Static and Cyclic Performance of HSC Beams with GFRP Laminates

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ABSTRACT—*This paper presents the experimental work conducted to examine the effectiveness of Glass Fibre Reinforced Polymer (GFRP) laminates on the performance of High Strength Concrete (HSC) beams under static loading and cyclic loading. For the experimental investigation, a total of fourteen beams of size 150mmm x 250mm in cross section with a total length of 3000mm were cast and tested. Two beams served as control beam and twelve beams were strengthened with three different configuration of GFRP laminates (Chopped Strand mat – CSM, Woven Roving – WR and Uni Directional Cloth – UDC) of 3mm and 5mm thickness. The study parameters considered for this research work included first crack load, deflection at first crack load, yield load, deflection at yield load, ultimate load, deflection at ultimate load, deflection ductility, deflection ductility ratio, energy ductility, energy ductility ratio, number of cracks and average spacing of cracks for high strength concrete beams with and without externally bonded GFRP laminates under static loading. Also, adequate data was obtained on the number of cycles, deflection, stiffness, crack width, number of cracks, average spacing of cracks, energy absorption and failure characteristics for high strength concrete beams with externally bonded GFRP laminates under cyclic loading. The results of the experiments carried out are presented and discussed in detail. The static and cyclic test results show that the beams strengthened with externally bonded GFRP laminates exhibit increased strength, enhanced flexural stiffness, sufficient ductility and composite action until failure.*

Keywords— cyclic**,** fibre, ductility, GFRP, laminate, strengthening

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1. INTRODUCTION

The Development of high strength concrete has been taken place in the last thirty years or so. Due to industrial demand the development of high strength concrete have improved rapidly because the industrial demand of new features in concrete members with serious advantages such as increased capacity and stiffness. The benefit of increased compressive strength is to lower volumes and produce smaller designs in terms of design prospective, thus allowing its immediate application into design.

The application of Fibre Reinforced Polymer (FRP) for strengthening and rehabilitation of reinforced concrete structures has become a promising technique. FRP may be applied as externally bonded reinforcement as well as internal reinforcing rods. The specific advantage of FRP is the high strength to weight ratio and ease of installation of the system. Strengthening reinforced concrete members using fibre reinforced polymers (FRP) has emerged as a potential method to address strength deficiency problems. Figure 1: shows the typical FRP strengthening systems for beams, slabs, columns and openings respectively.

Figure 1: FRP Strengthening Systems

This approach has shown significant advantages compared to traditional methods, mainly due to their outstanding mechanical properties of the composites. While rehabilitating, most of the infrastructure usually subjected to repeated loads which causes a structure to fail at load level below its static capacity. Thus fatigue loads should be taken into account while rehabilitating a structure. To resolve this problem Fibre Reinforced Polymer (FRP) has been proved to be an effective and promising solution for strengthening against fatigue loading.

The present research work has been undertaken for evaluating the performance of glass fibre reinforced polymer (GFRP) laminated high strength concrete beams. Emphasis has been given to the strength and deformation properties of GFRP strengthened HSC beams. Non-linear finite element analysis has been carried out to understand static response of the strengthened beams. Comparison has been made between the un-strengthened and strengthened beams and appropriate conclusions are drawn based on the results of investigation carried out

2. RESEARCH SIGNIFICANCE

This research work is significant on account of the investigation of static and cyclic behavior on high strength concrete beams strengthened with different GFRP configurations. This study is indented to evaluate the effect of Glass Fibre Reinforced Polymer (GFRP) laminates on the performance of high strength concrete beams under static and cyclic loading. A different type of GFRP laminates namely CSM, WR and UDC with different thicknesses 3mm and 5mm, static and cyclic loading conditions were the study parameters considered for assessing the strength and ductility of high strength concrete beams. The ultimate goal is to evaluate the strength and ductility of the high strength concrete beams with different GFRP configurations subjected to cyclic loading.

