Flexural Behavior of Glass Fiber–Reinforced High-Performance Concrete Beams Under Cyclic Loading

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Abstract— **This study examines the effect of cyclic loading on the mechanical properties of glass fiber–reinforced HPC. The flexural performance of High-Performance Concrete (HPC) is a key factor governing the structural behavior of concrete elements under repeated loading. Concrete beams of grade M40 were cast using steel reinforcement and varying percentages of glass fiber, with silica fume and fly ash incorporated as mineral admixtures. The specimens were tested to evaluate compressive strength, tensile strength, and flexural strength under cyclic loading conditions. The experimental results indicate a notable increase in compressive strength for HPC containing 0.5% glass fiber. Flexural strength improved by up to 15% for mixes with 1% glass fiber across all grades. Direct tensile strength was observed to be higher than split tensile strength, reflecting the enhanced tensile resistance provided by fiber reinforcement. In addition, the inclusion of glass fibers delayed crack initiation and reduced crack propagation in HPC beams subjected to cyclic loading. The findings demonstrate that glass fiber–reinforced HPC exhibits improved strength, ductility, and crack control, making it suitable for structural applications subjected to cyclic or repeated loading.**

Index Terms—**High Performance Concrete, Glass Fiber, Mineral Admixtures, Cyclic Loading**

I. INTRODUCTION

High-performance concrete (HPC) incorporating mineral admixtures such as silica fume and fly ash has gained attention due to its enhanced mechanical and durability properties. Silica fume improves strength and reduces permeability by refining the pore structure, while fly ash contributes to long-term strength through its pozzolanic reaction (Owens). Previous studies have shown that HPC significantly enhances the flexural capacity of RC beams, with strengthened members exhibiting two to three times higher load-carrying capacity compared to conventional beams.

Nonlinear finite element techniques have been employed to capture the complete structural response of RC beams under static loading, primarily through load–deflection behavior, post-peak response, failure modes, and crack development at various loading stages. The flexural behavior of reinforced concrete (RC) beams has been extensively studied using analytical and numerical approaches. Ductility performance has commonly been evaluated using displacement ductility indices and toughness parameters.

II. MATERIALS AND METHODOLOGY

A. Material used

Cement is a binding material in concrete that binds the other materials to form a compact mass. In this project work, OPC cement of 43 grade is used for experimental study. A concrete with better quality can be made with sand consisting of rounded grains rather than angular grains. River sand must be used and not sea sand as it contains salt and other impurities. Aggregate must be clean and free from impurities. The maximum size of aggregate used in this project is 12mm and 20mm. Portable tap water available in the laboratory was used for mixing concrete and curing purposes. Silica fume, also referred to as micro silica or condensed silica fume, is another material that is used as an artificial pozzolanic admixture. It is a product resulting from the reduction of high-purity quartz with coal in an electric arc furnace in the manufacture of silicon. It is extremely fine with particle sizes of less than 1 micron and has a specific surface area of about 20,000 m2/kg. For higher strengths, the use of silica fume is essential. Fly ash is the finely divided residue from the combustion of ground or powdered coal which is transported from the firebox by the fuel gases and is subsequently removed from the gas by electrostatic precipitators. High fineness, low carbon content, and good reactivity are the essence of good Fly ash. CERA HYPERPLAST is used to increase the workability of concrete. Cera plast is a high-range super-plasticizing admixture. It speeds up construction and increases workability and cohesion. Low porosity results in substantially improved water penetration resistance. Fe415 grade steel bars were used with 2 bars of 8mm diameter provided at both top and bottom. 6mm diameter stirrups are spaced at 150 mm c/c as shear reinforcement.

TABLE 1: Strength Properties of concrete

S.No	Strength Property	Values in N/Mm2	Identification of Specimen
1	Compressive strength	46.22	M40
2	Compressive strength	58.37	M40 + SILICAFUME + FLY ASH
3	Split tensile strength	3.6	M40
4	Split tensile strength	5.3	M40 + SILICAFUME + FLY ASH
5	Flexural strength test	4.2	M40
6	Flexural strength test	6	M40 + SILICAFUME + FLY ASH

B.Mix Proportion

M40 grade concrete was designed as per IS10262-2009. The mix ratio for casting the specimen used is 1:1.42:2.3 and the water-cement ratio is 0.41, cement is replaced with Silica fume, and Fly ash volume fractions of 0.5% and 1% are used for glass Fibers.

