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Flexural Behavior of Reinforced Concrete Slabs with HYSD and GFRP Reinforcement

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Abstract - *Reinforced concrete slabs are important components influencing serviceability performance through their flexural behaviour, stiffness, and deflection characteristics. Due to some considerations like the high elastic modulus and ductile behaviour, High Yield Strength Deformed (HYSD) steel bars are generally preferred for slab reinforcement. On the contrary, in recent times, Glass Fibre Reinforced Polymer (GFRP) bars have attracted interest as an alternative to steel reinforcement by its high tensile strength, corrosion resistance, and durability leverage. However, the lesser modulus of elasticity of GFRP bars leads to different flexural response behaviour, especially under service load levels, when compared to conventionally used steel reinforcement, calling for experimental verification. The present study investigates the flexural behaviour of concrete slabs reinforced with HYSD bars and GFRP bars nominally in laboratory conditions by applying experimental-analytical intervention. Four reinforced concrete slab specimens, which had the same material properties and geometric configurations, were tested; two slabs were reinforced with HYSD bars and the other two with GFRP bars. The flexural loading was carried out in an incremental manner while measuring mid-span deflection during loading. Experimentally determined deflections were compared with theoretical predictions made by elastic analysis formulations. The results presented indicate that under similar loading conditions, slabs reinforced with HYSD bars were stiffer and had lower deflections compared to those reinforced with GFRP bars. Even though higher deflections were recorded for GFRP-reinforced slabs, their flexural behaviour was generally stable. For both reinforcement types, it was found that experimental deflections exceeded theoretical predictions, with GFRP-reinforced slabs presenting the largest divergence. The study emphasizes the importance of experimental verification in establishing realistic assessment of serviceability for RC slabs reinforced by alternative reinforcement materials.*

***Key Words*: Reinforced concrete slabs; Flexural behaviour; HYSD reinforcement; Glass Fibre Reinforced Polymer (GFRP); Load–deflection response; Serviceability performance**

1. INTRODUCTION

Reinforced concrete (RC) slabs serve as one of the most important elements of any building structure. They act as primary load distribution components transferring imposed loads to various beams, columns, and supporting walls. The structural performance of these slabs is determined primarily by flexural behaviour, which governs serviceability aspects like deflection control, crack development, and stiffness characteristics. Excessive deflections or cracking may pose challenges to function, durability and comfort even when sufficient strength is given, thus making serviceability performance an important design consideration for slab elements. Although reinforced concrete slabs have always been incorporated with high-yield steel deformed (HYSD) bars because of its high flexible behavior and elasticity, reliable performance most especially under service and ultimate loading conditions has been the traditional application of HYSD in reinforced concrete slabs. Steel reinforced slabs possess good stiffness and a predictable load-deflection behavior supported by design guidelines under codal provisions; however, steel reinforcement is susceptible to corrosion under very harsh environmental conditions like coastal areas, industrial zones, and areas with exposure to chemicals and moisture. Corrosion causes loss of cross-sectional area, deterioration of bond, and reduced service life. Thus, the development of alternative reinforcement materials not so vulnerable to the incidence of deterioration has been greatly motivated. GFRP bars are increasing as a popular alternative to normal steel reinforcement because of their better internal tensile strength, resistance to corrosion, and lightweight. The most important advantage offered by GFRP reinforcement is its durability and degradation through environmental exposure. However, GFRP bars have a significantly lower modulus of elasticity than steel bars, which brings differential flexural response behaviour. Notably, GFRP concrete slabs tend to exhibit greater deflection and lower stiffness under service loads compared to steel-reinforced slabs, thus making serviceability behavior crucial in the design criterion. A lot of work has been done on the study of flexural behavior of reinforced concrete beams reinforced with steel and GFRP bars, but the experimental work relating to slab elements was relatively limited. Slabs differ from beams concerning a two-dimensional load-transfer method, boundary condition, and cracking pattern. Therefore, the slabs need separate study. Furthermore, the deflection at present is usually predicted with analytical methods on some simplified assumptions that may not include the actual behavior of the slabs after cracking. Thus, in this area, an experimental and analytical study needs to be performed on RC slabs reinforced with HYSD steel and GFRP under ambient conditions. The present study seeks to compare the flexural behavior of such RC slabs in terms of load deflection, as well as the differences between theoretical predictions and experimental observation, thus leading to furthering understanding on serviceability performance of slabs reinforced with both conventional and alternative reinforcement materials.