3. REVIEW OF LITERATURE

Heffernan and Erki (2004) investigated the fatigue behavior of reinforced concrete beams strengthened with carbon fibre reinforced plastic laminates. Twenty 3 m and six 5 m beams were loaded monotonically and cyclically in this study. The beams were of size 150 x 300 mm. Two beams, without and with CFRP strengthening were loaded monotonically to failure at a rate of 1 mm/min stroke rate. The remaining beams were loaded cyclically to failure. These beams were loaded by applying a sinusoidal loading pattern at a rate of 3 Hz. Three ranges of stress were applied, low stress 84.1 kN, medium stress 98.00 kN and high stress 112.00 kN. The authors concluded that beams strengthened with CFRP sheets exhibit enhanced fatigue life at all stress levels.

Tarek Almusalam (2006) studied the load-deflection behavior of RC beams strengthened with GFRP sheets subjected to different environmental conditions. A total of 84 beam specimens were prepared for this study. They were controlled by laboratory environment, outside environment, wet-dry alkaline water environment and second category coated with protection paint against ultraviolet rays. Each category consisted of un-strengthened and strengthened beams. The specimens of different wet-dry environments were exposed to a time cycle of two weeks inside the solution and two weeks outside the solution. The tests were carried out after 6, 12 and 24 months of exposure to different environmental conditions. The author concluded that none of the aforesaid environmental conditions have a noticeable influence on the flexural strength of the beams.

Tan, Saha and Liew (2009) carried out analytical and experimental investigations on GFRP- strengthened RC beams under the combined effect of sustained loading and tropical weathering. The author concluded that FRP strengthened RC beams under sustained loads exhibited larger deflections and crack widths, when subjected to tropical weathering at the same time. Also the author concluded that the GFRP strengthened RC beam showed decrease in deflections and crack width when compared to control beam. Both the strength and ductility of beams under sustained loads decreased with longer weathering periods.

Esfahani, Kianoussh and Tajari (2007) carried out an investigation on flexural behaviour of reinforced concrete beams strengthened by CFRP sheets. 12 concrete beam specimens with dimensions of 150 x 250 x 2000 mm length were cast and tested. Beam sections with three different reinforcing ratios (ρ) were used. Nine specimens were strengthened in flexure by CFRP sheets. The other three specimens were considered as control specimens. The length, width and number of layers of CFRP sheets varied in different specimens. The flexural strength and stiffness of the strengthened beams increased compared to the control specimens. The authors concluded that the design guidelines of ACI 440.2R-02 and ISIS Canada overestimate the effect of CFRP sheets in increasing the flexural strength of beams with small ρ values compared to the maximum value, $\rho_{max,}$ specified in these two guidelines.

Mahmut Ekenel and John (2009) proved that the fatigue resistance of RC beams can be improved by strengthening with CFRP fabrics. The increase in stiffness of the CFRP strengthened beam was approximately two times that of the un-strengthened beam. All CFRP-strengthened beams survived fatigue testing of 2 million cycles. Delaminations significantly decreased the stiffness of the CFRP-strengthened beams, the average decrease being 15% relative to specimens without defects.

Reza Mahjoub and Syed Hamid Hashemi (2010) presented experimental and analytical studies concerning the flexural strengthening of HSC beams by external bonding of FRP sheets. 6 concrete beam specimens with dimensions of 150 x 250 x 3000mm were cast and tested under 2 point loading. The principal variables included in their study were different layouts of CFRP sheets and tensile steel reinforcement ratio. They concluded that as the amount of tensile steel reinforcement was increased, the additional strength provided by the carbon FRP external reinforcement got reduced. Also their finite element model results showed good agreement with the experimental results.