C.Testing of Specimens

The following strengths of concrete are generally determined. Compressive strength test on cubes. Split tensile strength test on cylinders. Flexural strength test

III. RESULTS

a) Behavior of RCC And FRC Monotonic Loading

An experimental investigation on the behavior of RCC and FRC was carried out. The parameters like load carrying capacity and ductility were assessed. The results of the investigations are presented in this chapter.

b) Loading and Load Deflection Behavior

The beam specimen was placed on the loading frame as shown in the figure. All the beams were tested under two-point loading conditions. The monotonic load was applied by using a screw jack and to record the load precisely, a proving ring was used. The beam was gradually loaded by increasing the load level in each cycle such as 2, 4, 6, 8, 10,12,14 KN., etc. up to the maximum load of that cycle. At the end of each cycle, the load was gradually released and deflections during unloading were noted. The beam was loaded up to failure and the values of load at first crack and ultimate failure stage and crack pattern were noted. The cracks were marked by different colors showing clearly the failure patterns of the beam. As the load was increased in each cycle, the observed deflection was greater than in the earlier cycle. The load vs. corresponding deflection in each cycle has been plotted

c)Behavior and Mode of Failure

The beam was subjected to the cycle which exposed the behavior of the beam. As the load increases, the crack width is also increased and extended towards the neutral axis of the beam. The concrete was crushed and spalling down. Test Results of Control Specimen The experimental result for the control beams is tabulated in Table 2

d)Behavior of Beams Subjected to Cyclic Loading

An experimental investigation on the behavior of conventional reinforced concrete beams was carried out. The parameters like load carrying capacity, ductility, energy, Absorption, and stiffness degradation were assessed.

Table 2: Load Behaviour of Beams

S.NO	LOAD IN KN	CENTRAL DEFLECTION IN mm		
		RCC	FRC 1	FRC 2
1	0	0	0	0
2	1.5	3.5	0.377	0.418
3	3	9.3	0.957	0.804
4	4.5	1.54	1.51	1.315
5	6	2.11	1.959	1.726

6	7.5	2.7	2.359	2.268
7	9	3.34	2.759	2.907
8	10.5	3.95	3.359	3.417
9	12	4.6	3.943	3.88
10	13.5	5.19	4.459	4.323
11	15	5.84	5.079	4.7
12	16.5	6.61	5.547	5.094
13	18	7.29	6.159	5.482
14	19.5	8.2	6.659	5.926
15	21	9.65	7.417	6.567
16	22.5	10.8	7.875	7.027

Loading and Load Deflection Behavior

The beam specimen was placed on the loading frame as shown in the figure. All the beams were tested under two-point loading conditions. The forward and reverse cyclic load was applied by using a screw jack and to record the load precisely, a proving ring was used.

The beam was gradually loaded by increasing the load level in each cycle such as 2,4,6 KN. etc. up to the maximum load of that cycle. At the end of each cycle, the load was gradually released and deflections during unloading were noted.

The beam was loaded up to failure and the values of load at first crack and ultimate failure stage and crack pattern were noted. The cracks were marked by different colors show clearly the failure patterns of the beam. As the load was increased in each cycle, the observed deflection was greater than in the earlier cycle.

Ductility and Cumulative Ductility Characteristics

Ductility may be broadly defined as the ability of a structure to undergo inelastic deformations beyond the initial yield deformation with no decrease in the load resistance. A quantitative measure of ductility has to concern a bilinear load-deformation response. When a structure to cyclic loading, cumulative ductility up to any load point is defined as the sum of the ductility at the maximum load level attained in each cycle up to the cycle considered given in table 2

Energy and Cumulative Energy Absorption Capacity Characteristics

When the beam is subjected to reverse cyclic loading, such as those to be experienced during wind or earthquake, some energy is absorbed in each load cycle. It is equal to the work of straining or deformation of the structure to the limit of deflection.

The relative energy absorption capacities during various load cycles were calculated as the sum of the areas under the hysteric loops from the load-deflection diagram.

The cumulative energy absorption capacity of the beam was obtained by adding the energy absorption capacity of the beam during each cycle considered and the values are presented in table 3.

Behavior and Mode of Failure

The beam was subjected to 4th and 7th cycles to expose the behavior of the beam. As the load increases, the crack width is also increased and extended towards the top of the beam. The concrete was crushed and spalling down.

