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STUDY ON THE BEHAVIOUR OF RC BEAMS STRENGTHENED USING HYBRID FRP LAMINATES OF VARYING WIDTHS

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Abstract: Fiber reinforced polymers (FRPs) are high tensile continuous fibers oriented in a desired direction in a special resin matrix. They are used as a confining reinforcement, externally bonded to the reinforced concrete (RC) beams to enhance their structural behavior. They enhance the ductility, shear and flexural capacities of the confined member. This project presents an experimental and analytical study on RC beams with external flexure strengthening by hybrid FRP sheets, which is a combination of Carbon FRP(CFRP) and Glass FRP (GFRP). The usage of hybrid FRPs provide both strength and ductility to the RC beam. The effect of the width of strengthening arrangements on the behavior of RC beams is investigated using two-point loading test. The strengthening effect of the FRP layers are interpreted using load-deflection pattern, ductility and the ultimate strength of the RC beams. The results are then compared with that of a conventional non-retrofitted specimen and the enhancement in the structural behavior of the specimen are presented. The analytical study involves finite element modelling using ABAQUS 6.14 and comparison of the results. Strengthening using hybrid FRPs is expected to enhance the life of the structure and thus cut down construction costs.

***Index Terms* – CFRP, GFRP, Hybrid FRP, Strengthening, Finite element modelling.**

I. INTRODUCTION

The damage of structural elements such as bridges, buildings due to structural inadequacies (deterioration of materials or aging, poor maintenance, earthquakes) has directed research efforts towards devising an efficient and economical technique of repairing affected structures called as strengthening. Strengthening is defined as the enhancement of the performance of deficient structural elements in a structure to reduce the effects of earthquake, corrosion, etc. and increase its durability. Several techniques have been utilized in strengthening construction in numerous ways. The choice of the method of strengthening depends largely upon the cause and the extent of their damage. Fiber reinforced polymers (FRPs) with their excellent mechanical properties are of great use for strengthening of structures.

FRP composites are made up of high tensile strength fibers embedded in an epoxy resin matrix. They provide superior resistance to corrosion, low weight, high strength to weight ratio, high mechanical strength, a fast and economical way of rehabilitation or repair of beams, columns or slabs. Surface preparation is relevant in achieving a successful strengthening interaction in FRP and concrete. Therefore, the efficiency and quality of bond between the FRP composites and concrete plays a major role in transferring the stress between concrete structures and externally bonded FRP plates. The material properties of epoxy matrix of the fibers together with the properties of concrete substrate properties such as roughness, strength, cleanliness of the concrete surface may also be responsible for the quality or reliability of bond. Due to their excellent adhesive ability to both FRP and concrete, epoxy resins are mostly selected to bond them together. Most times when epoxy adhesives are used, water, alkalis and other contaminants from the surrounding environment may react with the epoxy influencing the curing rate as well as the degree of cure. These adverse effect on the epoxy significantly result in a major draw-back in the durability and mechanical properties of the bond between the FRP and concrete. Excessive fatigue deterioration could be experienced when RC beams are subjected to load repetitions. This emphasizes the desire to improve the fatigue performance and extend the fatigue life of RC beams using the system of strengthening with fiber reinforced polymer. The purpose of this work is to provide a review on the strengthening of RC beams by using FRP technique.

1.1 FRP Strengthening

One of the most widely used strengthening methods available is the epoxy bonded fiber reinforced polymer sheet, due to its high strength, light weight and simple installation method. A Fiber Reinforced Polymer (FRP) typically consists of high tensile continuous fibers oriented in a desired direction in a special resin matrix. These continuous fibers are bonded to the external surface of the member to be strengthened in the direction of the tensile force or as a confining reinforcement normal to its axis. FRP can enhance the shear, flexural, compression capacity and ductility of the deficient member. FRP strengthening is a quick, neat, effective and aesthetically pleasing technique to rehabilitate reinforced and pre-stressed concrete structures. Unlike steel plates, FRP systems possess high resistance against physical and chemical deterioration of the structure.