2. MATERIALS AND MIX PROPORTIONS

This experimental program was essentially set out to prepare four reinforced concrete slab specimens of M30 grade concrete, which were to represent conventional structural slab elements when ambient conditions apply. The materials selected and the mix proportions were so according to corresponding Indian Standard specifications to maximize the degree of uniformity, repeatability and reliability of results from the tests. Ordinary Portland Cement, grade 53 and according to IS 12269, was used as the main cementitious material in the experiments whose source should come from a single source and stored in totally dry condition to prevent moisture ingress to maintain quality consistency. Fine aggregate come from manufactured sand (M-sand) having specific gravity of 2.65. As far as the fine aggregate is concerned, it will follow the grading and quality requirements of IS 383 and will be completely free of the following: organic impurities, silt, and clay content. All coarse aggregates were crushed angular granite aggregate and were taken to maximum nominal size of 20 mm. Coarse aggregate was selected to achieve interlocking and strength of the concrete matrix and also according to IS 383 specifications. All the aggregates were kept in dry condition before batching to ensure accurate control of water–cement ratio during mixing. Concrete was mixed in such a way that a characteristic compressive strength of 30 MPa at 28 days would be obtained, with a water-cement ratio of 0.45. The chemical admixture was mixed in this mix to improve workability central to uniform compaction of concrete in slab moulds as normal-range in accordance with IS:9103. The admixture dosage was finely controlled to improve workability without endangering the aggregate beginner and bleeding or modifying adversely the setting time. The use of admixture clearly enabled efficient placement by concrete around reinforcement leading to more weighty and homogeneous specimens. The reinforcement scheme for the slab specimens comprises reinforcement bars situated near where the tension face was to ensure flexural action during testing. In the specified slabs, Glass Fiber Reinforced Polymer (GFRP) bars of 6 mm diameter were utilized as reinforcement while the other slabs were reinforced with conventional HYSD steel bars for comparative evaluation. GFRP bars conformed to specifications as per IS 18255:2023 and were reinforced for high tensile strength and low modulus of elasticity compared to steel reinforcement. Thus this variation between material properties was presumed to have an influence on flexural behavior, particularly deflections and stiffness responses. All such reinforcement received an adequate concrete cover to ensure proper embedding and bond within the depth of the slab. Each slab was 500 mm × 500 mm × 50 mm thick and was a thin slab similar to those found in building applications. An appropriate spacer was used to maintain a nominal concrete cover of 15 mm. concrete mixing was done in a mechanical mixer to achieve uniform incorporation of all constituents. Fresh concrete was placed inside steel molds in layers and compacted using mechanical vibration to eliminate entrapped air. After casting, specimens were set under laboratory conditions, demoulded after 24 hours, and then cured for appropriate periods until adequate strength had developed prior to carrying out tests. The mix proportions adopted for M30 concrete used in the study are summarized in Table 2.1.

