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MECHANICAL BEHAVIOUR OF CONCRETE SLABS REINFORCED WITH STEEL AND GLASS FIBRE-REINFORCED POLYMER BARS UNDER STATIC AND CYCLIC LOADING

PRIMERJAVA STATIČNEGA IN DINAMIČNEGA MEHANSKEGA OBNAŠANJA Z JEKLOM ARMIRANIH BETONSKIH PLOŠČ IN POLIMERNIH PLOŠČ OJAČANIH S STEKLENIMI VLAKNI

Lenin Sannasi, Roselin Rajarethinam

Department of Civil Engineering, Noorul Islam Centre for Higher Education, Kumaracoil, Kanyakumari District, Tamil Nadu

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Steel is a fundamental material for reinforced concrete structures in construction, but it has a relatively low corrosion resistance. To overcome this drawback an alternative material is required; thus, steel reinforcements in concrete are replaced with fibre-reinforced polymer bars due to their advantages such as high corrosion resistance, high tensile strength, non-magnetic behaviour, fatigue resistance, etc. A fibre-reinforced polymer (FRP) bar is an innovative solution and variable alternative to conventional steel reinforcement of civil engineering structures. The aim of using glass fibre-reinforced polymer (GFRP) bars is to control corrosion in reinforced concrete structures and improve the strength and durability of the structures. This study investigates the mechanical behaviour of conventional concrete slabs reinforced with steel and GFRP bars under static loading conditions. The objective is to compare the performance of slabs reinforced with these two materials, focusing on the key parameters such as load-bearing capacity, deflection, failure mode, and stiffness. Experimental results show that steel-reinforced slabs exhibit higher stiffness and resistance to deflection, with a more ductile failure mode, while GFRP-reinforced slabs, despite offering superior corrosion resistance, experience higher deflections and exhibit a more brittle failure. The study highlights the potential of GFRP bars as an alternative to steel reinforcement, particularly in environments prone to corrosion, while emphasizing the importance of considering the distinct mechanical behaviours of both materials for design and application purposes. Notably, GFRP-reinforced slabs demonstrated a 13-% higher ultimate load-carrying capacity compared to steel-reinforced slabs.

Keywords: conventional concrete, steel reinforcement, glass fibre-reinforced polymer bar

Jeklo je bistveni material za armirano-betonske konstrukcije v gradbeništvu, vendar ima slabo odpornost proti koroziji. Zato, da bi premagali to pomanjkljivost, je potrebno najti alternativne materiale. Tako lahko naprimer betonske plošče z jekleno armaturo nadomestimo s polimernim ploščami, ki so ojačane s steklenimi vlakni. Te imajo veliko prednosti; imajo visoko korozijsko odpornost in natezno trdnost, so nemagnetne in odporne proti utrujanju itd. Izdelava polimernih nosilcev ali plošč (GFRP; angl.: glass fibre reinforced polymer bars) ojačanih s steklenimi vlakni je inovativna rešitev in v veliko primerih dokaj sprejemljiv nadomestek za konvencionalno jekleno armaturo v gradbenih konstrukcijah. Cilj uporabe teh s steklom ojačanih polimernih armatur je nadzor korozije v armirano-betonski konstrukciji ter izboljšanje trdnosti in trajnosti konstrukcije. V tem članku avtorji opisujejo študijo mehanskega obnašanja konvencionalnih z jeklom armiranih betonskih plošč in polimernih plošč ojačanih s steklenimi vlakni pod statično ali dinamično obremenitvijo. Cilj študije je bil primerjati delovanje plošč, ojačanih s tema dvema materialoma, s poudarkom na ključnih parametrih, kot so nosilnost, deformacija, način odpovedi in togost. Eksperimentalni rezultati so pokazali, da imajo plošče ojačane z jeklom večjo togost in odpornost proti deformaciji z bolj duktilnim (plastičnim) načinom odpovedi. GFRP plošče pa kljub vrhunski odpornosti proti koroziji doživljajo večje deformacije in kažejo bolj krhek (cepilni) vzorec odpovedi. Avtorji v zključku študije poudarjajo, da imajo GFRP plošče in/ali nosilci določen potencial kot alternativa jeklenim armaturam, zlasti v okoljih, ki so nagnjena h koroziji. Hkrati pa poudarjajo pomen upoštevanja različnih mehanskih lastnosti obeh materialov za namene načrtovanja in uporabe. Omeniti velja še, da je GFRP plošča imela 13 % večjo končno nosilnost v primerjavi z jekleno armirano ploščo.