1.2 Materials Used for Strengthening

As per the Indian Standard, the following materials can be used to strengthen a deficient structure:

- Carbon Fibre Reinforced Polymer (CFRP)
- Glass Fibre Reinforced Polymer (GFRP)
- Steel Fibre Reinforced Polymer (SFRP)
- Natural Fibres (e.g.: Coir Fibre)
- Textile Fibres
- Polypropylene fibre

Each of the above materials have their own advantages. To get the maximum efficiency out of these materials, a combination of two or more fibres are used, which are termed as hybrid FRPs. In this project, a combination of carbon and glass fibre reinforced materials are used.

1.3 Need for Hybrid FRPs

Compared to GFRP, CFRP with the same fiber volume fraction as GFRP shows higher strength per layer and higher stress concentration at the end of curtailment of the FRPs when attached to beams. In order to have the same strength as CFRP, the larger thickness of GFRP sheet is needed, which tends to cause early debonding failures. Therefore, FRP with low elastic modulus and high strength is needed to minimize the premature failure. This is overcome by using hybrid FRP systems, prepared based on the conception that combining layers of CFRP and GFRP sheets may induce lower elastic modulus of the retrofitted RC beams than those retrofitted with CFRP sheets only and higher strength than those with GFRP sheets only.

II. Methodology

The basic properties of cement, fine aggregate, and coarse aggregates were determined by the various experimental investigations. The mix proportion was calculated, and the beam was designed. Six cubes of size 100 mm x 100 mm were cast to determine the characteristic strength of the mix. The three beams of grade M20 and dimensions 100 mm x 150 mm x 1500 mm, one each for different strengthening arrangements, were cast for studying their structural behavior. One of the three beams was marked as the conventional specimen, without any external strengthening arrangements. The second beam was strengthened using hybrid FRP in the flexure zone throughout its width, while the third one was strengthened in the flexure zone for a width of 90 mm. For FRP strengthening, a layer of GFRP was attached, followed by the attachment of a layer of CFRP. The inner layer needs impact resistance to sudden cracking of the beam, which is provided by GFRP. The outer layer needs higher tensile strength, which is provided by the CFRP layer.

III. Laboratory Investigations

The compressive strength test was performed on the samples during 7th and 28th day by using the compressive testing machine with standard loading rate. The compressive strength results are given below.

Table1

7-days compressive strength

Cube No.	Failure Load (kN)	Compressive strength (N/mm^2)
1	196	19.6
2	176	17.6
3	187	18.7
Average		18.6

Table 2

28-days compressive strength

Cube No.	Failure Load (kN)	Compressive strength (N/mm^2)
1	242	24.2
2	226	22.6
3	248	24.8
Average		23.86

IV. Numerical Investigations

4.1 Section Geometry

ABAQUS 6.14 was used as the finite element software for modelling and analysis of the beams. 14 beams were modelled with a constant cross-section of 100 mm x 150 mm and a span of 1500 mm. 2 numbers of 12 mm diameter Fe 500 HYSD bars were provided at the bottom as tension reinforcement with a clear cover of 10 mm and the same diameter hanger bars were provided at the compression face. The CFRP and GFRP laminates were modelled using the option "lamina". Varying widths of the FRP were provided as strengthening arrangements for various beams, which are listed in Table 3. The model must accurately simulate the full response to bending loads, including any relative movement between the FRP layers and reinforced concrete beam. To enable this, three different type of elements were used to model the steel reinforcement, concrete fill and the FRP laminates. The eight-node solid element was used to model the concrete, the four-node shell element was used to model the FRP laminates and the two-node truss element was used for the steel reinforcements as shown in figure 1.

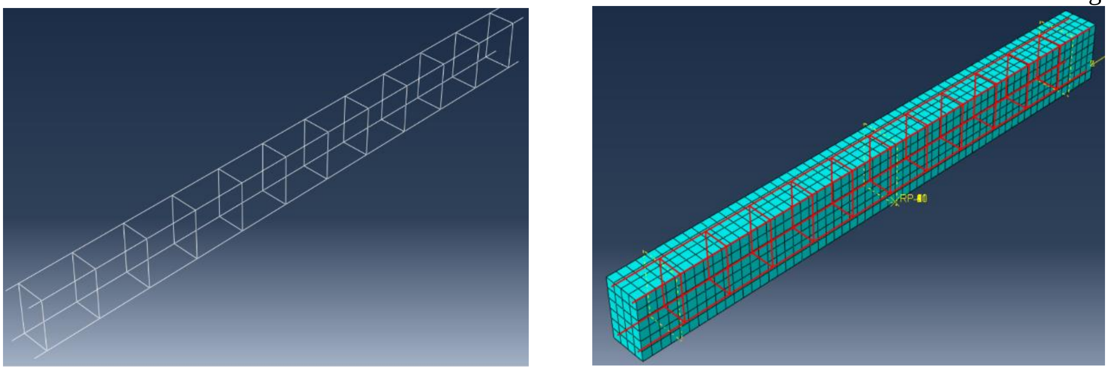


Fig.1: Finite Element model of beam (Reinforcement cage and Assembly of elements)

