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BEHAVIOR OF PRE-STRESSED CONCRETE BEAMS STRENGTHENED WITH FIBER REINFORCED POLYMER LAMINATES

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ABSTRACT: The main objective of this research work is to evaluate the static response of pre-stressed concrete beams strengthened with externally bonded Fibre Reinforced Polymer (GFRP) laminates at the soffit of beam. A total of fourteen beams of 3 m length and 150 mm x 250 mm in cross-section were cast and tested in the laboratory. Two unbonded post-tensioned beams served as reference beams and the remaining twelve beams were strengthened with GFRP laminates on their soffit. 7 beams cast with M35 grade concrete were strengthened with three different GFRP laminates having two different thicknesses 3 mm and 5 mm and tested under monotonically increasing loading and manual readings were recorded. Remaining 7 beams cast with M60 grade concrete were strengthened with three different GFRP laminates having two different thicknesses 3 mm and 5 mm and tested under monotonically increasing loading and manual readings were also recorded directly. The variables considered included grade of concrete, type of GFRP laminate and thickness of GFRP laminate. The GFRP laminates also varied in their configuration, viz., Chopped Strand Mat (CSM), Woven Roving (WR) and Uni- Directional Cloth (UDC). Responses of all the beams were evaluated in terms of strength, stiffness, ductility, composite action between concrete and external reinforcement and the associated failure modes for beams tested under static loading.Finite Element Method (FEM) based model has been proposed to predict the performance characteristics of pre-stressed concrete beams with and without externally bonded GFRP laminates. A reasonably close agreement has been obtained between the experimental and predicted results. Regression analysis has also been conducted and appropriate equations have been proposed for predicting the necessary performance parameters in respect of pre-stressed concrete beams with and without externally bonded GFRP laminates.

Keywords: deformation, ductility, fibre, GFRP laminates, regression, strength

I. INTRODUCTION

There are various kind of strengthening methods are available but every method cannot be suited for all cases, with the proper study of the case we have to decide the proper method which is suited for particular case. Externally bonded steel plates, steel or concrete jackets and external post-tensioning are just some of the many traditional techniques available. Composite materials made of fibers in a polymeric resin, also known as fiber-reinforced polymers (FRP), have emerged as an alternative to traditional materials and techniques. FRP system is defined as all the fibers and resins used to create the composite laminate, all applicable resins used to bond it to the concrete substrate, and all applied coatings used to protect the constituent materials. Coatings used exclusively for aesthetic reasons are not considered part of an FRP system. Nowadays mostly used strengthening material is Fiber Reinforced Polymer (FRP). Fiber Reinforced Polymer is made by combining fibers namely glass fibers, carbon fibers, Aranid fibers, Basalt fibers etc with polymers like epoxy resins.

II. OBJECTIVES OF THE STUDY

1. To examine the effect of GFRP plating on the strength and deformation capacity of pre-stressed concrete beams.
2. To study the effect of GFRP plating on ductility of pre-stressed concrete beams.
3. To examine the failure modes of test specimens.
4. To compare the experimental results with analytical results.
5. To propose a finite element based model using ANSYS software and to compare the experimental and analytical predictions.
6. To propose a regression equation for estimating the characteristics of pre-stressed concrete beams strengthened with and without GFRP laminates.

III. RESEARCH SIGNIFICANCE

This research work is significant on account of the investigation on flexural behaviour on pre- stressed 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 pre-stressed beams under static loading. GFRP laminates of different configurations such as CSM, WR and UDC with different thicknesses 3mm and 5mm and 2 different grade of concrete M35 and M60 were the study parameters considered for assessing the strength and ductility of pre-stressed concrete beams. The ultimate goal is to evaluate the strength and ductility of pre-stressed concrete beams with different GFRP configurations subjected to static loading. As part of this investigation, FEM based model, analytical model and regression based models have also been developed for estimating the strength, deformation and ductility characteristics of GFRP strengthened pre-stressed concrete beams.

IV. EXPERIMENTAL PLAN

DETAILS OF TEST SPECIMENS

The details of all the test specimens prepared for experimental work are presented in Table 3.1. The unbonded post-tensioned 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 3.1 Details of Test Specimens

Beam Designation	% Steel Reinforcement	Grade of Concrete	GFRP	
			Type	Thickness
T	0.603	35	-	0
TC1	0.603	35	CSM	3
TC2	0.603	35	CSM	5
TU1	0.603	35	UDC	3
TU2	0.603	35	UDC	5
TW1	0.603	35	WR	3
TW2	0.603	35	WR	5
S	0.603	60	-	0
SC1	0.603	60	CSM	3
SC2	0.603	60	CSM	5
SU1	0.603	60	UDC	3
SU2	0.603	60	UDC	5
SW1	0.603	60	WR	3
TW2	0.603	60	WR	5