Ključne besede: konvencionalni beton, jeklena armatura, polimerne palice in plošče, ojačanje polimerov s steklenimi vlakni

1 INTRODUCTION

The mechanical behaviour of concrete slabs reinforced with traditional steel reinforcement versus glass fibre-reinforced polymer (GFRP) bars has become a subject of growing interest in recent years. Steel has been the conventional reinforcement material due to its high strength and ductility, making it effective in resisting the applied loads in structural applications. However, the limitations of steel, such as susceptibility to corrosion, heavy weight, and the need for regular maintenance, have led to the exploration of alternative materials, with GFRP emerging as a promising option. GFRP bars, composed of glass fibres embedded in a polymer matrix, are known for their high tensile strength, corrosion resistance, and light weight. These characteristics make GFRP an ideal choice for reinforcing concrete slabs, especially in environments where corrosion is a concern or where weight is a limiting factor. Despite these advantages, the mechanical performance of GFRP-reinforced

*Corresponding author's e-mail:
leenin69@gmail.com (Lenin Sannasi)

concrete slabs differs from that of steel-reinforced slabs due to the unique behaviour of GFRP under load, including its low modulus of elasticity and brittle failure mode.

This study aims to investigate the suitability of using GFRP bars as reinforcement in conventional concrete structures (slabs). We compare the load-carrying capacity of cement slabs reinforced with steel and with GFRP. Under static loading, the mechanical behaviour of concrete slabs reinforced with steel and GFRP bars reveals distinct differences due to the material properties of both reinforcement types. Steel reinforcement, with its high modulus of elasticity, offers greater stiffness, which results in relatively low deflections under applied loads and a more gradual yielding behaviour before failure. This leads to a ductile response, where steel can undergo plastic deformation, providing a warning before complete failure.

In contrast, GFRP reinforcement, while offering high tensile strength and corrosion resistance, has a lower modulus of elasticity compared to steel, which leads to higher deflections under static loads. GFRP bars also exhibit a more brittle failure mode, as they lack the ability to deform plastically before failure. Consequently, GFRP-reinforced slabs tend to experience less deflection resistance and can fail suddenly without much warning, especially under high loads. This contrast in behaviour under static loading conditions highlights the need for a detailed comparison to understand the performance of GFRP as an alternative reinforcement in concrete slabs, especially for applications where long-term durability and maintenance concerns are critical. Glass fibres are basically made by mixing silica sand, limestone, folic acid and other minor ingredients. The mix is heated until it melts at about 1260 °C. The molten glass is then allowed to flow through fine holes in a platinum plate. The glass strands are cooled, gathered and wound. The fibres are then woven into various forms for use in composites. Based on an aluminium lime borosilicate composition, glass produced fibres are considered as the predominant reinforcement for polymer matrix composites due to their high electrical insulating properties, low susceptibility to moisture and high mechanical properties.

The fire resistance of CFRP-reinforced concrete beams was investigated, revealing that these beams exhibited greater stiffness compared to steel-reinforced beams. Under standard fire conditions and full service load, the failure mode observed was the crushing of concrete in compression.[1] Concrete slabs reinforced with GFRP bars demonstrated improved fire resistance with increased concrete cover and anchorage length. Slabs with a 51 mm cover and 500 mm anchorage length performed better under fire than those with a 31 mm cover and 250 mm anchorage.[2] Concrete beams reinforced with GFRP bars exhibited bi-linear load-deflection behaviour under static loading, with uncracked and cracked stages. Over-reinforced beams with higher reinforcement ratios (1.0 % and 2.0 %) displayed reserve capacity. Increased concrete strength reduced mid-span deflection more significantly at the 2.0 % reinforcement ratio (by 21 %) compared to 1.0 % (by 7 %).[3] BFRP bar pull-out specimens maintained similar bond stress-slip behaviour at both room and high temperatures, but bond strength decreased with increasing temperature. The reduction in bond strength was more severe for GFRP bars than BFRP bars, with the BFRP bond strength declining by 2.45–14.24 % between 70 °C and 220 °C, and by approximately 32 % at 270 °C.[4]

BFRP-reinforced slabs showed higher energy absorption and crack resistance under impact loading compared to steel-reinforced slabs, despite exhibiting more numerous and longer cracks. However, their lower ductility limits their suitability for earthquake-prone zones.[5] Concrete slabs reinforced with CFRP bars exhibited superior performance under impact loads compared to steel-reinforced slabs, attributed to their high strength and corrosion resistance. Another study also highlighted the significant influence of slab thickness and shear properties on the overall slab behaviour.[6] Reinforcing concrete panels with GFRP bars and three layers of glass cloth significantly improved impact resistance, increasing strike tolerance by 75.86 % compared to two layers. Increased slab thickness also enhanced impact resistance by 50.34 %, improving pre-cracking stiffness, post-cracking toughness, and overall durability.[7] A study on the impact resistance of GFRP-reinforced one-way concrete slabs showed that slabs with GFRP bars exhibited better performance than those with steel reinforcement. The GFRP-reinforced slabs experienced 25 % less strain and a 37.5 % reduction in time interval.[8]