The details of strengthening arrangements for the RC beams are as shown in figure 2.The width of the beam (B) being constant, the width of FRP (b) is varied and different b/B ratios are obtained.

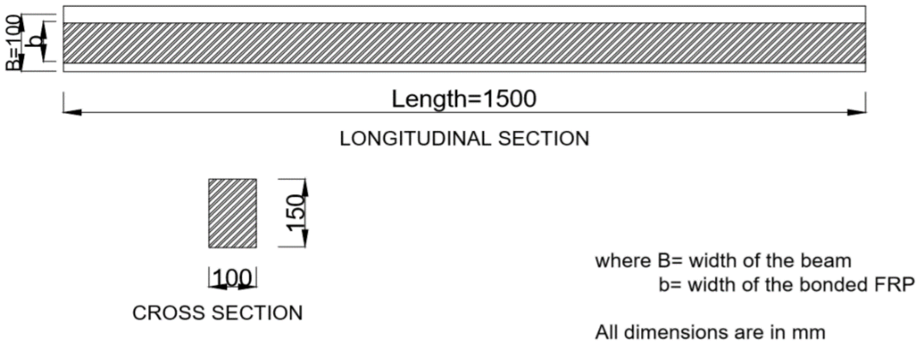


Fig.2: Details of FRP strengthening arrangement

Geometric details of finite element models are mentioned in the table 3.

Table 3: Geometric details of finite element models

SPECIMEN No.	TYPE OF STRENGTHENING	WIDTH OF FRP
Model-1	Conventional	Nil
Model-2	G-G	100 mm
Model-3	G-G	90 mm
Model-4	G-G	80 mm
Model-5	C-C	100 mm
Model-6	C-C	90 mm
Model-7	C-C	100 mm
Model-8	C-G	80 mm
Model-9	C-G	90 mm
Model-10	C-G	80 mm
Model-11	G-C	100 mm
Model-12	G-C	90 mm
Model-13	G-C	80 mm
Model-14	G-C	70 mm

4.2 Material Properties

The material properties for concrete are taken based on the past published research studies as derived from various experimental tests. Here, linear elasticity and non-linear plasticity of reinforcement steel and isotropic elasticity in combination with damaged plasticity model of concrete and plasticity of steel tube is introduced to develop a mechanical constitutive model. The physical properties of concrete are tabulated in Table 4. For the steel reinforcement, a trilinear stress -strain relationship was used with an isotropic hardening plasticity rule. Young's modulus was approximated as 2,00,000 MPa and Poisson's ratio was approximated as 0.3. the plastic plateau terminated when the strain of steel was set equal to 10 times of yield strain of the steel and stress increased up to ultimate strength of the steel, which is achieved when the strain of the steel is 0.1.

