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Comparative study of flexural strength of RC beams strengthened with steel and FRP bars

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Abstract – The present paper explores the flexural performance of fiber reinforced polymer (FRP) fortified in reinforced concrete (RC) beams. The RC beams are designed and analyzed for an effective span of 3 m. The beam is subjected to linear action of three different live loads acting as two point loads on RC beam. In all nine beams, three each are strengthened with carbon FRP, glass FRP and aramid FRP bars, respectively. The three different percentage of reinforcement ratios are taken for steel bars and FRP bars. More three beams are used as control specimens are strengthened with steel reinforcement bars designed as under-reinforced RC beam. Static responses of all the beams are evaluated in terms of strength, deflection and compositeness between FRP bars and concrete. The linear and non-linear FE analysis of steel reinforcement and FRP bars beams are carried out in finite element method ANSYS software. The finite element (FE) results are verified using linear analysis method using IS 456-2000 code for steel reinforcement bars and ACI 440-2006 for FRPs bars. The results show that the FRP strengthened beams exhibit increased flexural strength. The non-linear analysis of the beams shows more deflection at centre and load point as compared to linear FEM of the RC beams strengthened with FRPs and steel bars.

Keywords: deflection, flexural strengthening, FRP bars, linear, non-linear, steel reinforcement.

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I INTRODUCTION

Fibre reinforced polymer (FRP) is a composite material consisting of a polymer matrix fortified with fibers. The most frequent types of fiber used in structural applications are glass (GFRP), carbon (CFRP) and aramid (AFRP). The GFRP is the least costly but has lower strength and significantly lower stiffness compared to other alternatives. CFRP is the stiffest, long-lasting, and costlier. AFRP has improved durability and admirable impact resistance. FRP reinforcement is accessible in different forms such as bars, grids, prestressing tendons and laminates to serve a wide range of applications.

Earlier the use of FRP was limited to defence and aerospace engineering due to its high cost, but enhance in demand for the consumption of FRP in other fields around the world has aided the growth in research for better performance of composites at low costs.

The reinforcement has high durability and stiffness while the matrix binds the fibres together, allowing stress to be relocated from one fibre to another and producing a consolidated structure.

In the last some years, FRP materials have emerged as capable alternative refurbish materials for reinforced concrete (RC) structures. FRP plates or sheets can be bonded to the outer surface of concrete structures using high strength adhesives which increases the tensile strength of the member.

The present study focuses on using CFRP, GFRP and AFRP bars as an internal reinforcing material for RC beams.

II LITERATURE REVIEW

In last decade the various research works has been carried out on performance of FRP using experimental, analytical and numerical methods.

Hamoush and Ahmad (1990) [1] analytically investigated the behaviour of damaged concrete beams strengthened by externally bonded steel plates using linear elastic fracture mechanics and the finite element method (FEM). The results indicated that the flexural cracks exist within a short region in the mid-span of the beam.

Ritchie et al. (1990) [2] experimentally studied the effectiveness of strengthening concrete beams using FRP plates. The results showed a significant increase in stiffness and ultimate strength for beams strengthened with FRP plates.

Hussain et al (1995) [3] conducted a study on the flexural behaviour of pre-cracked RC beams strengthened externally by steel plates. The effects of plate thickness and end anchorage on ductility, ultimate load and failure mode were studied. A design procedure was suggested to avoid premature failure of plate. The results showed that the repaired beams exhibited higher strength than the virgin beams; the ductility of the repaired beams decreased with increase in plate thickness; the end anchorages provided only marginal effect in improving the ultimate strength.

Patil et al. (2013) [8] studied experimentally and analytically RC deep beams subjected to two point loading with three different *L*/*D* ratios (1.5, 1.6, 1.71) using non-linear FEM. The comparison of results between FEM and experimental were made in terms of strength, flexural strain and deflection of concrete beams. It was found that the smaller the span/depth ratio, the more pronounced was the deviation of strain pattern at mid-section of the beam. As the depth of the beam increases the variation in strength, flexural stress and deflection were found to be more in case of experimental work as compared to the non-linear FEM.

