six full-scale beams tested under two-point bending to evaluate the influence of reinforcement quantity and mesh layers on structural performance. Results indicated that increasing the number of GFRP bars and mesh layers enhanced the first cracking load by **147.1%** and the ultimate capacity by **72.6%**, while simultaneously reducing ultimate deflection by **27.3%**. Beams reinforced with additional mesh layers also exhibited improved crack resistance and stiffness. All the Beams reinforced with GFRP showed a brittle failure behavior as was expected because of the inherent behavior of GFRP. Beam weightReduced the weight of hollow-core beam to approximately 40% of that of the solid beam form, which showed the application of the hollow-core beam in light structures. Altogether, these results presented a hope and also a limitation of the GFRP Reinforcement to the Engineering structures and inspection other work is needed for enhancing the ductility and serviceability of such GFRP reinforcement in structural application.

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1. INTRODUCTION

There is no much to say about traditional concrete structure as sustainability vessel; when exposed to oxidation of still/reinforcements ", ' " " " " the corrosion change over is a great lost in the duration goods, quality of the durability in buildings [2,6,7,8]. This corrosion is one of the agents that can work the greatest destruction and signally cut down the life of a building. From publication, Alternative methods like epoxy coating and pore decrease have been suggested; but these methods are usually uneconomical and partly with an uncertain and/or low long-term success . There are also the disadvantages of higher construction expense and design limitation due to too-heavy self-weight of the conventional concrete members. In this view, Glass Fiber Reinforced Polymer (GFRP) bars has been described as poemate-corrosion less replacement of steel as appears to be in traditional construction [1, 2, 6].

Nevertheless, GFRP bars have limitations which have been well documented that limit their extensive use [3]. These factors include but are not limited to lower modulus of elasticity as compared to steel, which can result in excessive deflection in reinforced membersThe brittleness failure mode, that is with no relatively evident yield point, is another point that its main defect. This is an actual safety problem, when you can't bend like a bendy bus. With respect to the existing research on GFRP, one of the most remarkable issues is the low ductility of GFRP members [1, 2, 15, 16].

Meeting these essential requirements is the main goal of the present investigation, where the methodology to be used will be the application of the use of the GFRP in a new thinking of a la construction concept such as the ferrocement hollow-core beams. This hybrid construction has several benefits, such as the light weight and the good control of cracks of Ferrocement and the high strength and the resistance to corrosion of GFRP [4, 5]. Furthermore, there was a partial replacement of sand with waste rubber to enhance the flexibility and energy absorbing characteristics of the mortar [9].

The originality of this work is the holistic study on the mutual interaction of the concatenate of these three ingredients (ferrocement, a hybrid confining system, and a hollow core configuration). Indeed, there have been many researches that deal with a specific data such as reactive powder concrete beams [10,11], rubberized concrete [12,13], or GFRP reinforced members [15,16].It is weighted to study an integration of the three materials in order to introduce practical and sustainable technology to cover inevitable lacks of the two materials. The present study aims at studying the flexural behavior of these beams, in terms of first crack load, yield load, ductility, deflection etc., so that practical perspective can be developed for designing such structures for the present day constructions.
.see figure (1)

Figure (1) GFRP bars

2. METHOD

3.1 Introduction

This chapter describes the experimental work program conducted to study the structural performance of hollow ferrocement beams reinforced with Glass Fiber Reinforced Polymer (GFRP) bars. This section consists of the properties of the steel fibre used, the mix design of the rubber and ferrocement mortar, and the description of experimental specimens and testing procedures in the laboratory. This section also guarantees that all the materials and methods utilised are according to the corresponding standards and rules to guarantee the precision and trustworthiness of the result.

3.2 Experimental Program

A test program was conducted on of hollow ferrocement beam specimens. The primary aim was to investigate the effect of the amount of longitudinal reinforcement (GFRP bars) and the number of ferrocement mesh layers on the structural behavior of the beams. Each beam was constructed with a spanning longitudinal hollow core (height: 125 mm, width: 50 mm) running the entire length (1500 mm). Specimen height and width are 225 mm and 150 mm respectively. see figure (2)

The beams were further divided into two primary subgroups according to the amount of ferrocement mesh layers utilized (four or six layers). All beams were provided with GFRP rebars of 8 mm in diameter, and the number of rebars used was different in beam (2, 4, or 6). Both the bars of the reinforcement cage (with 10 mm diameter) and the stirrups, were 6 mm in diameter. see table (1)

3.3 Materials Properties and Mix Design

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The rubberized ferrocement mortar was prepared to achieve a target compressive strength of 35 MPa after 28 days. Before the beams were manufactured, the mechanical properties of all reinforcement materials were determined through standard tests. This included tensile strength tests for steel bars and stirrups, as well as the characterization of the GFRP bars.

The workability of the fresh ferrocement mortar was evaluated through several tests: Mini Flow Test, Mini V-Funnel Test, Mini Column Segregation Test, and mini J-Ring Test.