A study on geopolymer two-way concrete slabs reinforced with FRP bars after exposure to elevated temperatures showed that slabs with BFRP bars had better elevated temperature resistance than those with GFRP bars, even with the same reinforcement ratio. Similar performance was observed for slabs exposed to 350 °C and ambient temperature, while significant differences were noted for specimens exposed to 550 °C and 650 °C.[9] Another study presented a method to calculate the longitudinal reinforcement ratio for GFRP-reinforced concrete (GFRP-RC) beams by setting the flexure crack width at 0.5 mm as the design limit state. Experimental and finite element analyses confirmed the accuracy of the proposed method, showing good agreement between theoretical and experimental bending moments, indicating high safety and reserve strength of GFRP RC beams.[10] A study on feasibility of using GFRP bars in concrete columns showed that GFRP offers superior bond properties and a compressive capacity comparable to steel. However, the brittleness of GFRP bars, along with lower stiffness, necessitates special design considerations, particularly in seismic regions.[11] Columns fully reinforced with GFRP demonstrate performance comparable to those of columns reinforced entirely with steel or a steel-GFRP hybrid. However, when GFRP is used for longitudinal reinforcement and steel for stirrups, the columns exhibit a 16 % decrease in the axial load capacity, and a 22 % reduction in the axial displacement.[12] Beams reinforced with GFRP main bars and 200 mm GFRP stirrup spacing failed in diagonal shear, with cracks extending from the support through the compression zone to the nearest loading point.[13]

This study focuses on comparing the mechanical behaviour of conventional concrete slabs reinforced with steel and GFRP bars, particularly in terms of their load-carrying capacity, deflection, and failure mechanisms. The aim is to evaluate how GFRP reinforcement can be a viable alternative to steel, especially in applications where the environmental conditions or other factors make GFRP an advantageous material. Understanding the mechanical behaviour of both materials under different loading conditions will contribute to the development of guidelines for the design and application of GFRP-reinforced concrete structures.

1.1 Research significance

This research investigates the effect of steel and FRP-bar reinforcement in conventional concrete slabs under static loading, with a focus on comparing the load-carrying capacity, durability, and mechanical behaviour of slabs reinforced with these two materials. While steel has been the conventional reinforcement for cement-concrete structures, the use of FRP bars, such as glass FRP (GFRP) and basalt FRP (BFRP), is gaining attention due to their superior corrosion resistance, light weight, and non-conductive properties. Despite the growing interest in FRP bars, there is limited research on their performance in cement-concrete structures, especially when compared to the widely used steel reinforcement. By exploring the performance of conventional concrete slabs reinforced with both steel and FRP bars, this study aims to fill this research gap and assess the potential of FRP bars to enhance the structural performance, longevity, and resilience of concrete under various load conditions. This research offers valuable insights into alternative reinforcement materials for conventional concrete, contributing to the development of more sustainable and durable construction practices.

1.2 Advantages of GFRP bars used in construction

- Corrosion resistant: Ideal for use in coastal, marine, and chemical environments.
- High strength-to-weight ratio: Strong but much lighter than steel.
- Non-magnetic: Suitable for MRI rooms and electronic facilities.
- Durable: Resistant to chemicals, UV rays, and harsh weather.
- Thermal and electrical insulator: Safe for use in areas needing insulation.
- Easy to handle and transport: Lightweight and simple to work with on site.
- Low maintenance: Reduces long-term repair and replacement costs.
- Customizable properties: Can be manufactured to meet specific needs.

1.3 Disadvantages of GFRP bars used in construction

- High initial cost: More expensive than traditional steel reinforcement.
- Brittle failure: Fails without warning, unlike steel which shows ductile behaviour.
- Limited design codes: Fewer standardized design guidelines compared to steel.
- Poor fire resistance: Losses strength at high temperatures.
- Difficult to bend on site: Cannot be bent after manufacturing like steel bars.

2 EXPERIMENTAL PART

2.1 Materials

2.1.1 Cement

53-grade Ordinary Portland Cement (OPC), conforming to IS:12269–2013, was mainly used for preparing the specimens. The important properties of cement are given in **Table 1**.

Table 1: Properties of cement

S. No.	Tests performed	Experimental values	Requirements as per IS:12269-2013
1	Standard consistency	30 %	28–32
2	Initial setting time	50 minutes	Not less than 30
3	Final setting time	360 minutes	Not more than 600
4	Specific gravity	3.12	3.15
5	Fineness (<90 microns)	2.8 %	<10 %
6	3rd day compressive strength of cement	30.5 N/mm^2	Greater than 27.0 N/mm^2
7	7th day compressive strength of cement	41.5 N/mm^2	Greater than 37.0 N/mm^2
8	28th day compressive strength of cement	57.5 N/mm^2	Greater than 53.0 N/mm^2

2.1.2 Aggregates

The M-sand conforming to IS:383–1970 was used as the fine aggregate and crushed granite stones with a maximum size of 20 mm were used as the coarse aggregate. The properties of fine and coarse aggregates are presented in **Table 2**.

The gradation of the fine aggregate is detailed in **Table 3** and graphically illustrated in **Figure 1**.