Yasmeen, Susanne, Ola, Ghazi and Yahia (2010) investigated the behaviour of structurally damaged full-scale reinforced concrete beams retrofitted with CFRP laminates in shear or in flexure experimentally. The main variables considered by them were the internal reinforcement ratio, position of retrofitting and the length of CFRP. The experimental results indicates that beams retrofitted in shear and flexure by using CFRP laminates are structurally efficient and are restored to stiffness and strength values nearly equal to or greater than these of the control beams. The authors found that the efficiency of the strengthening technique by CFRP in flexure varied depending of the length. The main failure mode in the experimental work was plate debonding in retrofitted beams.

Tianlai, Chengyu, Junqing and Hongxiang (2011) investigated the fatigue behaviour of concrete beams strengthened with glass-fibre composite under flexure. Seven beams of 150 x 250 x 2500 mm size were used for this study, one beam was tested under monotonic loading, six beams were tested under cyclic loading, one non-strengthened beam and five beams strengthened with two layers of GFC sheet. The authors concluded that the failure mode of reinforced concrete beams strengthened with GFC under fatigue loading followed reinforcing steel fracture. Bonded GFC sheets reduce the stress in reinforcing steel and contribute to bridging the cracks in concrete.

Ferrier (2011) investigated reinforced concrete beams with externally bonded FRP subjected to fatigue loading. The results showed that the strengthening improves the fatigue behaviour of RC beams. With a load corresponding to 84% of the carrying capacity of RC beam, the fatigue behaviour of the beam was much improved. Further the results for the larger beams showed that the overall behaviour of RC beams was improved with the use of external FRP strengthening: a better fatigue behaviour was obtained, with a 40% increase in the service load.

Ravikant, Uttamasha and Choubey (2013) studied the effect of cyclic loading on the flexural behaviour of FRP strengthened RC beams. 12 RC beams of size 120 x 240 x 1900mm were cast. 9 beams were strengthened with FRP and the remaining 3 beams were un-strengthened. Three types of tensile percentage steel (0.545%, 0.818% and 1.09%) were considered in this study. The authors concluded that flexural strengthening of RC Beams using FRP exhibit additional strength and ductility. Failure of FRP strengthened under-reinforced RC beams initiated with yielding of steel followed by sudden FRP rupture.

4. EXPERIMENTAL PLAN

Details of Test Specimens

The details of all the test specimens prepared for experimental work are presented in Table 1. The beams were laminated with 3 different GFRP configurations (Chopped Strand Mat (CSM), Woven Roving (WR) and Uni-Directional Cloth (UDC) of varying thickness 3 mm and 5 mm thickness.

Table 1: Details of Test Specimens

Beam Designation	% Steel Reinforcement	GFRP		Type of Loading
		Type	Thickness	
CBHSC-S	0.603	-	0	Static
C3HSC-S	0.603	CSM	3	Static
C5HSC-S	0.603	CSM	5	Static
W3HSC-S	0.603	WR	3	Static
W5HSC-S	0.603	WR	5	Static
U3HSC-S	0.603	UDC	3	Static
U5HSC-S	0.603	UDC	5	Static
CBHSC-C	0.603	-	0	Cyclic
C3HSC-C	0.603	CSM	3	Cyclic
C5HSC-C	0.603	CSM	5	Cyclic
W3HSC-C	0.603	WR	3	Cyclic
W5HSC-C	0.603	WR	5	Cyclic
U3HSC-C	0.603	UDC	3	Cyclic
U5HSC-C	0.603	UDC	5	Cyclic

The concrete used for all beam specimens had a compressive strength of 67MPa. The concrete consisted of 450 kg/m^3 of ordinary Portland cement, 780 kg/m^3 of fine aggregate, 680 kg/m^3 of coarse aggregate, 450 kg/m^3 of medium aggregate, 0.36 water/cement ratio and 0.8% of hyperplasticizer (Glenium B233). HYSD bars of characteristic strength 466MPa were used for the longitudinal reinforcement. The specimens were provided with 8mm diameter stirrups at 125 mm spacing. Three types of GFRP laminates were used for the study, namely, Chopped Strand Mat (CSM) Woven Roving (WR) and Unidirectional Cloth (UDC) of 3mm and 5mm thickness. Glass fibre reinforced polymer laminates having the following configurations were used for the investigation.

i. Chopped Strand Mat (CSM)
ii. Woven Roving (WR)
iii. Uni-Directional Cloth (UDC)

The glass fibre reinforced polymer laminates were applied on the soffit of the beam specimens using epoxy adhesive. Figures: 2 to 4 shows the fibre configurations used in this study.