Table 4: Concrete Damaged Plasticity properties

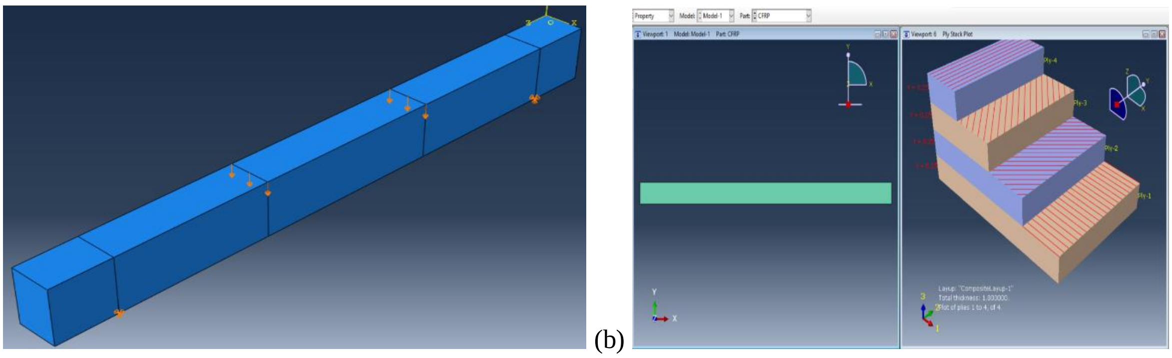
Grade of concrete	M20	Plasticity Properties	
		Dilation angle	31
Concrete Elasticity		Eccentricity	0.1
E (MPa)	22360.68	fb0/fc0	1.16
Poisson's Ratio	0.3	K	0.67
		Viscosity parameter	0.001
Concrete Compression behaviour		**Compression Damage Property**	
Yield stress (MPa)	**Inelastic strain**	**Damage parameter**	**Inelastic strain**
10.2	0	0	0
12.8	0.000077	0	0.000077
15	0.0001736	0	0.0001736
16.8	0.0002887	0	0.0002887
18.2	0.0004226	0	0.0004226
19.2	0.0005757	0	0.0005757
19.8	0.0007472	0	0.0007472
20	0.0009377	0	0.0009377
19.8	0.0011472	0.01	0.0011472
19.2	0.0013754	0.04	0.0013754
18.2	0.0016226	0.09	0.0016226
16.8	0.0018868	0.16	0.0018868
15	0.0021736	0.25	0.0021736
12.8	0.0024774	0.36	0.0024774
10.2	0.0028	0.49	0.0028
7.2	0.0031415	0.64	0.0031415
3.8	0.0035019	0.81	0.0035019
Concrete Tensile Behaviour		**Tensile Damage Property**	
Yield stress (MPa)	**Cracking strain**	**Damage parameter**	**Cracking strain**
2	0	0	0
0.02	0.0009434	0.99	0.0009434

4.3 Meshing

Three-dimensional meshes created for finite element analysis need to consist of tetrahedra, pyramids, prisms or hexahedra. Those used for the finite element difference methods usually need to consist of piecewise structured arrays of hexahedra known as multi-block structured meshes. A mesh is otherwise a discretization of a domain existing in one, two or three dimensions. Quadrilateral meshing is done to the model by fixing the global seed as 20. For concrete, the global seed is fixed as 25 and for the laminates, it is fixed as 10. The cell shape is a basic four-sided one as shown in the figure 5.1. It is most common in structured grids. Quadrilateral elements are usually excluded from being or becoming concave.

4.4 Boundary and Loading Conditions

Boundary and loading conditions used are shown in figure 3. The ends of the beam are simply supported. At the hinged end U1, U2, U3 are restrained and at the roller end U1 and U2 are restrained from translation. The beam is setup for two-point concentrated loading at one-third spans from either end. A displacement-controlled loading concept was adopted and 50 mm displacement was allowed on each of the load points.



(a) (b)

Fig.3: (a) Boundary and loading conditions (b) Stacking sequence of FRP layers

4.5 Interaction

The interaction between concrete and steel reinforcement was modelled as "Embedded", where the truss element simulating the reinforcement were assumed to be perfectly bonded to the concrete. So, the relative movement (slip) between the internal reinforcement and the concrete was not specifically modelled. Whereas, in the FRP strengthened specimen, a General Surface interaction between the outer surface of reinforced concrete beams and the inner surfaces of FRP laminates was provided with the concrete surface as the Master surface. Similarly, the second layer of FRP laminate was also modelled using the General Surface interaction tool. The shear stress at the interface of concrete and FRP is generated with a specified value of friction coefficient. A friction coefficient of 0.47 was used based on validation from a prior published study.

4.6 Analysis

Non-linear analysis was carried out by enabling the "nlgeom" option in the load step and STATIC RIKS method was created. This option forces the FEA to perform an iterative solution, updating the stiffness matrix based on the incremental nodal displacements at each of the equilibrium iterations.