Table 2: Properties of fine and coarse aggregates

S. No.	Property	Fine aggregate	Coarse aggregate	
			20 mm	12.5 mm
1	Specific gravity	2.62	2.87	2.82
2	Fineness modulus	2.78	6.8	6.2
3	Density	1985 kg/m^3	1780 kg/m^3	1730 kg/m^3
4	Water absorption	0.64 %	0.24 %	0.22 %

Table 3: Particle size distribution of fine aggregate

IS sieve classification (mm)	Weight retained (g)	Percentage retained	Cumulative % retained	Percentage passing	Specified limits
10	0	0	0	100	100
4.75	55	5.5	5.5	94.5	90–100
2.36	130	13	18.5	81.5	75–100
1.18	198	19.8	38.3	61.7	55–90
0.6	226	22.6	60.9	39.1	35–59
0.3	200	20	80.9	19.1	8–30
0.15	180	18	98.9	1.1	0–10
Pan	11	1.1	100	0	

The particle size distribution of the coarse aggregate is detailed in **Table 4**. The gradation chart for the coarse aggregate is graphically shown in **Figure 2**.

Table 4: Particle size distribution of coarse aggregate

IS sieve classification (mm)	Weight retained (g)	Percentage retained	Cumulative % retained	Percentage passing	Specified limits
20	0	0	0	100	
12.50	590	11.80	11.8	88.2	85–100
10.00	2400	48.00	59.8	40.2	0–45
4.75	1864	37.28	97.1	2.9	0–10
2.36	146	2.92	100.0	0.0	–

2.1.3 Steel

The selection of reinforcement size and diameter was made in accordance with IS:1786–1985. 8-mm diameter bars were subjected to tensile stress using a universal testing machine.

2.1.4 GFRP as reinforcement

The 8-mm diameter GFRP bars were utilized as an internal reinforcement instead of traditional steel bars. A comparison of the material properties of GFRP bars and steel bars is provided in **Table 5**.

Table 5: Property comparison of GFRP bars and steel bars

S. No.	Material characteristics	GFRP bars	Steel bars
1	Density	1850 kg/m^3	7850 kg/m^3
2	Coefficient of thermal expansion	10.8 x 10^{-6}/^{o}C	12 x 10^{-6}/^{o}C
3	Tensile strength	750 MPa	500 MPa
4	Elastic modulus	50 GPa	200 GPa
5	Poisson ratio	0.25	0.30

2.1.5 Water

The water used for the mixing process must be clean, free from organic impurities, and devoid of harmful substances that could adversely affect the properties of the mortar. The use of saltwater is strictly prohibited to prevent adverse effects on the properties and durability of the mortar. Potable water is recommended for mixing and curing concrete slabs.

2.2 Mix design for conventional concrete

In this study, the mix design was prepared in accordance with the Indian Standard Guidelines specified in IS:10262–2009. The characteristic compressive strength of the concrete used in the study was 20 N/mm^2. Mix proportions for conventional concrete are presented in **Table 6**.

Table 6: Mix proportions for conventional concrete

Cement (kg)	M-sand (kg)	Coarse aggregate (kg)		Water-cement ratio
		20 mm	12.5 mm	
320.0	727	758	505	0.5

The mix ratio used in the experimental study is 1:2.272:2.369:1.579:0.5.

2.3 Casting and testing of reinforced slabs

2.3.1 Design

The slabs were designed according to the Indian design code IS 456:2000, with dimensions of (900 × 450 ×

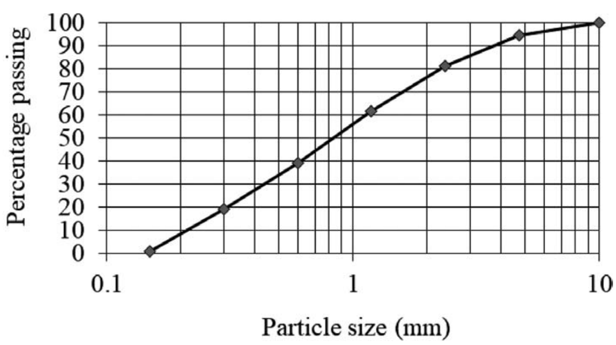

Figure 1: Gradation curve for fine aggregate

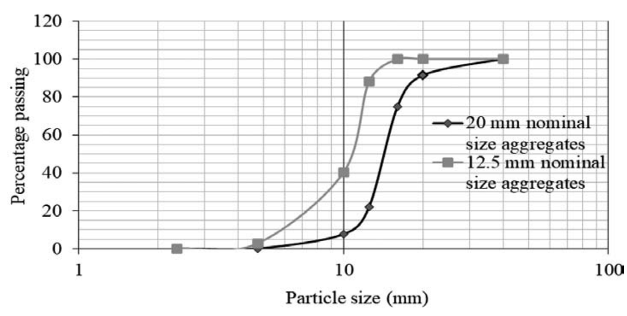

Figure 2: Gradation curve for coarse aggregate

Figure 3: Placing of the reinforcement in the mould

50) mm. A clear cover of 10 mm was maintained uniformly on all sides of the slabs.

2.3.2 Casting of reinforced slabs

Plywood moulds with dimensions of (900 × 450 × 50) mm were prepared for the casting of the slabs. The required reinforcements were arranged, and the casting process was carried out. Cover blocks were placed, and the reinforcements were positioned after greasing the sides of the mould to ensure easier demoulding. The concrete was poured into the mould, and the surface of the specimens were levelled and smoothened. The specimens were demoulded after 24 h and cured in water for 28 d. **Figures 3** and **4** show the process of casting an RC slab specimen, including the step of placing the reinforcement into the mould.