Table-2.1: Mix Proportion

Water (l/m^3)	**Cement** (kg/m^3)	**Fine aggregate** (kg/m^3)	**Coarse aggregate** (kg/m^3)	**Dosage of Admixture** (kg/m^3)
148	345	823	1104	17.25
0.43	1.00	2.38	3.20	0.05

3. EXPERIMENTAL PROGRAM

The experimental program aimed at studying the flexural behavior of reinforced concrete slabs reinforced with High Yield Strength Deformed (HYSD) steel bars and Glass Fiber Reinforced Polymer (GFRP) bars in the ambient laboratory conditions. Four reinforced concrete slab specimens were cast using M30 grade concrete with the same material properties, reinforcement layout, and curing conditions ensuring uniformity. Each of the slabs measured 500 mm × 500 mm × 50 mm, with reinforcements placed close to the tension face and adequate concrete cover provided for proper bond and embedment. Comparison of flexural response was enabled by having two of the specimens reinforced with HYSD steel bars and the other two with GFRP bars. All slabs were tested after curing for flexural loading under room temperature. The load was applied incrementally through a calibrated loading device, whilst mid-span deflections were measured with the help of dial gauges throughout the loading process. The experimental observations were majorly concerned with load-deflection behavior, stiffness characteristics, and cracking response of the slabs. The experimentally obtained values were then compared with theoretical deflections that were derived through elastic analysis formulations, therefore getting a measure of the divergence between analytical prediction and actual behavior of the slab.

3.1 Specimen Details and Identification

The experimental investigation was comprised of four slab specimen's reinforced using M30-grade concrete. All the slabs have the same size of 500 mm × 500 mm × 50 mm, and they have a single layer of reinforcement placed at the tension face for flexural action under loading. Adequate concrete cover was maintained to ensure proper bonding and embedment of reinforcement. Two slabs were reinforced with conventional High Yield Strength Deformed (HYSD) steel bars, while the other two slabs were reinforced with Glass Fibre Reinforced Polymer (GFRP) bars for comparison of flexural behavior under environmental conditions. Specimen identification details are presented in Table 3.1.

Table-3.1: Specimen Identification

Specimen ID	Reinforcement Type
S1	HYSD
S2	HYSD
S3	GFRP
S4	GFRP

3.2 Test Setup and Support Conditions

For each slab specimen, tests under flexural loading in room temperature should be undertaken employing a loading frame fitted with a hydraulic jack. There are two opposing edges supported by steel supports mounted on a loading chair, while allowing free edge along the remaining sides. The supporting arrangement allows for rotation at the edges of the slabs as well as strictly vertical reaction forces, hence, creating one-way simply supported boundary conditions. Load cells were used in applying concentrated vertical load to the center of the slab through stiff loading plate, to ensure uniform application and produce flexural bending. All the slab specimens were flexural loaded at ambient temperature using a loading frame integrating a hydraulic jack. The slabs were, however, laid on steel supports mounted on a loading chair so that the load could act on the edge along two opposite edges, whereas the remaining edges remained free. The arrangement allows rotation at slab edges and has only vertical reaction forces, thus simulating one-way simply supported boundary conditions. Load applied vertically at the center of the slab through a rigid loading plate ensures uniform load transfer and induces flexural bending.

3.3 Loading Procedure

The flexural loading was incrementally raised with the help of a calibrated hydraulic jack. In loading increments of small magnitude, the exact observation of load-deflection behaviour was made possible during the whole course of testing. At each loading increment, the applied load was recorded, followed by the corresponding mid-span deflection values. The loading was continued until an excessive deflection with visible cracking was observed on the slab, indicating flexural failure.

3.4 Instrumentation and Measurements

The mid-span deflections were recorded by the dial gauge having a least count of 0.01 mm, placed directly beneath the slab center. Observations during the test were made on the initiation and propagation of cracks. Crack patterns were manually marked for understanding the flexural cracking behaviour of the slabs. The main parameters recorded during testing included applied load and corresponding mid-span deflection, along with cracking pattern and overall flexural response.

4. RESULTS AND DISCUSSIONS

Flexural Testing of Reinforced Concrete Slab Specimens: Results and Discussion of the Structural Response of Specimens Under Load This section will deal further with the analysis of the load-deflection characteristics of the slabs, the stiffness variation, and the effect of different types of reinforcements. The load-deflection characteristics, stiffness variation, and reinforcement type influence the slabs' response. The other parts include the comparison of the experimental tests and the anticipated theoretical predictions for analyzing the applicability of the analytical models in the study.