Jayajothi et al. (2013) [9] carried out the non-linear FE analysis of RC beams strengthened in flexure and shear by

FRP laminates and they found that the ultimate load carrying capacity of all the strengthened beams is higher as compared to the control beams.
More and Kulkarni, (2014) [10] studied flexural behaviour of RC beams of M25 grade of concrete strengthened with fiber reinforced polymer (AFRP) polymer sheets.
Viradiya and Vora (2014) [12] investigated the RC beams strengthened with FRP laminates using non-linear FEM and experimental work. Based on the experimental and analytical results and observations, it was concluded that the ultimate load carrying capacity of the strengthened beam is higher when compared to the control beam without FRP laminates.

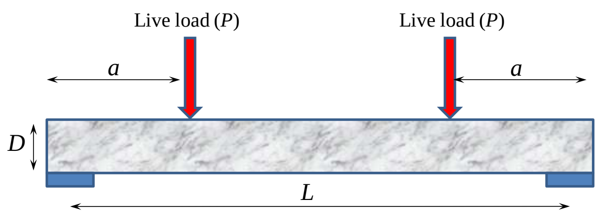
II. OBJECTIVES

The main objectives of the present study are:

- To observe the effect of strengthening of simply supported RC beam subjected to two point loads reinforced with steel, CFRP, GFRP and AFRP.
- To investigate the beam subjected to three different reinforcement ratios and static live loads. The beams are analysed using theoretical and linear and non-linear FEM using ANSYS software.
- To evaluate the load-deflection and compositeness between various FRP bars used in the present study and concrete.

III. FINITE ELEMENT MODELLING

The RC beams are analysed using FEM ANSYS software. The modeling of RC concrete beam involves defining element type for materials, real constant, material properties, loading, meshing and boundary conditions. The beam model is having length (*L*) = 3 m, cross-section 250 mm × 300 (*B* ×*D*) mm as shown in Figure 1. The quarter RC beam is modeled, taking *L* =*L*/2, *B* = *B*/2 and *D* = *D* due to symmetry as shown in Figure 1. The element types used for FE model of RC beam are shown in Table 1 [6].



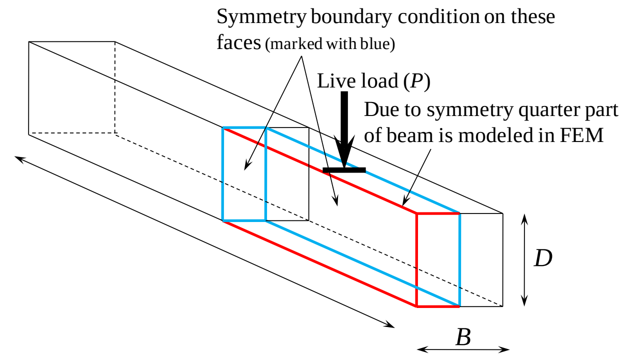


Figure 1: FEM model of RC beam.

Table 1: Element types FE model of RC beam

Material	Element type
Concrete	Solid65
Steel/CFRP/GFRP/AFRP reinforcement bars	Link 8

A Solid65 element is used for modeling concrete. This element has eight nodes in numbers with three degrees of freedom (dof) at each node translation in the nodal *x*, *y*, and *z* directions. A schematic view of the Solid65 element is shown in Figure 2.

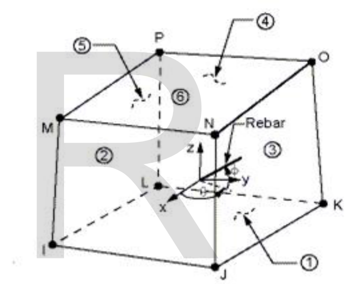


Figure 2: Solid65 element used for modeling concrete.

A Link8 element is used for modeling steel, CFRP, GFRP and AFRP reinforcement bars is shown in the Figure 3. This element has two nodes with three dof translations in the nodal *x*, *y*, and *z* directions.

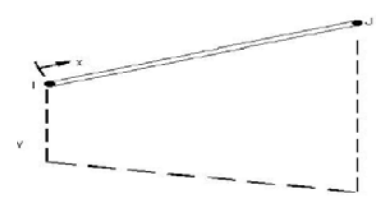


Figure 3: Link8 element for modeling reinforcement bars.

The material properties of concrete and steel are taken as per IS 456-2000 [4] and FRPs are taken from ACI 440-2006 [5] as shown in Table 2. The characteristic compressive strength of the concrete is taken as 25 N/mm^2 corresponding to M25 grade of concrete.