2.3.3 Testing of the specimens

All the slabs were tested under uniform loading conditions, with a point load applied at mid-span. Simply supported boundary conditions were provided at the supports. The testing was conducted using a flexural testing machine, which offers a loading accuracy within ±1 %, in compliance with IS 1828 and BS1610 standards. The test setup for the reinforced slabs is shown in **Figure 5**.

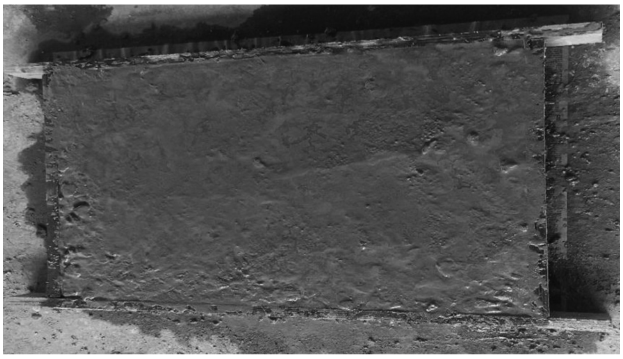

Figure 4: Casting of a specimen

Figure 5: Testing of a fire-damaged slab

2.3.4 Mode of failure

In general, most of the tested slabs failed due to concrete crushing at mid-span. For all the conventional concrete slabs, reinforced with both steel and GFRP bars, initial flexural cracks were observed to develop in the constant-moment region. Additionally, several diagonal cracks near the supports were observed. As the applied load increased, one of these cracks extended diagonally towards the nearest loading point. The conventional concrete slabs failed due to the crushing of the concrete in the high-moment region on the top surface, as shown in **Figure 6**. The failure exhibited extreme brittleness, initiating at one end of the slab and originating from the support.

The mode of failure of conventional concrete slabs reinforced with steel and GFRP bars differs due to the distinct material properties of the reinforcement.

Steel-reinforced slabs: In the slabs reinforced with steel bars, the failure mode is typically governed by

Figure 6: Failure mode of a fire-damaged slab

yielding of the steel followed by concrete crushing. Steel reinforcement exhibits ductile behaviour, allowing the slab to undergo significant deformations before failure. This ductility provides ample warning before collapse, characterized by visible cracking and plastic hinge formation. Cracks generally form perpendicularly to the tensile stress, and as the load increases, the cracks widen, eventually leading to failure when the compressive strength of the concrete is exceeded.

GFRP-reinforced slabs: In the slabs reinforced with GFRP bars, the failure mode is distinct due to the brittle nature of GFRP. GFRP bars do not exhibit yielding, and the failure is often sudden, occurring when the tensile strain limit of the GFRP bars is exceeded or when the concrete in compression fails. Common failure mechanisms in GFRP-reinforced slabs include:

- Tensile rupture of GFRP bars: Since GFRP has a higher tensile strength but lower strain capacity compared to steel, failure can occur abruptly without significant deformation.
- Concrete crushing in the compression zone: Similar to steel-reinforced slabs, failure in GFRP-reinforced slabs can be governed by concrete crushing if the compressive zone exceeds its capacity.
- Bond failure between GFRP and concrete: The bond between GFRP bars and concrete plays a critical role in load transfer. If the bond fails, the slab may experience delamination or reduced load-carrying capacity.

2.3.5 Comparative analysis

- Crack behaviour: Steel-reinforced slabs exhibit narrower and more controlled cracks due to the ductility of steel, while GFRP-reinforced slabs often display wider cracks due to the lower modulus of elasticity of GFRP.
- Energy absorption: Steel-reinforced slabs have a higher energy absorption capacity, making them more resilient under dynamic or impact loads, whereas GFRP-reinforced slabs are more suited for environments requiring corrosion resistance.
- Failure warning: The brittle nature of GFRP provides minimal warning before failure, emphasizing the need for precise design and monitoring.

Understanding these failure modes is crucial for designing and optimizing slabs reinforced with steel and GFRP bars, ensuring safety and performance under expected loading conditions.

3 RESULTS AND DISCUSSION

3.1 Load-carrying capacity of conventional concrete slabs under static loading

During the static vertical load test, the load was applied continuously until it reached ultimate vertical load. After this stage, the load was brought to 'no-load' condition. The ultimate load at failure, along with a significant vertical deflection, was observed for both steel- and GFRP-reinforced concrete slabs. Load-deflection curves for concrete slabs were developed by plotting the applied loads against the resulting deflections as shown in **Figure 7**.

The ultimate loads sustained by the conventional concrete slabs under static loading are listed in **Table 7**. For a visual representation, **Figure 8** illustrates the evaluation of the ultimate load-carrying capacity of the slabs under static loading conditions.