Note: CSM-Chopped Strand Mat; WR – Woven Roving; UDC - Uni-Directional Cloth

MATERIAL PROPERTIES

The concrete used for T-series beam specimens had a compressive strength of 42 MPa. The designed mix proportion was 1: 1.30: 2.35 : 0.42. The concrete consisted of 474 kg/m^3 of ordinary Portland cement, 616 kg/m^3 of fine aggregate, 1114 kg/m^3 of coarse aggregate and 199 kg/m^3 of water. The concrete used for S-series beam specimens had a compressive strength of 69MPa. The designed mix proportion was 1: 1.35 : 2.19 : 0.29. The concrete consisted of 498 kg/m^3 of ordinary Portland cement, 672 kg/m^3 of fine aggregate, 1091 kg/m^3 of coarse aggregate and 144 kg/m^3 of water. For both T and S-series beam specimens HYSD bars of characteristic strength 436 MPa were used for the longitudinal reinforcement. Pre-stressing wires of 7mm diameter having ultimate stress 1532 MPa, breaking load 59.1KN and 4 percentage elongation were used. The specimens were provided with 8mm diameter (characteristic strength 287MPa) stirrups at 150 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

Glass fibre reinforced polymer laminates having the following configurations were used for the investigation.

- Chopped Strand Mat (CSM)
- Woven Roving (WR)
- Uni-Directional Cloth (UDC)

The glass fibre reinforced polymer laminates were applied on the soffit of the beam specimens using epoxy adhesive. Figs. 3.2 to 3.4 show the fibre configurations used. The properties of GFRP are shown in Table 3.2.

TEST PROCEDURE

The pre-stressed beams strengthened with and without FRP were tested under four point- bending in a loading frame of 100T capacity. The beams were supported on hinge at one end and roller at the other end. The details of test set-up are shown in Fig. 3.22. Two - point loads were applied through a spreader beam. The load was applied using a hydraulic jack and proving ring arrangement.

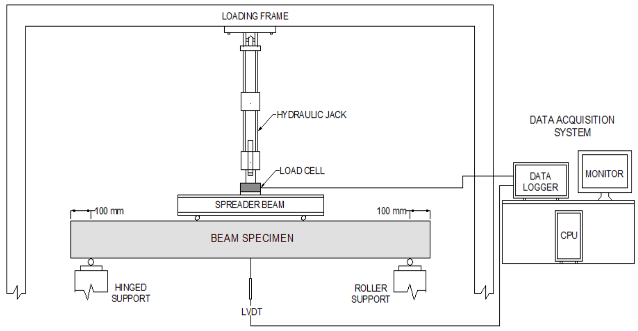

Fig. Details of Instrumentation

The deflections at mid-span and load points were measured using Linear Variable Displacement Transducer (LVDT). The deflections corresponding to load are recorded through 20-channel data acquisition system. Similarly load and strain are collected through a 20-channel data acquisition system. The performance parameters such as ultimate load, deflection, crack pattern, failure mode were observed during the test. The loading was continued until failure and all the measurements were taken at all stages of loading. The details of static test set-up and the associated instrumentation are shown in Fig.

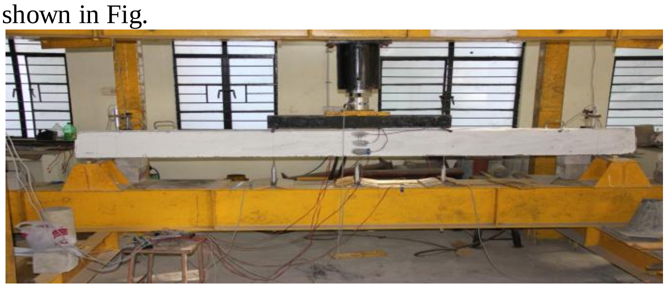

Fig. Test Set-up for Static Loading

V. RESULTS AND DISCUSSION

STATIC RESPONSE OF TESTED BEAMS

The static test results of experimental investigation carried out on fourteen beams which included two control beams and twelve GFRP strengthened beams are presented and discussed in this chapter The study parameters considered for this research work included yield load, deflection at yield load, ultimate load, deflection at ultimate load, deflection ductility, deflection ductility ratio, energy ductility, energy ductility ratio and number of cracks.The test results on the strength and deformation properties of the control beam and GFRP strengthened pre-stressed concrete beams at different load levels are presented in Table 4.1. The load-deflection responses of tested beams (T-series and S-series) are shown in Figs. 4.1 and 4.2.