V. Experimental Investigations

To study the flexural behaviour, three reinforced concrete beams of length 1500 mm and cross-section area 100 mm x 150 mm were cast. Two numbers of 12 mm diameter Fe 415 grade steel bars were provided as the compression reinforcement and tension reinforcement respectively. Two-legged 8 mm diameter stirrups were provided at 130 mm spacing throughout the length of the beam as shear reinforcement. The test was carried out in a 50T loading frame. The beams were simply supported and subjected to two-point loading over an effective span of 1200 mm. A hydraulic jack of 100 kN capacity was used to apply the load. Dial gauges were placed at the mid-span and under the load points to record the deflection of the beam during the test. The deflection of the beam to the applied load was observed and the load-deflection curve was plotted. The load was applied at a constant rate until failure and the crack pattern of the beams were noted. Experimental tests were carried out for b/B ratios of 1.0 and 0.9.

(a)  (b) 

Fig.4: Flexural strength test on beams

(a)Conventional (b) Flexure strengthened with b/B=1.0

VI. Results And Discussions

6.1 Responses From Numerical Investigation

A typical load vs deflection curve is plotted for the results obtained from analytical investigation on all the 14 specimens. The chart compares the load deflection pattern of various strengthening arrangements on the RC beams. The deflection at mid span section is considered for comparison.

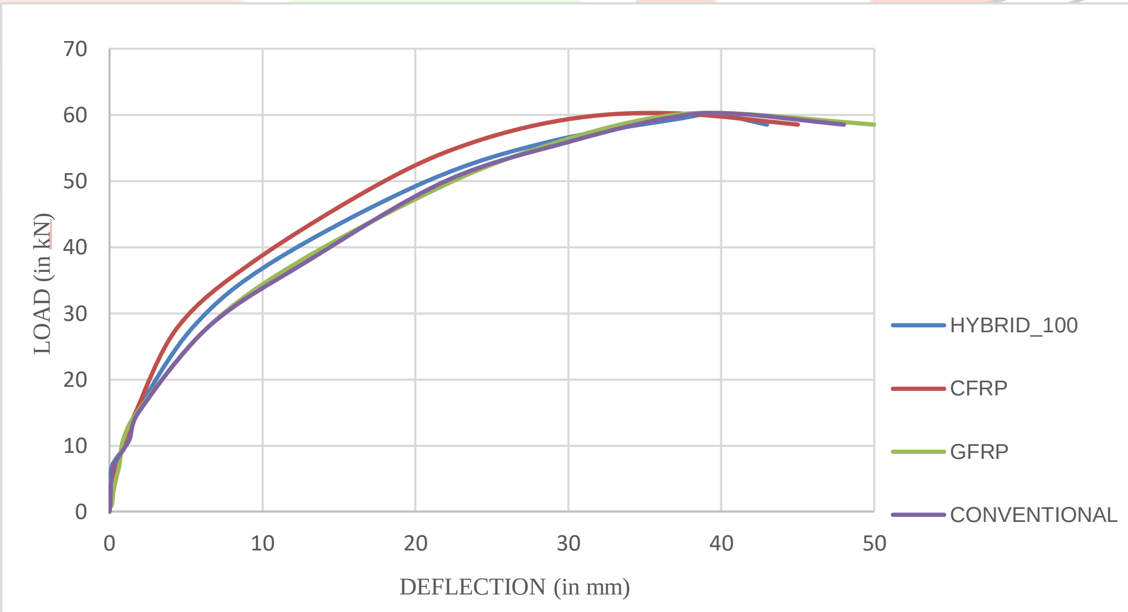


Fig.5: Mid-span load-deflection curves for different FRP retrofits obtained from numerical study