Table 7: Ultimate load-carrying capacity of cement-concrete slabs under static loading

S. No.	Description	First crack load		Load at failure	
		Load (kN)	Deflection (mm)	Load (kN)	Deflection (mm)
1	Conventional slab with steel reinforcement	11.2	3.42	16.2	5.85
2	Cement-concrete slab with GFRP reinforcement	12.54	3.28	18.4	5.56

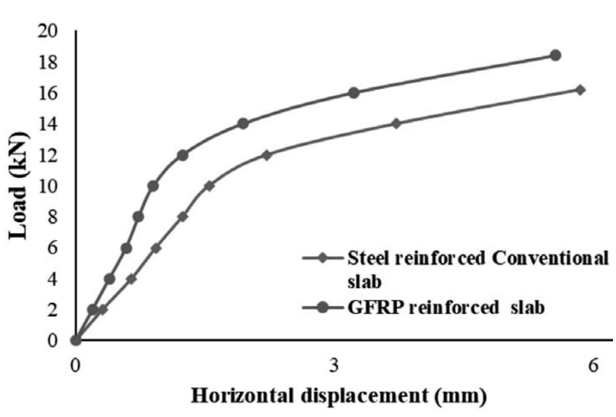

Figure 7: Load versus deflection curves of conventional slabs reinforced with steel and GFRP bars

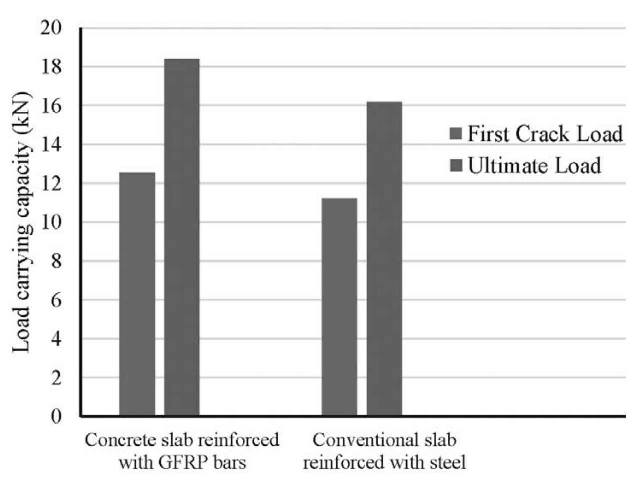

Figure 8: Load-carrying capacity of conventional slabs reinforced with steel and GFRP bars

Table 8: Stiffness degradation and energy dissipation of a steel-reinforced conventional slab

Cycle number	Peak load (kN)	Displacement (mm)	Stiffness (kN/mm)	Stiffness degradation (%)	Energy dissipation (kN-mm)	Cumulative energy dissipation (kN-mm)
1	3	0.6	5.00	–	0.4	0.4
2	6	1.4	4.29	14.29	1.3	1.7
3	9	2.6	3.46	30.77	4.08	5.78
4	12	3.9	3.08	38.46	10.8	16.58
5	15	6	2.50	50.00	16	32.58

Table 9: Stiffness degradation and energy dissipation of a GFRP-reinforced concrete slab

Cycle number	Peak load (kN)	Displacement (mm)	Stiffness (kN/mm)	Stiffness degradation (%)	Energy dissipation (kN-mm)	Cumulative energy dissipation (kN-mm)
1	3	0.55	5.45	–	0.37	0.37
2	6	1.35	4.44	18.53	1.4	1.77
3	9	2.55	3.53	35.32	4.08	5.85
4	12	3.8	3.16	42.14	8.6	14.45
5	15	5.85	2.56	53.04	15.25	29.7
6	16.5	7.3	2.26	58.61	18.7	48.4

The conventional slab exhibited an ultimate load-carrying capacity of 16.2 kN, while the GFRP-reinforced slab achieved approximately 18.4 kN. This indicates a reduction of about 12 % in load-carrying capacity of the steel-reinforced slab compared to the GFRP-reinforced slab. This increase can be attributed to the superior properties of GFRP as a reinforcement material. GFRP has a high strength-to-weight ratio, offering greater tensile strength while being lightweight. Its corrosion resistance ensures long-term structural integrity, unlike conventional steel, which may degrade in aggressive environments. Additionally, GFRP provides efficient stress distribution and improved bonding with concrete due to its surface texture, resulting in enhanced composite action and better load transfer. These factors, along with the material's ability to resist tensile forces effectively and improve the slab's flexural behaviour, allow the GFRP-reinforced slab to sustain higher loads before failure.

3.2 Load-carrying capacity of conventional concrete slabs under cyclic loading

Slabs with dimensions of (900 × 450 × 50) mm, identical to those used in the static load test, were prepared for the cyclic load test. This test was conducted using a flexural testing machine, employing the same setup as that used for the static load test. The load was manually applied up to the peak load for each cycle and then released to return to the no-load condition. The load was then applied incrementally in successive cycles. During the first cycle, the load was gradually increased from 0 kN to a peak of 3 kN and then released back to the no-load condition. In the second cycle, the load was increased from 0 kN to a peak of 6 kN, maintaining an incremental pattern of 3 kN per cycle. This process was repeated until the ultimate load was reached, resulting in the failure of the specimen. Displacement was measured both at the no-load condition and at the peak loads during the loaded stage. Additionally, to construct the hysteresis curve, displacement was recorded throughout both the loading and unloading phases of each cycle.