4.1 Load and Deflection Behaviour

The experimental load-deflection response of the reinforced concrete slab specimens from flexural testing is outlined in Table 4.1. The flexural response of the slabs was assessed in terms of stiffness characteristics, ultimate load-carrying capacity, and maximum mid-span deflection. All specimens started with a slightly linear response; thereafter, after the cracking process set in, the responses were nonlinear.

Table-4.1: HYSD Reinforced Slab-S1

Load (kN)	Deflection (mm)
0	0.0
5	0.6
10	1.4
15	2.6
20	3.6
22	4.1

Table-4.2: HYSD Reinforced Slab-S2

Load (kN)	Deflection (mm)
0	0.0
5	0.7
10	1.6
15	2.9
18	3.8
21	4.4

Table-4.3: GFRP Reinforced Slab-S3

Load (kN)	Deflection (mm)
0	0.0
4	1.0
8	2.4
12	4.0
16	5.8
18	6.8

Table-4.4: GFRP Reinforced Slab-S4

Load (kN)	Deflection (mm)
0	0.0
4	1.1
8	2.7
12	4.5
15	6.0
17	7.2

4.2 Theoretical Versus Experimental Deflection

Deflections were theoretically calculated based on elastic analyses using idealised material behaviour with respect to uncracked section properties. The comparisons between theoretical predictions and experimental measurements revealed that the deflected values observed experimentally were always higher for all slab specimens. This deviation always increased with the progression of load but was more pronounced in GFRP-reinforced slabs. The discrepancies identified in these experiments are attributed to cracking effects, bond behaviour, or material nonlinearity, none of which are accurately represented by the simplified elastic analysis approach.

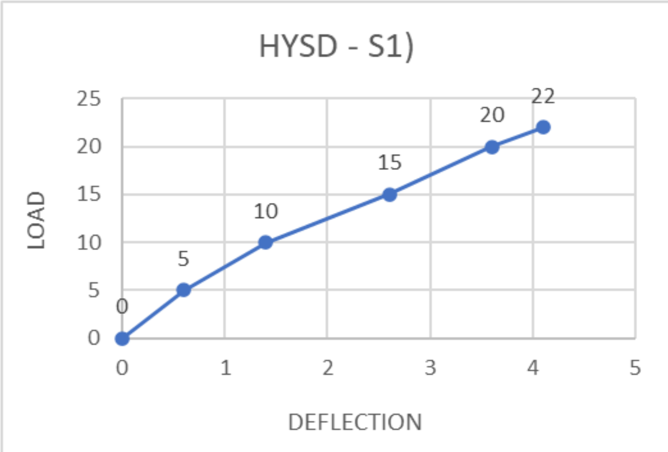

Chart -1: Load Deflection Curve for HYSD (S1)

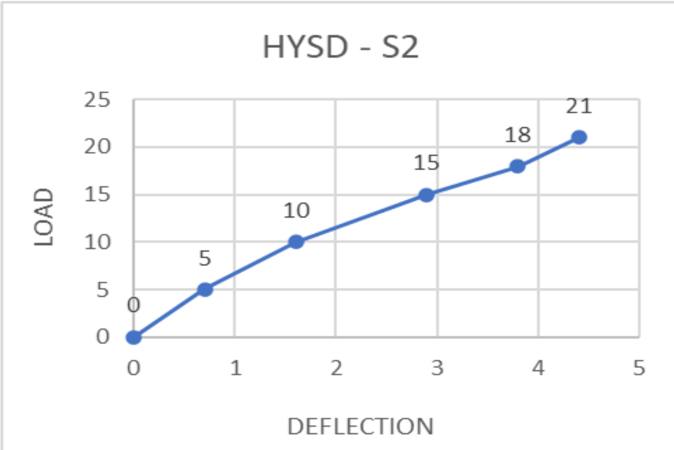

Chart -2: Load Deflection Curve for HYSD (S2)