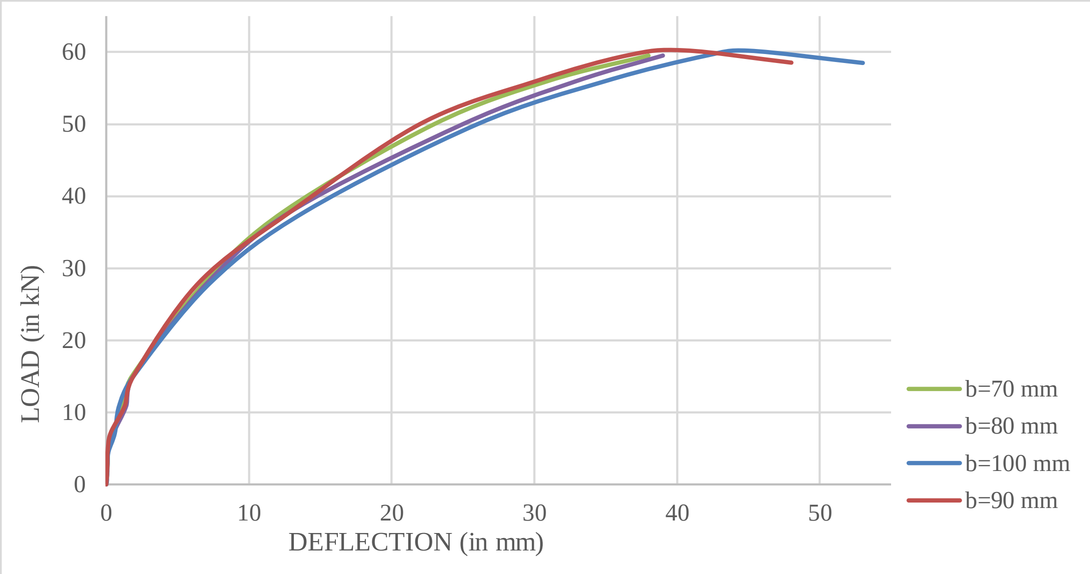


Fig.6: Mid-span load-deflection curves for varying widths of hybrid FRPs obtained from numerical study

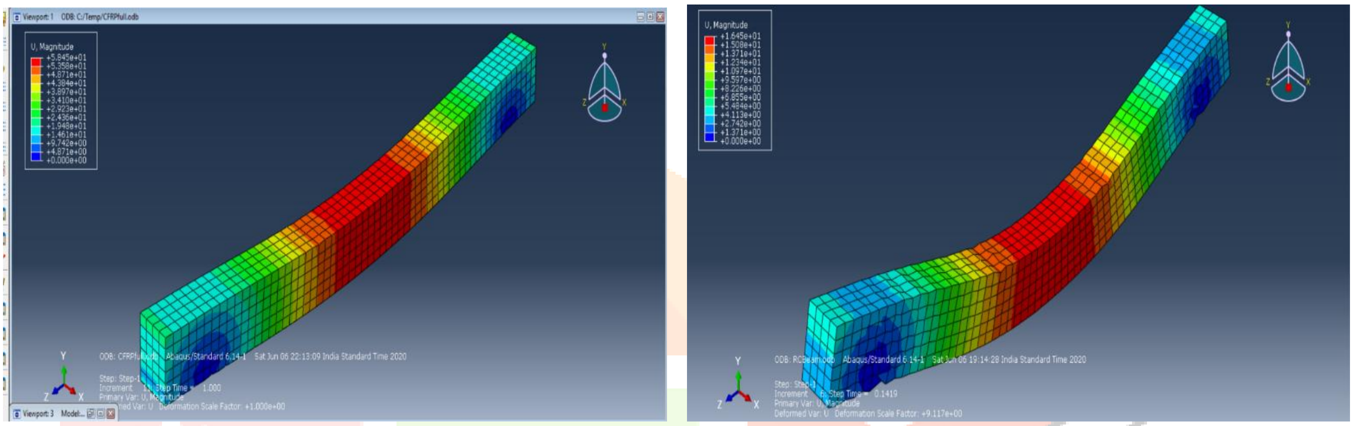


Fig.7: Deflection contour of RC beams with and without FRP strengthening

As seen above, the deflection of the beams have considerably reduced when Fiber Reinforced Polymers are used as an external strengthening system.

The ultimate load capacities of various strengthening arrangements of FRPs as obtained from numerical study are listed below in table 5.

Table 5: Ultimate load capacities RC beams with varying strengthening arrangements as obtained from numerical study

SPECIMEN No.	TYPE OF STRENGTHENING	WIDTH OF FRP	ULTIMATE LOAD (kN)
Model-1	Conventional	Nil	58
Model-2	G-G	100 mm	59
Model-3	G-G	90 mm	58
Model-4	G-G	80 mm	58
Model-5	C-C	100 mm	60
Model-6	C-C	90 mm	58
Model-7	C-C	80 mm	57
Model-8	C-G	100 mm	59
Model-9	C-G	90 mm	57
Model-10	C-G	80 mm	56
Model-11	G-C	100 mm	62
Model-12	G-C	90 mm	60
Model-13	G-C	80 mm	59
Model-14	G-C	70 mm	57

6.2 Results From Experimental Investigation

Flexural strength test was carried out on the beams in a 50 T loading frame using a hydraulic jack. The beams were loaded until failure and the deflection was noted for each load increments. Deflection of the beams corresponding to various loads were noted using a dial gauge and the load vs deflection curves were plotted. Ultimate loading capacity of each beam was also noted.