3.4 Manufacturing and Curing

During the casting phase, the molds were carefully cleaned and lubricated. The mortar was poured using simple tools with minimal vibration due to its high workability. Test specimens (cylinders and prisms) were cast simultaneously with the beams. All specimens were placed in a water curing environment (water at room temperature) for 28 days. After the curing period, the properties of the hardened mortar were examined through standard tests: compressive strength using three 50 mm diameter and 150 mm height cylinders, splitting tensile strength from three cylinders, and flexural strength using three 40 mm × 100 mm × 400 mm prisms.

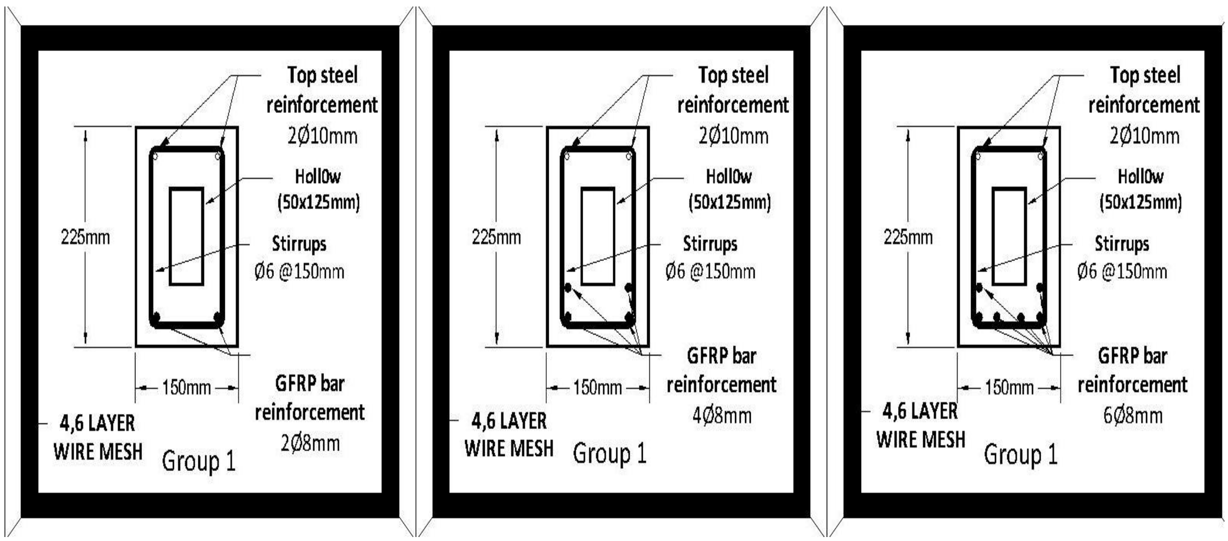

Figure 2. first group

Table 1. Speciemen

symbol	No. Of wire Mesh	No. Of bars
GR-2-4	4	2
GR-4-4	4	4
GR-6-4	4	6
GR-2-6	6	2
GR-4-6	6	4
GR-6-6	6	6

3. RESULTS AND DISCUSSION

This section presents a comprehensive analysis and interpretation of the experimental results obtained from the hollow ferrocement beams reinforced solely with GFRP bars. The discussion focuses on how the quantity of longitudinal reinforcement and the number of welded wire mesh layers influenced key structural parameters, including load-deflection behavior, ultimate capacity, and failure modes.

3.1 First Cracking Load (Pcr)

The first cracking load (Pcr) is a critical indicator of a beam's initial behavior, reflecting the tensile strength of the composite before the appearance of visible cracks. Table 2 summarizes the experimental results for all specimens.
Impact of Mesh Layers
The first cracking load of the GFRP-reinforced beams (GR-series) was affected with an increasing in C-steel wires mesh layers. Cracking resistanceThe first cracking load was always higher for the six-layer specimens than for the four-layer ones. For example, the
Pcr of beam G.R.2. 6 (8.21 KN) was 88.7% greater than that to G.R.2. 4 (4.35 KN). Similarly, the
Pcr of beam G.R.4. 6 (6.74 KN) were 50.8% and 73.2% higher compared to G.R.4 EditorGUI5r 92 respectively. 4 (4.47 KN). The increase of maximum tensile strength to prove that adding more number of layers of mesh assist to improve the tensile as the initial one.

Impact of Longitudinal Reinforcement

The amount of GFRP reinforcement also had a strong impact on the first cracking load. Out Of these, for GFRP beams having four mesh layers Pcr increased to 4·35 KN in G.R.2. 4 to 7.33 KN in G.R.6. 4. In 6 MLs of the beams also, the Pcr increased from 8.21 kN in G.R.2. 6 to 10.75 KN in G.R.6. 6.