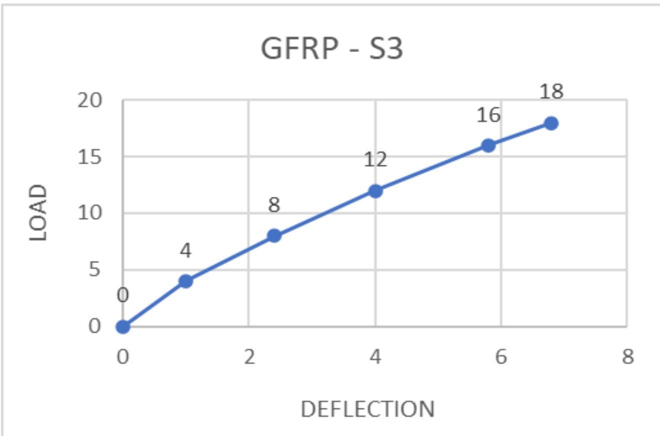

Chart -3: Load Deflection Curve for GFRP (S3)

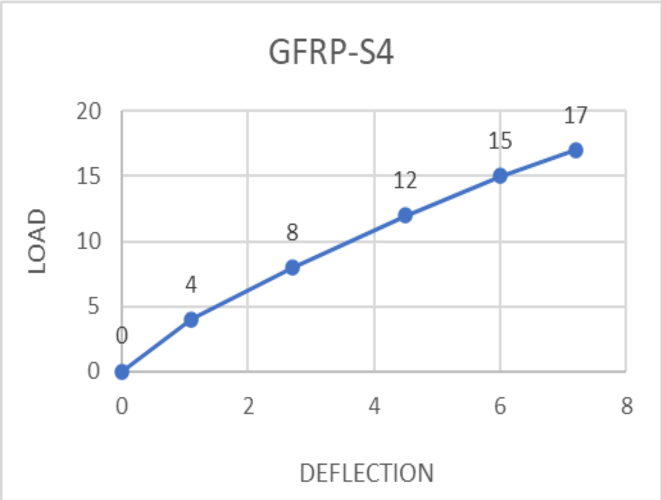

Chart -4: Load Deflection Curve for GFRP (S4)

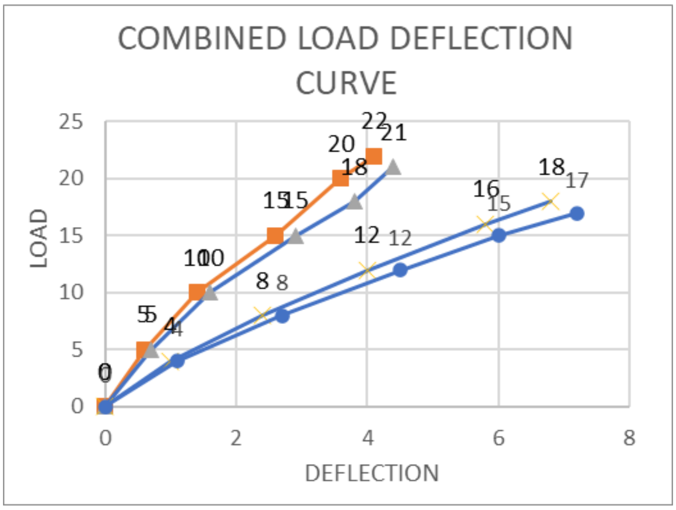

Chart -5: Combined Load Deflection Curve

4.3 Comparison between HYSD And GFRP Reinforced Slabs

In the comparative evaluation of test results, slabs reinforced with HYSD steel bars showed higher stiffness and lower deflections under the same loading conditions than GFRP-reinforced slabs. The primary reason for this behavior is related to the higher modulus of elasticity of steel reinforcement that provides higher resistance to flexural deformation. On the contrary, GFRP bars reinforced slabs have comparatively greater deflections because of lower elastic modulus of GFRP reinforcement. However, the load deflection response of GFRP-reinforced slabs remained stable and gradual, without sudden or brittle failure, indicating satisfactory flexural performance under surrounding conditions.