Stiffness, stiffness degradation, energy dissipation, and cumulative energy dissipation were determined based on the load versus displacement (hysteresis) curve. The stiffness for each cycle was calculated by dividing the peak load by the corresponding displacement. Stiffness degradation was evaluated as the number of cycles increased. Energy dissipation for each cycle was calculated by measuring the area enclosed by the hysteresis loop for that cycle. The total energy dissipation was determined by summing the areas of all the loops, representing the cumulative energy dissipation over the entire hysteresis curve. **Figures 9** and **10** show the hysteresis

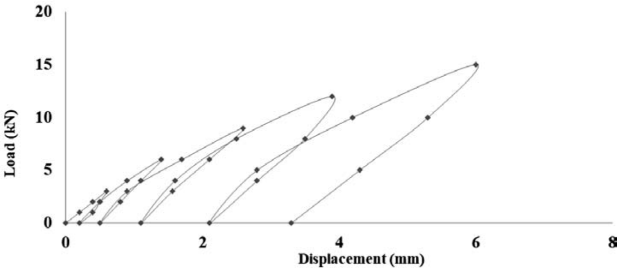

Figure 9: Hysteresis behaviour of a steel-reinforced concrete slab

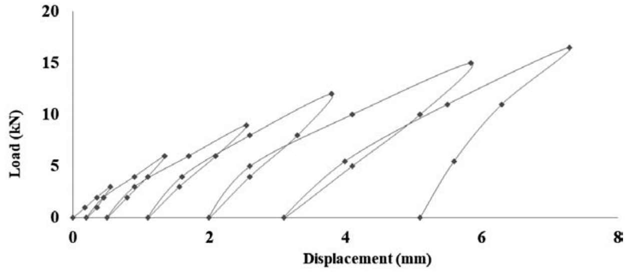

Figure 10: Hysteresis behaviour of a GFRP-reinforced concrete slab

behaviour of conventional concrete slabs reinforced with steel and GFRP bars. **Tables 8** and **9** present the stiffness degradation and energy dissipation characteristics of conventional concrete slabs reinforced with steel and GFRP bars, respectively.

For the steel-reinforced concrete slab, the maximum load recorded was 15 kN, accompanied by the corresponding maximum lateral displacement of 6 mm. The initial stiffness of the slab was 5.0 kN/mm, and it is evident that the stiffness continuously degraded throughout all cycles. After 5 cycles, the stiffness was reduced from 5 kN/mm to 2.5 kN/mm. In contrast, energy dissipation increased with each subsequent cycle. After 5 cycles, the energy dissipation increased from 0.4 kN·mm to 16 kN·mm. The total cumulative energy dissipation was 32.58 kN·mm.

For the GFRP-reinforced conventional concrete slab, the maximum load recorded was 16.5 kN, with the corresponding maximum lateral displacement of 7.3 mm. The initial stiffness of the slab was 5.45 kN/mm, and it is clear that the stiffness progressively degraded throughout all cycles. After 6 cycles, the stiffness decreased from 5.45 kN/mm to 2.26 kN/mm. On the other hand, energy dissipation increased with each successive cycle. After 6 cycles, energy dissipation increased from 0.37 kN·mm to 18.7 kN·mm, with the total cumulative energy dissipation reaching 48.4 kN·mm.

GFRP has several advantages that make it a viable alternative in specific applications requiring a higher ultimate load-carrying capacity compared to steel-reinforced slabs. These advantages include:

- Corrosion resistance: Unlike steel, GFRP does not corrode, making it highly suitable for structures exposed to harsh environmental conditions such as marine, industrial, or chemically aggressive environments.
- Light weight: GFRP is significantly lighter than steel, which reduces the overall dead load of a structure and facilitates easier handling, transportation, and installation.
- High strength-to-weight ratio: While the stiffness may be lower, GFRP offers a high tensile strength relative to its weight, making it efficient in specific structural applications.
- Non-magnetic and non-conductive: GFRP is ideal for structures where electromagnetic interference or electrical conductivity must be minimized, such as MRI rooms or power plants.
- Durability: GFRP's resistance to environmental degradation ensures long-term performance, reducing maintenance costs over the lifecycle of a structure.

4 CONCLUSION

Static results showed that a GFRP-reinforced slab has a higher load-carrying capacity than a steel-reinforced slab. The ultimate load-carrying capacity of the GFRP-reinforced slab is 13 % higher than that of the conventional slab. Cyclic-load results showed hysteresis behaviour of all slabs. Based on the hysteresis behaviour, stiffness degradation and energy dissipation per cycle were estimated for all slabs. Thus, the initial stiffness values for the conventional slab and GFRP-reinforced slab were found to be 5 kN/mm and 5.45 kN/mm, respectively. The total cumulative energy dissipation of the conventional slab, and GFRP-reinforced slab were 32.58 kN·mm and 48.4 kN·mm, respectively. The total cumulative energy dissipation of the fibre-reinforced slab was 32.69 % higher than that of the conventional slab.