Impact of Hollow Core and Rubberized Mix

The first cracking load of the hollow rubberized beams was much lower than that of a conventional solid reference beam (Ref 1), with Pcr = 80 KN. The existence of the hollow core directly reduced the moment of inertia of the section, and, hence, its flexural rigidity, which resulted in the appearance of the cracks at a smaller load. Recycled rubber in the mix also caused a slight decrease in tensile strength and a decrease in the first crack load. This compromise is acceptable for providing a lighter and a more sustainable beam and a 40% decrease in self-weight.

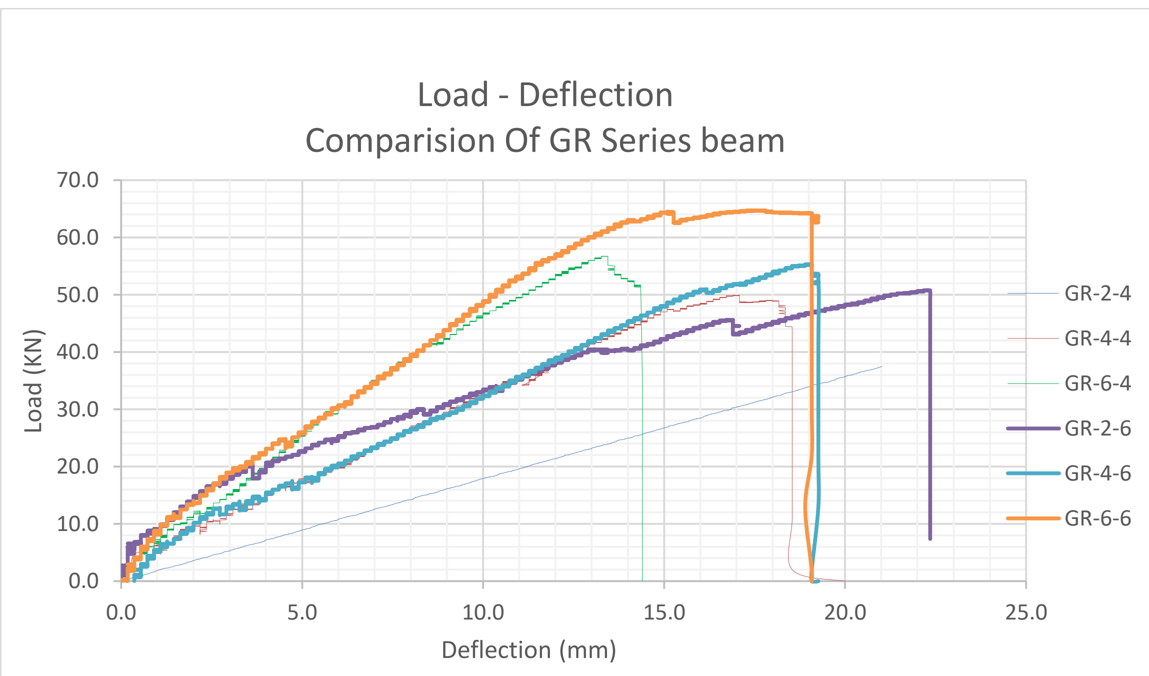

Figure 3. Load–Deflection Curves of GFRP-Reinforced Beams (GR-series).

Figure 3 shows the load–deflection behavior of GFRP-reinforced beams. Increasing longitudinal bars from two to six significantly improved cracking and ultimate load capacities. For example, GR-6-6 had a much higher ultimate load than GR-2-4, showing the contribution of more reinforcement. All GFRP beams failed suddenly and brittlely at ultimate load, highlighting a known limitation of GFRP. While deflections were larger than in steel or hybrid beams, ductility remained limited, stressing the need for reinforcement systems to reduce brittle failure.

3.2 Ultimate Load (Pu)

Table 4-2 shows the maximum flexural capacity of the tested beams before failure, represented by the ultimate load (Pu). The experimental results demonstrated that the value of
Pu for the GFRP-reinforced beams (GR-series) was directly influenced by the quantity of longitudinal reinforcement and the number of ferrocement mesh layers.
Increasing the number of GFRP bars consistently led to a rise in the ultimate load. For example, the ultimate load for beam G.R.6.4 at 56.72 kN was 51.4% higher than G.R.2.4 at 37.49 kN. Similarly, increasing the number of mesh layers from four to six also increased the ultimate load. Beam G.R.6.6 showed a 14.1% increase in ultimate load to 64.71 kN compared to G.R.6.4 at 56.72 kN. This enhancement is attributed to the additional confinement provided by the mesh, which improved the composite's ability to resist compression and enhanced the section's overall integrity.
When comparing GFRP-reinforced beams to a conventional solid control beam, the GFRP beams exhibited a significantly lower ultimate load. This is an expected trade-off for the substantial reduction in self-weight and material use achieved by the hollow design