Table 2: Material properties

Parameters	Concrete	Steel	AFRP	AFRP	AFRP
Unit wt. (N/mm^2)	2.5×10^{-5}	7.85×10^{-5}	1.6×10^{-5}	2.1×10^{-5}	1.4×10^{-5}

Ultimate compressive strength (N/mm^2)	25	NA	NA	NA	NA
Tensile strength (N/mm^2)	2.5×10^{-4}	2×10^{-5}	1.52×10^{-5}	4.14×10^{-4}	8.27×10^{-4}
Elastic modulus (N/mm^2)	22	415	2070	552	1172
Poisson's ratio	0.2	0.3	0.2	0.2	0.2

To obtain accurate outcomes from the Solid 65 element, the use of a rectangular mesh is recommended. Hence, the mesh is set up such that square or rectangular elements are formed. No meshing is carried out for the reinforcement, because individual elements are created in the modeling. The meshing of the beam is shown in Figure 4.

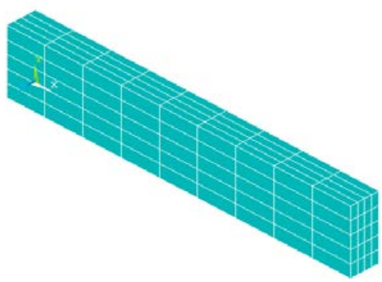


Figure 4: Meshing of finite element beam model.

In order to assure that the model acts the same way as the investigational beam, boundary conditions and loading need to be applied. The beam is simply supported at the ends and two point loading is applied at symmetrical position in the form of concentrated load along the line of action of load. Boundary conditions are required to constraint the model to get a unique solution.

In all nine beams, three each are strengthened with CFRP, GFRP and AFRP bars, respectively. More three beams are used as control specimens are strengthened with steel reinforcement bars designed as under-reinforced RC beam. Table 3 shows the details of applied live loads and reinforcement ratios [4, 5]. The reinforcement ratio for FRP beams is less than steel reinforcement.

Table 3: Details of reinforcement ratio and live load on beam

Beam	Live load (kN)	Reinforcement ratio (%)			
		Steel	CFRP	GFRP	AFRP
B1, B4, B7, B10	7.5	0.27	0.17	0.27	0.17
B2, B5, B8, B11	9.8	0.35	0.27	0.37	0.27
B3, B6, B9, B12	12.1	0.41	0.37	0.47	0.37

The reinforcement details of beam specimens are shown in Table 4. In top and bottom reinforcement for beam B1 to B3 steel is used, beam B4 to B6 CFRP is used, beam B7 to B9 GFRP is used and beam B10 to B12 AFRP is used.

Table 4: Details of beam reinforcement

Beam	Main reinforcement	Reinforcement ratio (%)	Stirrups
B1	4 -Ø 8 mm	0.27	Ø8 mm @ 300mm
B2	2 -Ø 8 mm & 2 -Ø 10 mm	0.35	Ø8 mm @ 300mm
B3	4 -Ø 10 mm	0.41	Ø8 mm @ 300mm
B4	4 -Ø 6.4 mm	0.17	Ø6.4 mm @ 300mm
B5	2 -Ø 6.4 mm & 2 -Ø 9.5 mm	0.27	Ø6.4 mm @ 300mm
B6	4 -Ø 9.5 mm	0.37	Ø6.4 mm @ 300mm
B7	5 -Ø 6.4 mm	0.27	Ø6.4 mm @ 300mm
B8	3 -Ø 6.4 mm & 2 -Ø 9.5 mm	0.37	Ø6.4 mm @ 300mm
B9	5 -Ø 9.5 mm	0.47	Ø6.4 mm @ 300mm
B10	4 -Ø 6.4 mm	0.17	Ø6.4 mm @ 300mm
B11	2 -Ø 6.4 mm & 2 -Ø 9.5 mm	0.27	Ø6.4 mm @ 300mm
B12	4 -Ø 9.5 mm	0.37	Ø6.4 mm @ 300mm

IV. RESULTS AND DISCUSSIONS

In order to check the accuracy of the present FEM model of the linear RC beam, the FEM results are compared with the theoretical approach [11]. The beam is analysed using theoretical approach based on IS 456-2000 and ACI 440-2006. For a simply supported beam with two point loading condition the deflection is calculated as [7]:

Deflection at centre $$Wa[3l^2 - 4a^2]/24EI \qquad (1)$$

Deflection at load point – $$Wa^2[3l - 4a]/6EI \qquad (2)$$

Table 5 (a) and (b) show the comparison of deflection at centre and load point, respectively based on theoretical and linear FEM. It is seen that linear FEM and theoretical values of deflection are having very small difference. This validates the present FEM RC beam model for FRPs and steel bars.