Table Strength and Deformation Properties Pertaining to various Load Levels

Beam Designation	Yield load (kN)	Deflection at Yield Load (mm)	Ultimate Load (kN)	Deflection at Ultimate Load (mm)
T	18.62	3.08	50.52	39.25
TC1	20.00	3.00	59.56	42.00
TC2	22.24	3.10	63.00	44.86
TW1	25.60	3.24	70.20	55.20
TW2	23.24	3.93	79.44	64.50
TU1	33.74	4.09	85.26	68.00
TU2	36.12	4.53	97.58	75.50
S	20.43	10.70	70.50	62.34
SC1	30.70	11.70	78.00	68.45
SC2	35.86	11.70	82.30	71.30
SW1	35.14	12.00	83.50	73.86
SW2	42.70	12.37	87.60	77.65
SU1	45.00	13.03	93.50	83.98
SU2	48.86	13.57	108.70	89.58

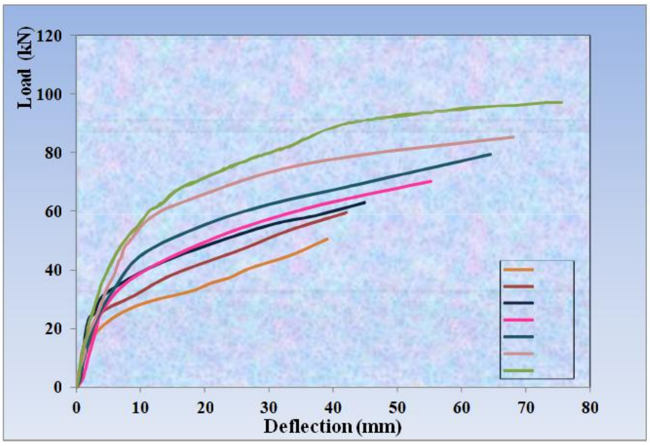

Fig. Load-Deflection Response of Control and GFRP Strengthened T-series PSC Beams

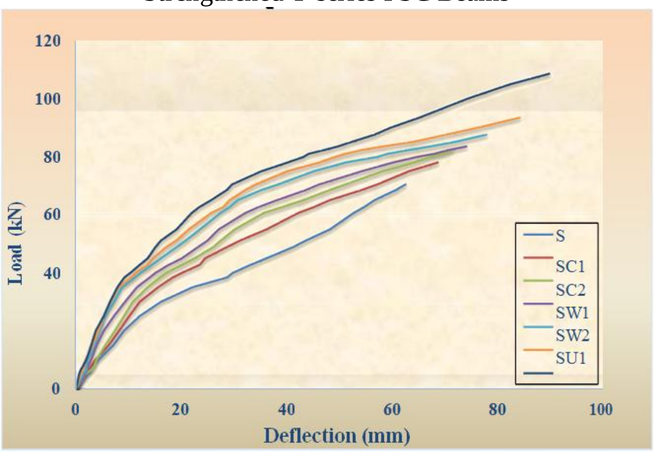

Fig. 4.2 Load-Deflection Response of Control and GFRP

Strengthened S-series PSC Beams

The load-deflection response of all specimens shown in Figs. 4.1 and 4.2 exhibit three regions of behaviour. At low load levels, stiffness of beam 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 yield stage and ultimate stage were obtained experimentally. 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 intensit y.

Fig. 4.3 shows the effect of GFRP laminates on various load levels for T-series beams. The beams strengthened with 3mm thick CSMGFRP, WRGFRP and UDCGFRP exhibit an increase of 7.41%, 37.49% and 81.20% respectively in yield load when compared to control beam and those with 5mm thick CSMGFRP, WRGFRP and UDCGFRP laminates showed an increase up to 19.44%, 24.81% and 93.98% respectively in yield load when compared to control beam. The beams strengthened with 5mm thick CSMGFRP, WRGFRP and UDCGFRP exhibit an increase of 17.89%, 38.95% and 68.76% respectively in ultimate load when compared to control beam and those with 5mm thick CSMGFRP, WRGFRP and UDCGFRP laminates showed an increase upto 24.70%, 57.24% and 93.15% respectively in ultimate load when compared to control beam.Fig. 4.4 shows the effect of GFRP laminates on various load levels for S-series beams. The beams strengthened with 3mm thick CSMGFRP, WRGFRP and UDCGFRP exhibit an increase of 50.27%, 72.00% and 120.26% respectively in yield load when compared to control beam and those with 5mm thick CSMGFRP, WRGFRP and UDCGFRP laminates showed an increase up to 75.53%, 109.01% and 139.16% respectively in yield load when compared to control beam. The beams strengthened with 5mm thick CSMGFRP, WRGFRP and UDCGFRP exhibit an increase of 10.64%, 18.44% and 32.62% respectively in ultimate load when compared to control beam and those with 5mm thick CSMGFRP, WRGFRP and UDCGFRP laminates showed an increase up to 16.74%, 24.26% and 54.18% respectively in ultimate load when compared to control beam.