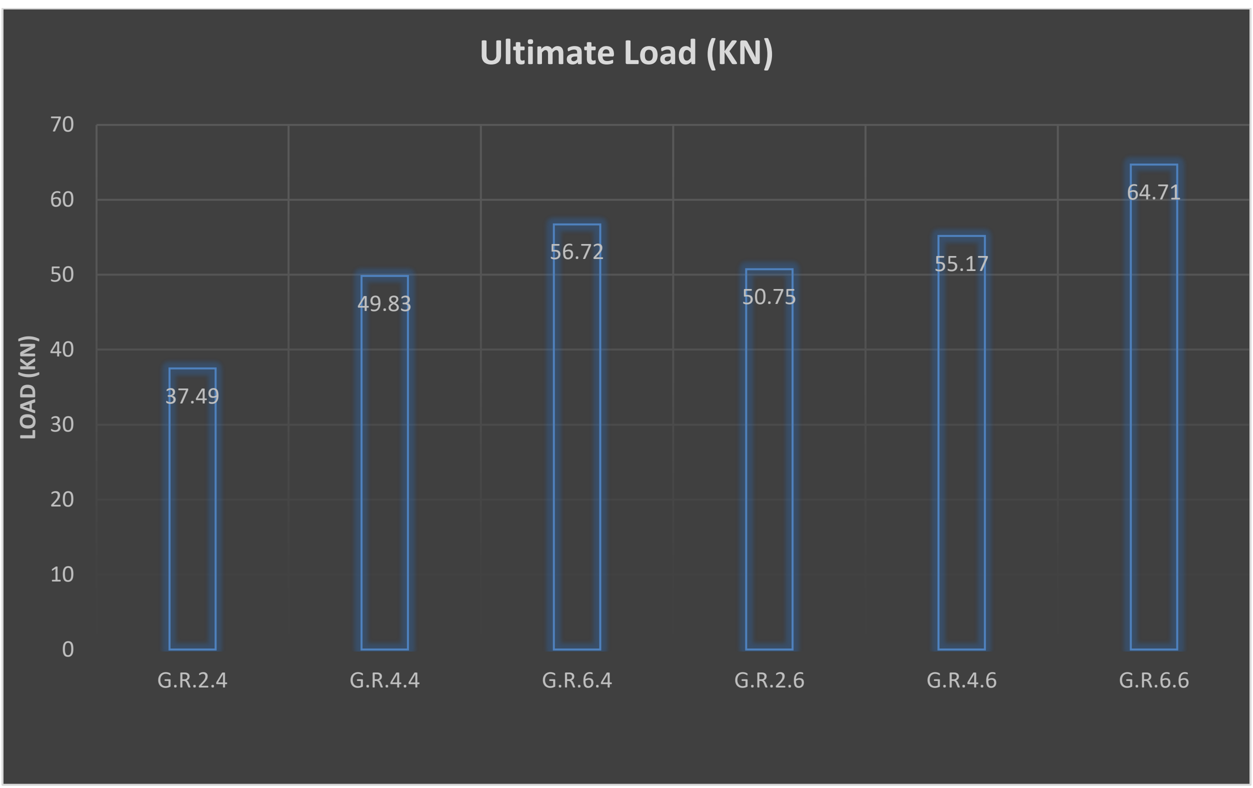

Figure 4. Ultimate Load (Pu) Comparison for All Hollow Rubberized Ferrocement Beams.

Figure 4 shows the ultimate load (Pu) for all tested specimens. The results clearly demonstrate how the quantity of GFRP reinforcement affects flexural capacity. Beams reinforced with GFRP (GR-series) had ultimate loads ranging from about 37.49 kN (GR-2-4) to 64.71 kN (GR-6-6).

Increasing the number of GFRP bars significantly improved the ultimate capacity. For instance, the ultimate load for beam G.R.6.4 was 56.72 kN, which was 51.4% higher than G.R.2.4 at 37.49 kN. This shows that adding more GFRP bars directly increases the load-carrying capacity of the beam.

3.3 Deflection Behavior (Δu)

The ultimate deflection (Δu) is a key parameter that reflects the deformability of the beams and provides insight into serviceability and ductility. The measured values for all specimens are summarized in Table 4-2.

GFRP beams showed the highest ultimate deflections. For example, G.R.2.4 had an ultimate deflection of 21.02 mm. This is attributed to the low modulus of elasticity of GFRP.

Effect of Reinforcement Quantity

The ultimate deflection decreased with an increase of the quantity of GFRP bars. For example, G.R.2. 4 with two GFRP bars, and the ultimate deflection was 21.02 mm, which reduced to 13.266 mm in G.R.6. 4 with six GFRP bars. This tendency means that the stiffness becomes higher as the reinforcement ratio is increased, leading to smaller deformation.

Impact of Mesh Layers

More layers of wire mesh also helped to control deflection. Six layer beams typically reported smaller Δu values as compared to the four layers counterparts. For instance, G.R.4. 6, the ultimate deflection was 18.899 mm, which was smaller than G.R.4. 4 having four layers with a deflection of 16.9 mm. This supports the fact that mesh confinement helps in the restriction of hyperelastic deformation.