In conclusion, the study of failure behaviour, load-carrying capacity, and performance under static and cyclic loading reveals significant differences between steel-reinforced and GFRP-reinforced concrete slabs. Under both static and cyclic loading, conventional concrete slabs reinforced with steel exhibited ductile failure characteristics, with a gradual progression of cracks and significant energy absorption. These slabs were able to withstand larger deformations and provided visible warning signs before failure, offering improved resilience under repeated or dynamic loading conditions. The failure occurred due to concrete crushing in the high-moment region, accompanied by yielding of the steel reinforcement.

On the other hand, the GFRP-reinforced slabs demonstrated excellent load-carrying capacity and performed well under both static and cyclic loading. Despite their brittle failure mode, these slabs exhibited superior corrosion resistance and sustained substantial loads before failure, making them highly suitable for environments prone to corrosive exposure. The failure in GFRP-reinforced slabs was primarily due to the tensile rupture of the bars or concrete crushing, but their ability to retain structural integrity under demanding conditions highlights their effectiveness as a reinforcement material.

Both static and cyclic loading tests revealed that while the steel-reinforced slabs offer greater energy absorption and deformation capacity, the GFRP-reinforced slabs excel in durability and resistance to environmental factors, performing admirably even under cyclic loading. This makes GFRP an attractive alternative for applications requiring long-term durability and strength, particularly in harsh or corrosive conditions. Ultimately, the choice of reinforcement material depends on the specific requirements of the application, balancing between factors such as energy dissipation, resilience, and long-term durability in corrosive environments. Understanding the failure modes and performance characteristics of these reinforcement types is essential for designing safer, more efficient concrete structures.

5 REFERENCES

[1] M. M. Rafi, A. Nadjai, F. Ali, Fire resistance of carbon FRP reinforced-concrete beams, Magazine of Concrete Research, 59 (**2017**), doi:10.1680/macr.2007.59.4.245

[2] E. Nigro, G. Cefarelli, A. Bilotta, G. Manfredi, E. Casenza, Fire resistance of concrete slabs reinforced with FRP bars - Part I: Experimental investigations on the mechanical behaviour, Composites: Part B, 42 (**2011**), 1739–1750

[3] M. Goldston, A. Remennikov, M. N. Sheikh, Behaviour of concrete beams reinforced with GFRP bars under static and impact loading, Journal of Reinforced Plastics and Composites, 30 (**2016**)

[4] L. Chenchen, D. Gao, Y. Wang J. Tang, Effect of high temperature on the bond performance between BFRP bars and concrete, 141 (**2017**)

[5] K. Ramakrishnan, K. Vinodhini, Impact Testing on Reinforced Concrete Slab with BFRP Bars as Reinforcement, International Journal of Engineering and Advanced Technology, 8 (**2019**)

[6] H. T. Khamies, M. K. Medhlom, Effect of impact load on the performance of concrete slab reinforced by CFRP bars, Journal of Engineering and Sustainable development, 25 (**2021**)

[1] A. M. Ali, Behaviours of reinforced concrete panels under impact loads (falling mass), Journal of Hunan University, 49 (**2022**)

[7] Y. A.Salih, A. I. Abdula, M. M. Jomaah, Impact resistance of GFRP reinforced concrete one-way slabs, Inf. Sci. Lett., 11 (**2022**) 4, 1267–1275

[8] S. H. Mohmmad, M. E. Gulsan, A. Cevik, Behaviour of geopolymer concrete two way slabs reinforced by FRP bars after exposure to elevated temperature, Arabian Journal for Science and Engineering, 47 (**2022**), 12399–12421

[9] J. Tu, Q. Zhao, K. Gao, The design of concrete beams reinforced with GFRP bars based on crack width, Materials, 15 (**2022**), doi:10.3390/ma15186467

[10] E. Alsuhaibani, M. Alturki, S. M. Alogla, O. Alawad, M. K. Alkharisi, E. Bayoumi, A. Aldukail, Compressive and Bonding performance of GFRP reinforced concrete columns, Buildings, 14 (**2024**), doi:10.3390/buildings14041071

[11] Seleem S. E. Ahmad, Mohamed Yones, Mahmoud Zaghlal, Hesham Elemam, Ahmed E. Elakhras, Experimental investigation of the eccentric performance of columns reinforced by steel and GFRP bars and strengthened with GFRP NSM bars and Mat Techniques, International Journal of Concrete Structures and Materials, 19 (**2025**), 32

[12] Selase A.K. Kpo, Charles K. Kankam, Charles Osei Ababio, Daniel Tetteh Tackie, Investigation on the shear performance of concrete beams reinforced with glass fiber reinforced polymer (GFRP) bars, Asian Journal of Advanced Research and Reports, 19 (**2025**) 4, 119–137