Figure 2: Chopped Strand Mat (CSM)

Figure 3: Woven Roving (WR)

Figure 4: Uni-Directional Cloth (UDC)

The properties of GFRP are presented in Table 2.

Table 2: Properties of Glass Fibre Reinforced Polymer (GFRP)

Sl. No.	Type of GFRP	Thickness (mm)	Tensile Strength (MPa)	Ultimate Elongation (%)	Elasticity Modulus (MPa)
1.	Chopped Strand Mat	3	126.20	1.69	7467.46
2.	Chopped Strand Mat	5	156.00	1.37	11386.86
3.	Woven Rovings	3	147.40	2.15	6855.81
4.	Woven Rovings	5	178.09	1.98	8994.44
5.	Uni-Directional Cloth	3	446.90	3.02	13965.63
6.	Uni-Directional Cloth	5	451.50	2.60	17365.38

5. TESTING PROCEDURE

The beams strengthened with FRP and unstrengthened beams were tested under four point-bending in a loading frame of 500kN capacity. The beams were supported on hinge at one end and roller at the other end. Two - point loads were applied through a spreader beam. The load was applied using a hydraulic jack and proving ring arrangement. The deflections at mid-span and load points were measured using mechanical dial gauges of 0.01mm accuracy. The deflection measurement upto ultimate stage was accomplished using a specially designed mechanical dial gauge. The crack width was measured and monitored using crack detection microscope with a least count of 0.02mm accuracy. Crack development and propagation was monitored during the process of testing. The loading was continued until failure and all the measurements were taken at all stages of loading. The details of test set-up and the associated instrumentation are shown in Figures 5 and 6.

Figure 5: Experimental Test Set-up for Static Loading

Figure 6: Experimental Test Set-up for Cyclic Loading

6. TEST RESULTS AND DISCUSSION

Static Response of Tested Beams

The static test results of experimental investigation carried out on seven beams which included one control beam and six GFRP strengthened beams are presented and discussed in this chapter The study parameters considered for this research work included first crack load, deflection at first crack load, yield load, deflection at yield load, ultimate load, deflection at ultimate load, deflection ductility, deflection ductility ratio, energy ductility, energy ductility ratio, number of cracks and average spacing of cracks. The test results on the strength and deformation properties of the control beam and GFRP strengthened high strength concrete beams at different load levels are reported in Table 3. The load-deflection characteristics of test beam are shown in Figure 7.

Table 3: Strength and Deformation Properties Pertaining to various Load Levels

Sl.No	Beam Designation	1st Crack Load (kN)	Deflection at 1st Crack Load (mm)	Yield Load (kN)	Deflection at Yield Load (mm)	Ultimate Load (kN)	Deflection at Ultimate Load (mm)
1	CBHSC-S	9.5	0.91	35	2.34	55	7.03
2	C3HSC-S	12.5	1.01	40	3.09	65	8.95
3	C5HSC-S	14.0	1.18	45	3.78	90	12.00
4	W3HSC-S	15.5	1.23	45	3.91	70	9.44
5	W5HSC-S	17.5	1.31	50	4.17	100	12.82