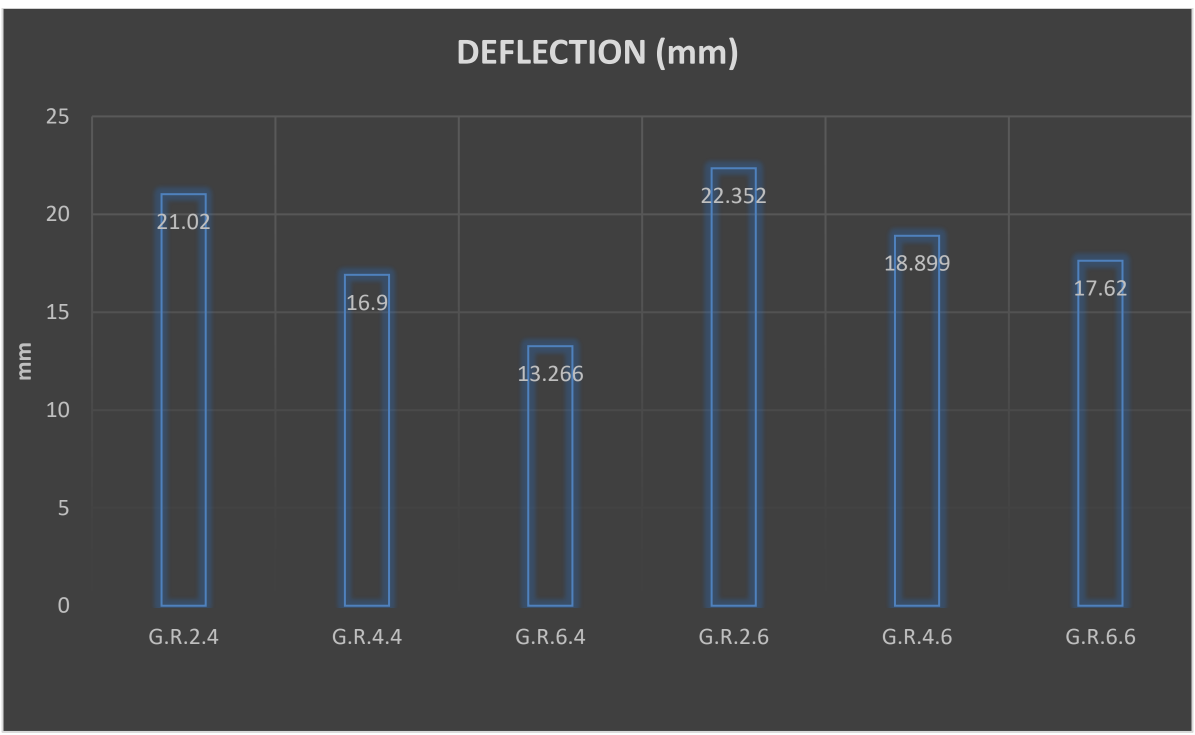

Figure 5. Ultimate Deflection (Δu) Comparison of Hollow Rubberized Ferrocement Beams

The ultimate deflection (Δu) of the tested beams is shown in Fig. 5, which explains the impact of the reinforcement type and amount on the deformability. The deflection in the GRP-reinforced beams (GR series) was found to be the maximum, in between 18 mm to 21 mm. This is because of the.

low elastic modulus of GFRP which allows greater deformations prior to failure.

The experimental results reveal that an increase in the number of GFRP bars not only increases the load bearing capacity, but also improves the stiffness of the beam, which in turn decreases the ultimate deflection. This is a classical trade-off of GFRP-reinforced structures. For instance, the total deflection of beam G.R.2. 4 (21.02 mm) reduced to 13.266 mm of beam G.R.6. 4, with an increased ratio of reinforcement.

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Although capable of substantial deflection, the GFRP beams failed in a brittle manner. Their lack of discernible yielding prior to failure makes them less reliable and poses a critical hazard.

3.4 Ductility Index (μΔ)

Ductility index The ratio of ultimate deflection to yield deflection (Δu / Δy) expresses how much deformation a beam can undergo beyond yielding before it fails. This property plays an important role in structural safety and energy absorption. The measured values of all specimens of the gfrp are tabulated in Table 4-2.

Effect of Reinforcement Type

The GFRP-reinforced beam (GR-series) had lower ductility with indices value between 1.15 and 1.33. This low ductility is one of the main drawbacks of using GFRP itself as a reinforcing material and is in line with its inherently brittle failure behavior, lacking (any noticeable) yield plateau or significant plastic strain. The GFRP reinforced beams showed a sudden brittle failure mode which was caused by the abrupt failure of the GFRP bars without any prior warning or considerable deformation.