GFRP-reinforced slabs, in contrast, as their name suggests, has comparatively more deflections because of the lower elastic modulus of GFRP reinforcement. However, the load-deflection response of GFRP-reinforced slabs remained stable and progressive over time, without sudden failure or completes brittle failure, which shows flexibility under ambient conditions.

5. CONCLUSIONS

According to experimental and analytical investigations done on ambient conditions reinforced concrete slabs, the following would be derived as conclusions:

1. Flexural behavior of reinforced concrete slabs has been differentially affected by the type of reinforcement used, particularly regarding stiffness and deflection response.
2. In their fight against a similar load, slabs reinforced with HYSD steel bars were stiffer and had smaller midspan deflections, mainly because of the higher modulus of elasticity of the steel reinforcement compared to their GFRP counterparts.
3. Depending on the load application, GFRP-reinforced slabs exhibited higher deflections; however, gradual and stable shall load-deflection response was observed which didn't show any abrupt change typical of sudden failure or brittle failure.
4. The load-deflection response of all slab specimens during the initial stage was linear, whereas nonlinear behavior was observed after cracking commenced, which is characteristic of flexural behavior of reinforced concrete members.
5. The load-carrying capacity of slabs reinforced with HYSD was at best comparably equal to GFRP-reinforced slabs slightly higher, thereby reflecting the contribution of steel reinforcement to flexural resistance.
6. Experimental deflections during the course of testing were reported higher than the deflections calculated theoretically by elastic analysis for every specimen.
7. As the load was increased, the difference between the theoretical and experimental deflections kept increasing, thus creating a greater differentiation for GFRP-reinforced slabs.
8. Greater differences above those for GFRP-slab deflections can be attributed to cracking status, loss of stiffness, bond behavior, and the material nonlinearity not taken care of in some simplified analytical models.

9. Theoretical analysis based on uncracked section properties drastically under-predicted the deflections, thus highlighting the importance of experimental verification in establishing the serviceability behavior of GFRP slabs.

10. This study concludes that the serviceability criteria, especially deflection control, control the design of GFRP-reinforced RC slabs under ambient conditions.

6. RECOMMENDATIONS

[1] Glass Fibre Reinforced Polymer (GFRP) bars may be considered as an alternative to conventional HYSD steel reinforcement in reinforced concrete slabs where durability, corrosion resistance, and long-term performance are critical, provided that serviceability limits are carefully satisfied.

[2] Since GFRP-reinforced slabs exhibit higher deflections due to the lower modulus of elasticity of GFRP bars, deflection control should be treated as a governing design criterion in comparison with strength-based design.

[3] Analytical deflection models based on elastic theory should be used with caution for slabs reinforced with GFRP bars, as they tend to underestimate actual deflections observed experimentally. Appropriate stiffness reduction factors or modified analytical approaches are recommended.

[4] Experimental validation is strongly recommended when assessing the flexural and serviceability performance of reinforced concrete slabs reinforced with alternative reinforcement materials such as GFRP.

[5] For practical applications, hybrid reinforcement strategies combining steel and GFRP bars may be explored to achieve a balance between stiffness, ductility, and durability.

[6] Future experimental studies may be extended to investigate the influence of reinforcement ratio, slab thickness, and support conditions on the flexural behaviour of GFRP-reinforced slabs.

[7] Numerical and finite element modelling studies are recommended to complement experimental investigations and to develop improved predictive models for load–deflection behaviour of slabs reinforced with GFRP bars.

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