(a)  (b) 

Fig.8: Deflected shapes of the beams
(a) Conventional (b) FRP strengthened

Table 6 shows the flexural strength and energy dissipation values of the three beams respectively.

Table 6: Flexural strength and Energy dissipation (Experimental)

Beam specimen	Load capacity (kN)	Energy dissipation (kJ)	Flexural strength (N/mm^2)	Displacement Ductility (Δu - Δy) (mm)
Conventional	53	19.95	35.3	23
FRP strengthened (b/B=1.0)	65	23.5	43.3	31
FRP strengthened (b/B=0.9)	59	21.45	39.35	27

6.3 Comparison of Experimental and Numerical Results

The following graphs show the load-deflection curves of the conventional, flexure-strengthened and flexure-shear strengthened beams respectively:

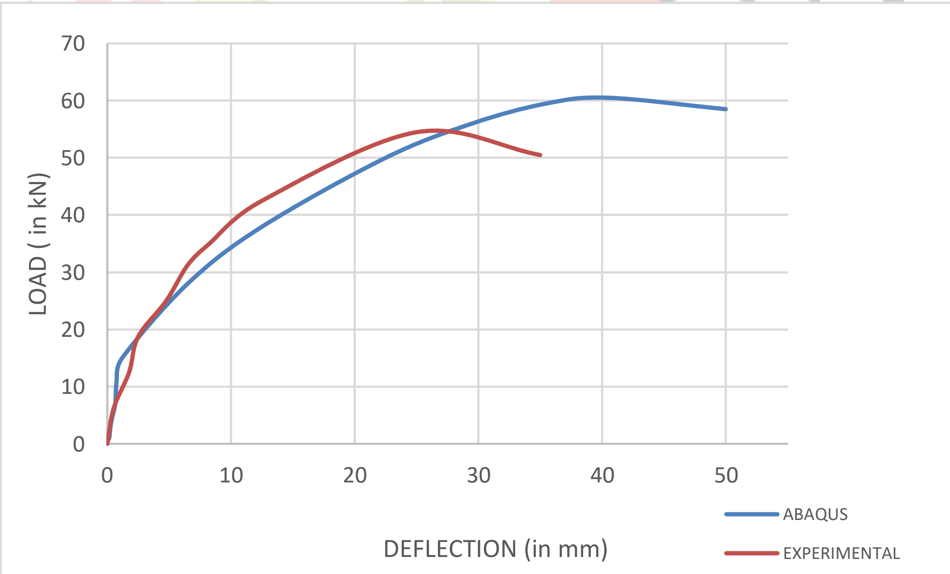


Fig.9: Experimental vs ABAQUS generated load-deflection curves for conventional beam