Effect of Reinforcement Quantity and Mesh Layers

The number of GFRP bars and mesh layers had a direct impact on the ductility of the beams. Beams with higher reinforcement ratios generally exhibited less ultimate deflection (
Δu) but carried a higher ultimate load. Increasing the number of bars or ropes usually decreased ductility by increasing stiffness and limiting post-yield deformation. The number of wire mesh layers also had a secondary impact; beams with six layers displayed slightly reduced ductility compared to four-layer beams due to the enhanced confinement that restricted deformation. However, the overall trend remained dominated by the type of longitudinal reinforcement.

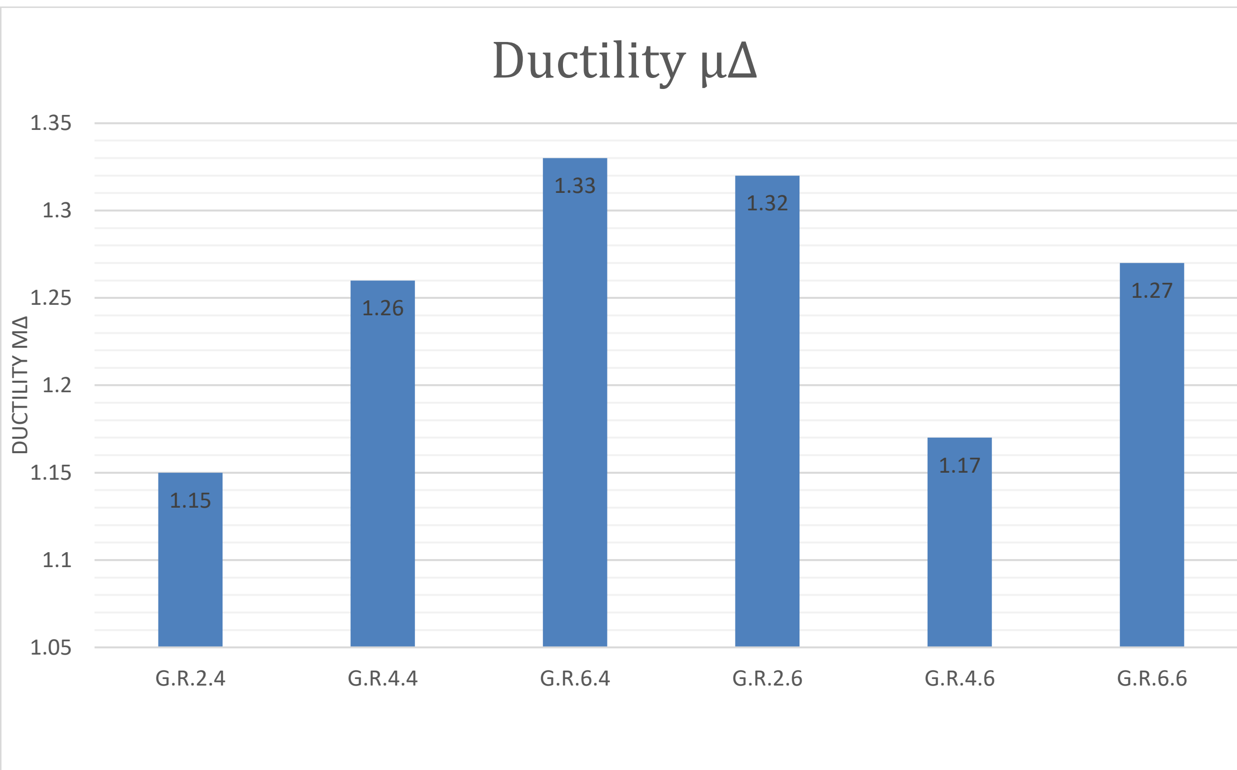

Figure 6. Ductility Index (μΔ) Comparison of Hollow Rubberized Ferrocement Beams.

Figure 6 illustrates the ductility index (μΔ) for the tested beams. A distinct hierarchy is evident among the reinforcement types.GFRP beams (GR-series) recorded the lowest ductility, with μΔ values ranging between 1.15 and 1.33. This limited post-yield deformability reflects the brittle nature of GFRP, which tends to fracture suddenly once its tensile capacity is reached. The GFRP-reinforced beams failed in a sudden, brittle manner. This behavior highlights the primary limitation of using GFRP alone as a reinforcement material, which is its brittle failure mode that lacks a distinct yield point or significant plastic deformation. The GFRP-reinforced beams displayed a gradual, ductile failure that provided a clear warning before total collapse.