Cycle No.	Cumulative ductility factor			Cumulative energy absorption		
	RCC	FRC 1	FRC 2	RCC	FRC 1	FRC 2
1	0.49	0.11	0.48	1.8	0.6	3
	0.86	0.45	0.8	7.8	3	9
2	1.93	1.1	1.42	20.4	6.3	18
	2.99	2.1	2.31	33.3	13.3	27.5
3	4.96	3.3	3.27	47.7	21.3	51
	6.48	4.3	4.42	69.3	33.9	75
4	9.62	6.4	7.08	96.6	48.3	105
	11.51	7.89	8.34	120.9	67.2	153

Table 4 Control Specimen Test Results

	Cycle No	Forward				Reverse			
		1	2	3	4	1	2	3	4
	Maximum Load kN	4.5	9	13.5	18	4.5	9	13.5	18
RCC Δy = 1.7mm	Central Deflection mm	0.84	1.82	3.36	5.34	1.3	3.74	5.33	6.61
Δy = 3.5mm	Ductility Factor	0.49	1.07	1.97	3.14	0.37	1.06	1.52	1.89
	Energy Absorption mm	1.8	12.6	14.4	27.3	6	12.9	21.6	24.3
	Central Deflection mm	0.3	1.9	3.7	5.6	2.2	6	7	8.4
FRC 1	Ductility Factor	0.111	0.703	1.21	2.07	0.338	0.923	1.076	1.29
Δy = 2.7.mm Δy = 6.5.mm	Energy Absorption mm	0.6	3.3	7.8	14.4	2.4	7.2	12.6	18.9
	Stiffness Kn /mm	2.25	1.37	3.5	1.5	2.1	1.8	2.4	1.6
	Central Deflection mm	1.3	1.7	2.6	7.2	2.1	5.8	7.5	8.2
FRC 2	Ductility Factor	0.48	0.62	0.6	2.66	0.32	0.89	1.15	1.26
Δy = 2.7.mm Δy = 6.5.mm	Energy Absorption mm	3	9	13.5	30	6	19.5	24	48
	Stiffness Kn /mm	9	12	25.5	55.5	6	25.5	49.5	97.5

Table 3 Experimental Results of Beam

IV.FIGURES

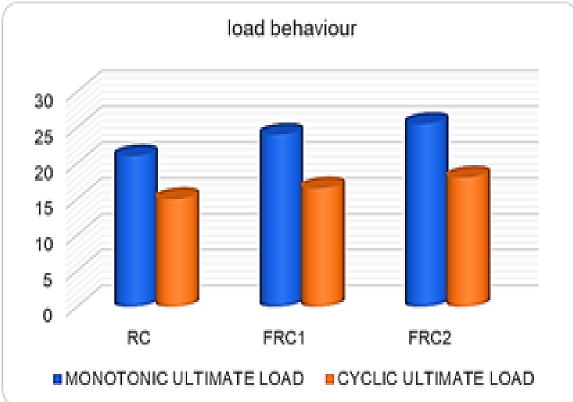

Figure 1: Comparison Of Load Carrying Capacity of Monotonic and Cyclic Loading

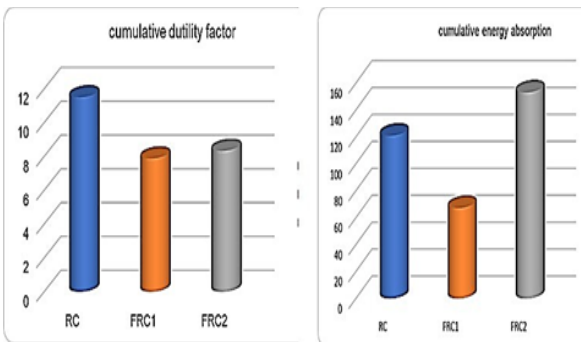

Figure 2 -Comparison Of Cumulative Ductility Factor, Energy Absorption Factor with Load Cycles

V. CONCLUSION

The ultimate load-carrying capacity of the FRC 1 beam is 14% higher than that of the conventional beam. The ductility of the conventional is decreased by 1.45 times that of the FRC 1 beam. The energy absorption of conventional is 1.8 times that of FRC 1 beam. Load carrying is marginal The ductility of the FRC 2 beam is 1.5 times that of the FRC 1 beam. Energy absorption of the FRC 2 beam is nearly twice that of the FRC 1 beam.

In General, it is concluded that the inclusion of glass fiber for the HPC beam does not increase the structural characteristics. The use of 1% glass fiber may give good results when compared with 0.5% fiber as given in Table 4.

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