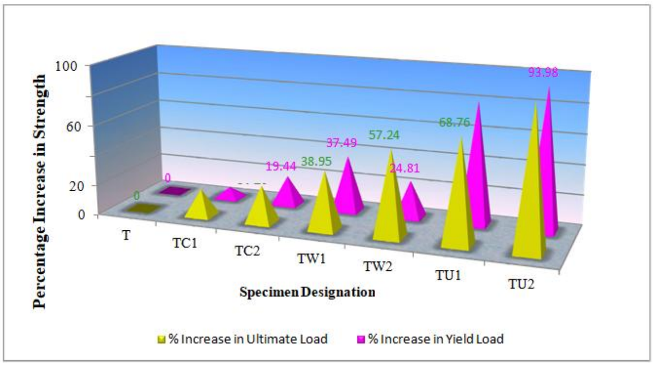

Fig. Effect of GFRP Plating on Strength for T-series Beams

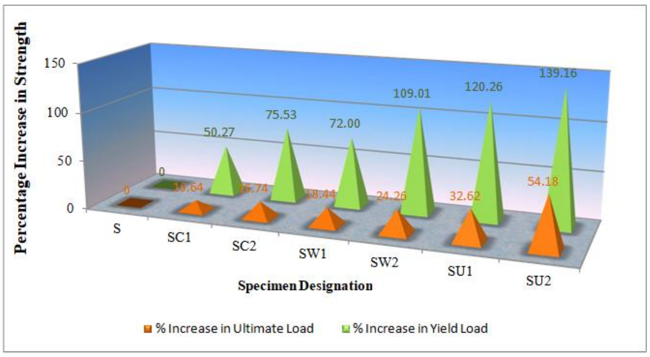

Fig. 4.4 Effect of GFRP Plating on Strength for S-series Beams

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. Figs. 4.5 and 4.6 shows the effect of GFRP laminates on deflection at various load levels for T-series and S-series beams.

VI. CONCLUSIONS

The epoxy bonding of GFRP laminates offers an attractive means of strengthening RC beams in flexure. Based on the results obtained from laboratory experiments, non-linear finite element analysis, modeling with artificial neural network and their discussions, the following conclusions are drawn.

- GFRP laminates properly bonded to the tension face of PSC beams can enhance the flexural strength capacity substantially. The strengthened beams exhibit an increase in flexural strength upto 24.70% with CSMGFRP, 57.24% with WRGFRP and 93.15% with UDCGFRP laminate for T-series beams and an increase of 16.74% with CSMGFRP, 24.26% with WRGFRP and 54.18% with UDCGFRP laminate for S-series .
- At any given load level, the deflections and the crack widths in the strengthened PSC beams are reduced significantly compared to the unstrengthened beams. At the ultimate load level of the reference specimens, strengthened beams exhibit a decrease of deflection upto 38.85% with CSMGFRP, 69.43% with WRGFRP and 80.89% with UDCGFRP laminate for T-series beams and a decrease of 16.59% with CSMGFRP, 35.84% with WRGFRP and 51.88% with UDCGFRP laminate for S-series .
- The reduction in crack width for T-series beams, at ultimate load level was found to be 24.68% with 3mmCSMGFRP, 48.73% with 3mm WRGFRP, 54.43% with 3mm UDCGFRP, 43.67% with 5mm CSMGFRP, 51.91% with 5mm WRGFRP and 55.70% with 5mm UDCGFRP when compared to the control beam.
- All the PSC beams strengthened with GFRP laminates experience flexural failure. None of the beams exhibit premature failure of the laminate. An examination of the crack distribution indicates that the size and density of cracks are less in the strengthened beams than in the un-strengthened beam.
- The PSC beams strengthened with externally bonded GFRP laminates provide adequate ductility to ensure a ductile mode of failure. The GFRP strengthened PSC beams exhibit an increase in deflection ductility of 30.84% and an increase in energy ductility of 59.64% with 5mm UDCGFRP with respect to the control beam.
- The ultimate loads obtained from experiments agree well with the values predicted using analytical work.

SCOPE FOR FUTURE STUDY

The present research work is significant on account of the investigation on flexural behaviour on pre-stressed concrete beams strengthened with different GFRP configurations. In future study strengthening of pre-stressed concrete beams could be done using externally bonded Hybrid Fibre Reinforced Polymer (HyFRP) Laminates, which may conquer the strength and ductility properties obtained through externally bonded Glass Fibre Reinforced Polymer (GFRP) laminates.

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