3.5 Initial Stiffness (K_0)

The initial stiffness (K0), defined as the slope of the load-deflection curve in the elastic region, indicates how resistant a beam is to deflection under service loads. Table 4-2 summarizes the calculated stiffness values for all specimens.
Effect of Reinforcement Type
The GFRP beams consistently showed the lowest stiffness values. For instance, G.R.2.4 achieved a stiffness of approximately 1.6 kN/mm, while G.R.6.6 reached a stiffness of 4.52 kN/mm. This trend is attributed to the low modulus of elasticity of GFRP.
Effect of Reinforcement Quantity
Increasing the number of GFRP bars enhanced stiffness. In the GFRP series, stiffness improved from 1.6 kN/mm (G.R.2.4) to 4.52 kN/mm (G.R.6.6). This indicates that the reinforcement ratio strongly influences stiffness.

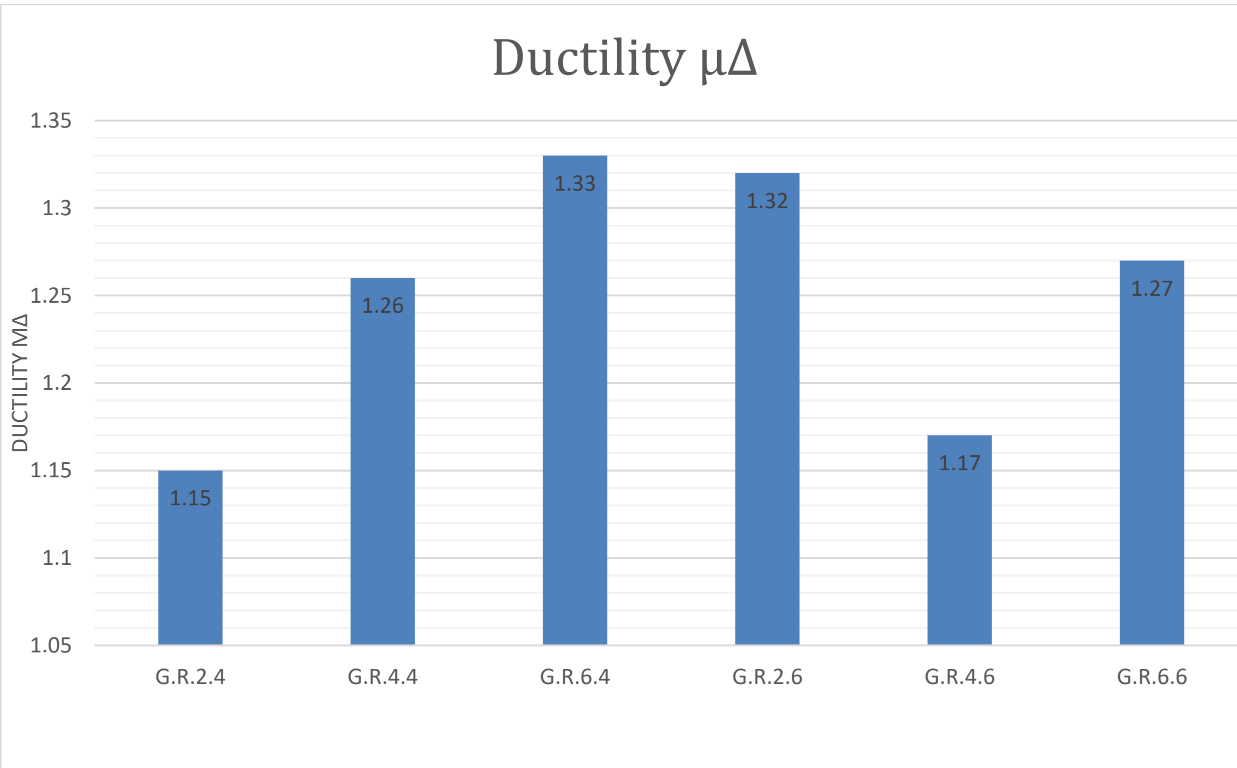

Figure 7. Initial Stiffness (K_0) Comparison of Hollow Rubberized Ferrocement Beams.

The initial stiffness (K0) of the tested beams is shown in Figure 7. The results for the
With respect to modulus of elasticity, GFRP beams (GR-series) present the lowest values, between 3.0 kN/mm and 4.5 kN/mm. This is ascribed to the low modulus of elasticity of GFRP bars, resulting in more flexible characteristics under service loads. Although this flexibility is advantageous for greater deflection, it diminishes the stiffness necessary for practical structural uses.
Results show that stiffness was improved by increasing GFRP bars. For instance, the stiffness of the GFRP series increased by about 1.6 kN/mm (G.R.2. 4) to 4.52 kN/mm (G.R.6. 6). Furthermore, the beneficial effect was secondary when the additional layers were added to the mesh. The former filter type revealed a modestly greater_SIGNAL SIX than the latter filter type_SIGNAL TOP.

K0 better than four-layered specimens, as a result of a better cracking control, and stress distribution.