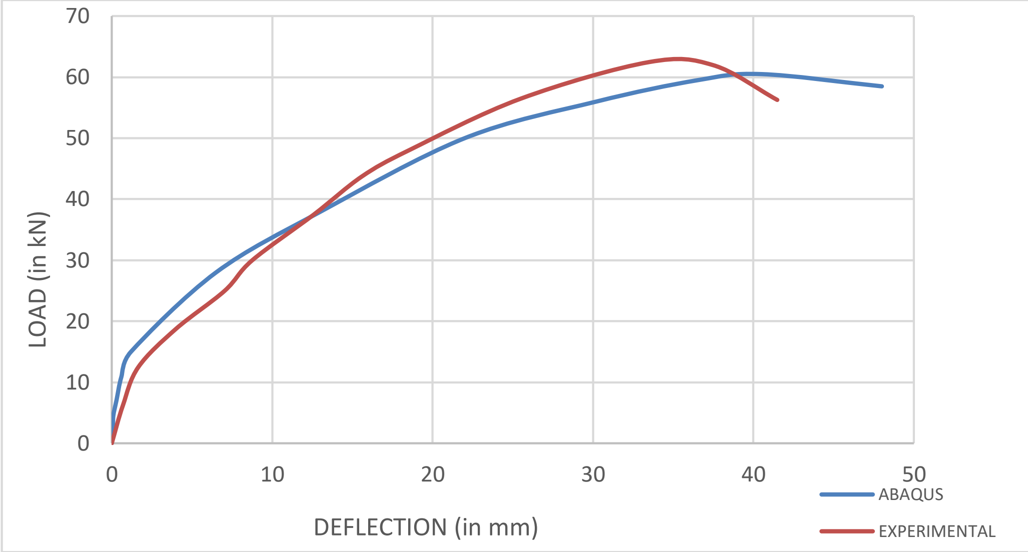


Fig.10: Experimental vs ABAQUS generated load-deflection curves for beam specimen with b=100 mm

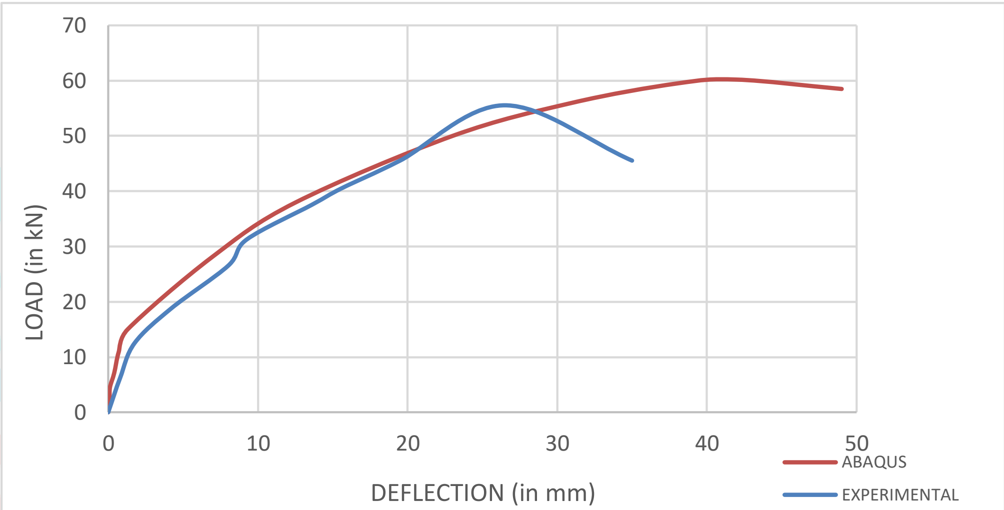


Fig.11: Experimental vs ABAQUS generated load-deflection curves for beam specimen with b=90 mm

VII. CONCLUSIONS

Based on the numerical and experimental investigations stated in the previous chapters, the following conclusions were drawn:

[1] Hybrid FRPs can be used in place of conventional FRPs in order to provide strength as well as impact resistance to the structure.

[2] The loading capacity of FRP strengthened beam (b=100 mm) increases by about 21.6% in comparison with the conventional specimen. But, the loading capacity for lower b/B values of FRP strengthening arrangements reduced as compared to the specimen with b/B=1.

[3] The failure of FRP bonded specimen were predominantly due to debonding of FRPs. FRP strengthened specimen showed an increased ductility as compared to conventional beams. Energy dissipation was also found to be higher for FRP strengthened specimen.

[4] Crushing of concrete in compression zone was found to be controlled in a FRP strengthened specimen. Also, strain hardening was found to occur, which would help in predicting the failure of a structure.

[5] It should be pointed out that the suggested Finite Element analysis can overestimate the loading capacity of the retrofitted specimen in the current study. However, it could precisely predict the displacement capacity obtained from experimental results.

[6] The larger width of FRP (i.e., for higher area of contact) allows the full establishment of the edge regions of FRP and concrete, thus increasing the load-carrying capacity. The strengthening nature of the Fiber reinforced polymer laminates may thus be attributed to the area of contact of the FRP material with the concrete structure, for a given width of the beam.

[7] There is an acceptable agreement between the Finite Element results and the experimental tests under monotonic loading until the occurrence of yielding. However, due to localized failure of FRP and uncertainties in material properties, some discrepancies were observed between the Finite Element and experimental load-displacement curves particularly in the post yielding behavior.

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