6	U3HSC-S	21.0	1.37	68	4.32	120	16.13
7	U5HSC-S	24.5	1.46	76	4.46	145	19.44

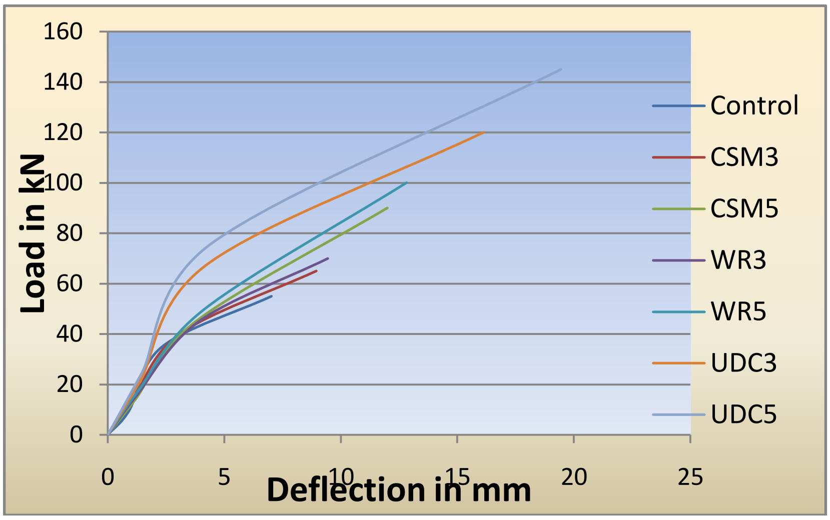

Figure 7: Load-Deflection Response of Control and GFRP Strengthened HSC Beams

The load-deflection response of all specimens as shown in Fig. 4.1 exhibits three regions of behaviour. At low load levels, the reinforced high strength concrete beam stiffness is relatively high indicating that the concrete behaves in a linear elastic manner. As the load increases, the extreme fibre stresses in bending increase until the tensile strength of concrete is reached. This causes flexural cracking initially in the constant moment region. Flexural cracking causes a marked reduction in stiffness as shown by a sudden change of gradient in the response.

Effect of GFRP Plating on Strength

The loads carried by all the test beams at first crack stage, yield stage and ultimate stage were obtained experimentally. The first crack loads were obtained by visual examination. The yield loads were obtained (by inspection) corresponding to the stage of loading beyond which the load- deflection response was not linear. The ultimate loads were obtained corresponding to the stage of loading beyond which the beam would not sustain additional deformation at the same load intensity.

The effect of GFRP strengthened beams on first crack load exhibit max an increase of 157.89% for the beam strengthened with 5mm thick UDCGFRP laminate when compared to control beam. The beams strengthened with 3mm thick CSMGFRP, WRGFRP and UDCGFRP exhibit an increase of 31.5%, 63.16% and 121.05% respectively when compared to control beam, those with 5mm thick CSMGFRP, WRGFRP and UDCGFRP laminates showed an increase up to 47.37%, 84.21% and 157.89% respectively when compared to control beam.

The effect of GFRP strengthened beams on yield load exhibit max an increase of 117.14% for the beam strengthened with 5mm thick UDCGFRP laminate when compared to control beam. The beams strengthened with 3mm thick CSMGFRP, WRGFRP and UDCGFRP exhibit an increase of 14.29%, 28.57% and 94.29% respectively when compared to control beam, those with 5mm thick CSMGFRP, WRGFRP and UDCGFRP laminates showed an increase up to 28.57%, 42.86% and 117.14% respectively when compared to control beam.

The effect of GFRP strengthened beams on ultimate load exhibit max an increase of 163.64% for the beam strengthened with 5mm thick UDCGFRP laminate when compared to control beam. The beams strengthened with 3mm thick CSMGFRP, WRGFRP and UDCGFRP exhibit an increase of 18.18%, 27.27% and 118.18% respectively when compared to control beam, those with 5mm thick CSMGFRP, WRGFRP and UDCGFRP laminates showed an increase up to 63.64%, 81.82% and 163.64% respectively when compared to control beam.

Effect of GFRP Plating on Deflections

Deflection of a beam primarily depends on the loading, span, moment of inertia of the section and elasticity modulus of concrete. Bonding of GFRP laminates to the soffit of a beam results in an increase in cross-sectional area and stiffness. This increase in stiffness influences the deflection behaviour of the plated beams during pre-cracking, cracking and post-cracking stages.