3.6 Failure Modes and Crack Patterns

Detailed investigation of all the specimens showed distinct behavior in the initiation, propagation of cracks and corresponding failure depending on the type of reinforcement. 1a Beams strengthened with GFRP (GR-series) typically developed their first visible crack at a relatively low level of load, generally in the tension zone and at midspan or in the vicinity of midspan. With an increase in load, extensive surface fine cracks were formed and propagated rapidly. However, when the ultimate loads were attained, failures were sudden and brittle, where the GFRP bars snapped with little warning. Such a brittle failure is typical of the nature of GFRP and indicates that GFRP has limitation to be used for structural purposes where large deformation is needed. Characteristic curves for them were those of a nearly linear until the ultimate load, and then of a sudden collapse.

3.7 Overall Discussion and Key Findings

The experimental study has given an in-depth information on bend behaviour of hollow rubberized ferrocement beams with GFRP bars as reinforcement. The test results emphasized the effect of type of reinforcement, reinforcement ratio, number of mesh layers on strength, ductility, stiffness, and failure modes.

- Pcr First cracking load (Pcr): The Pcr of beams that were reinforced with GFRP only were lower than those of the other reinforcement types. Addition of mesh layers in these beams resulted in a delay in the crack initiation time and increased their crack resistance.
- Ultimate Load (P u): The GFRP-reinforced beam had the least ultimate load capacity among the tested groups. This is due to the nature of GFRP itself where the reinforcement type is identified as the significant variable affecting ultimate capacity as per the investigation.
- Deflection Characteristics (Δu): The ultimate deflection of GFRP beams was the maximum due to the lowest modulus of elasticity of the materials.
- Ductility (μΔ): The ductility parameter of GFRP beams is found to be the minimum value around 1.1–1.3. This follows directly from the brittle failure behaviour of GFRP which is an inherent weakness in the structural application of this material.
- Slope (K0): The initial stiffness of the GFRP girders was generally the smallest. The research verified that stiffness is mainly affected by the type of reinforcement, and among them GFRP develops the lowest stiffness.
- Modes of failure: GFRP reinforced beams failed catastrophically in a brittle manner characterised by instantaneous failure of the GFRP bars without warning or measurable deflection.

Key Findings:

- GFRP beams were found to be the least ductile among all tested groups, which is a significant drawback for structural safety.
- The use of GFRP resulted in high ultimate deflections, highlighting the material's low modulus of elasticity.
- GFRP beams failed suddenly and in a brittle manner, without providing a clear warning before collapse.

Table 2 Final result of 6 Beams

Beam Symbol	Load(KN) (Pcr)	Load(KN) $\mathbf{P_u}$	Deflection(mm)	Stiffness K_0 kn/mm	Ductility $\mu\Delta$
G.R.2.4	4.35	37.49	21.02	1.6	1.15
G.R.4.4	4.47	49.83	16.9	3.17	1.26
G.R.6.4	7.33	56.72	13.266	4.68	1.33
G.R.2.6	8.21	50.75	22.352	2.67	1.32
G.R.4.6	6.74	55.17	18.899	3.12	1.17
G.R.6.6	10.75	64.71	17.62	4.52	1.27

4. CONCLUSION

Based on the experimental results and the analysis of the structural performance of the tested specimens, the following conclusions can be drawn:

- The use of hollow core in the ferrocement beams successfully reduced the overall self-weight and material consumption, which is a significant advantage in sustainable construction.
- Increasing the number of welded wire mesh layers from four to six consistently resulted in an increase in both the first cracking load (Pcr) and the ultimate load (Pu).
- The quantity of longitudinal reinforcement had a direct and significant impact on the beams' performance. A higher reinforcement ratio led to a higher ultimate load and, in most cases, a corresponding decrease in ultimate deflection.
- The GFRP-reinforced beams showed a brittle, non-yielding failure behavior, which is a primary limitation of using GFRP alone as a reinforcement material.
- The ferrocement matrix, with its dense wire mesh, was highly effective in controlling crack propagation across all specimens. The beams developed a large number of fine, well-distributed cracks rather than a few wide, localized ones.

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	**Prof. Dr. Aziz I. Abdullah** is an experienced academic/researcher and a notable in civil engineering based on his long career at universities in Iraq, Jordan and Malaysia. His research work is in the areas of strengthening and rehabilitation of structures, ferrocement and dynamic and impact loading. He has served in several managerial and leadership posts, such as the Head of the Civil Engineering Department of Jerash University and a Member in the Advisory Board of Arab's Impact Factor. He also once was the Head of the Department of Environmental Engineering, the Assistant Dean to the College of Engineering, as well as the former Head of Research and Development in Tikrit University.
	**Musab F. Maher** is a well-motivated person with extensive real estate development experience in Tikrit, Saladin Governorate. His area of expertise is strengthening and rehabilitation of structures, which is the meeting point of his academic work and practical experience. He also has research interests in ferrocement, and both dynamic and impact loading that are very important in achieving the new resilient infrastructure. This rare and valuable blend of trade street experience and academic hocus-pocus provides him with a wicked sense of how to make stuff with deep knowledge of application as well as structure.