The decrease in deflection at first crack load was found to be 10.99% with 3mmCSMGFRP, 35.16% with 3mm WRGFRP, 50.55% with 3mm UDCGFRP, 29.67% with 5mm CSMGFRP, 43.96% with 5mm WRGFRP and 60.44% with 5mm UDCGFRP when compared to the control beam.

The decrease in deflection at yield load was found to be 32.05% with 3mmCSMGFRP, 67.09% with 3mm WRGFRP, 84.62% with 3mm UDCGFRP, 61.54% with 5mm CSMGFRP, 78.21% with 5mm WRGFRP and 90.60% with 5mm UDCGFRP when compared to the control beam.

The decrease in deflection at ultimate load was found to be 27.31% with 3mmCSMGFRP, 34.28% with 3mm WRGFRP, 129.45% with 3mm UDCGFRP, 70.70% with 5mm CSMGFRP, 82.36% with 5mm WRGFRP and 176.53% with 5mm UDCGFRP when compared to the control beam.

Effect of GFRP Plating on Ductility

Ductility of reinforced concrete beams is essentially a measure of their energy absorption capacity. Ductility of a beam is its ability to sustain inelastic deformation without any loss in its load carrying capacity, prior to failure. Ductility can be expressed in terms of deformation or energy. The deformation can be deflection, strain or curvature. The load-deflection curves in Figure 7: revealed that strengthening by bonding GFRP laminates positively influence the overall structural ductility of the strengthened beams.

Cyclic Response of Tested Beams

The influence of cyclic loading on the behaviour of high strength concrete beams with and without GFRP laminates is discussed in this section. All the test specimens were subjected to cyclic loading until failure. Adequate data was obtained on the number of cycles, load, deflection, stiffness, crack width, number of cracks, average spacing of cracks, energy absorption and failure characteristics of high strength concrete beams with and without GFRP laminates. The results pertaining to the objectives of the study are discussed and presented in this chapter. Cyclic test results of hybrid fibre reinforced concrete beams with and without GFRP laminates are presented in Tables 4.

Table 4: Results Pertaining to Ultimate Stage of Cyclic Loading

Beam Designation	No. of Cycles	Deflection at Ma. Load in mm	Stiffness in kN/mm	Crack Width in mm	No. of Cracks	Average Spacing of Cracks in mm	Energy Absorption in kN-mm
CBHSC-C	9	22.5	4.12	0.22	14	91	426.16
C3HSC-C	11	27.5	3.49	0.24	15	63	789.26
C5HSC-C	13	32.5	3.06	0.34	20	58	755.91
W3HSC-C	12	30	2.89	0.30	16	59	883.67
W5HSC-C	14	35	2.82	0.30	21	54	963.39
U3HSC-C	14	35	2.74	0.30	22	48	1228.95
U5HSC-C	16	40	2.57	0.28	24	43	1586.12

7. CONCLUSIONS

The epoxy bonding of GFRP laminates offers an attractive means of strengthening beams in flexure. Based on the result obtained from laboratory experiments the following conclusions are drawn.

1. An overall evaluation of the flexural test results and load – deflection curves indicates that reinforced high strength concrete beams strengthened with UDCGFRP laminates exhibit higher load carrying capacity and ductility.
2. The reinforced high strength concrete beams strengthened with 5mmUDCGFRP laminate exhibit an increase of 80% in ultimate load when compared with the control beam.
3. The reinforced high strength concrete beams strengthened with 5mmUDCGFRP laminate exhibit a decrease of 80% in deflection at ultimate load when compared with the control beam.
4. Flexural cracks were occurred in all the beam specimens.
5. All the beam specimens failed in flexure mode only.
6. Under cyclic loading, for reinforced high strength concrete beams strengthened with 5mmUDCGFRP laminates, the number of cycles got increased of 43.75%,

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