Figure 5 shows the centre point deflection for RC beam subjected to three different live loads using linear FEM. The deflection values are compared for different FRPs. with the steel reinforcement bars. Figure 6 shows the load point deflection for RC beam subjected to three live loads using linear FEM. The central deflection values are more than the load point deflection. In case of beams with FRPs the deflection values are almost same as steel reinforcement beam but the percentage of reinforcement ratio is comparatively less.

Table 5:

(a) Deflection at centre (mm)

Beam	Load (kN)	Deflection at centre (mm)							
		Steel		CFRP		GFRP		AFRP	
		ANSYS	Theoretical	ANSYS	Theoretical	ANSYS	Theoretical	ANSYS	Theoretical
B1,B4,B7,B10	7.5	0.081	0.081	0.093	0.098	0.120	0.376	0.10	0.17
B2,B5.B8,B11	9.8	0.116	0.100	0.139	0.124	0.156	0.472	0.15	0.22
B3,B6.B9.B12	12.1	0.163	0.12	0.174	0.150	0.57	0.567	0.19	0.27

(b) Deflection at load point (mm)

Beam		Deflection at load point (mm)

		Steel		CFRP		GFRP		AFRP	
		ANSYS	Theoretical	ANSYS	Theoretical	ANSYS	Theoretical	ANSYS	Theoretical
B1,B4,B7,B10	7.5	0.077	0.067	0.088	0.088	0.115	0.326	0.10	0.16
B2,B5.B8,B11	9.8	0.11	0.084	0.132	0.111	0.149	0.406	0.14	0.20
B3,B6.B9.B12	12.1	0.154	0.10	0.165	0.132	0.56	0.486	0.18	0.24

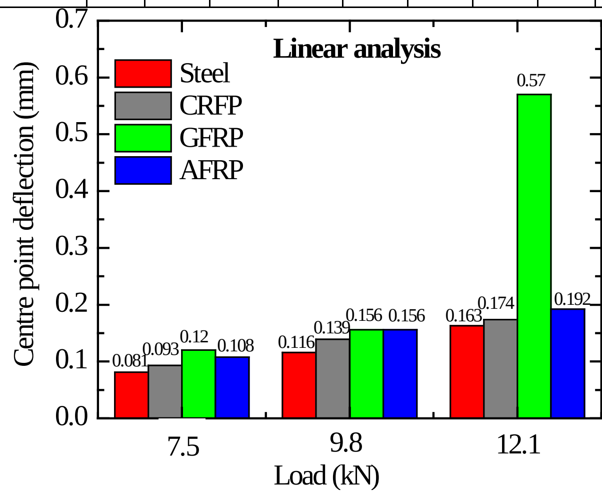


Figure 5: Load Vs centre point deflection for linear FEM.

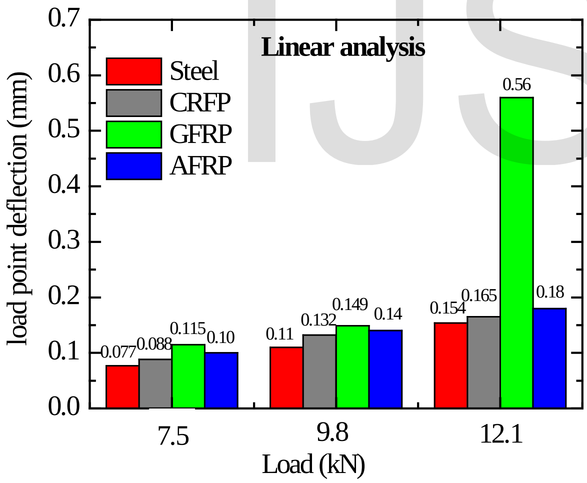


Figure 6: Load Vs load point deflection for linear FEM.

Figure 7 shows the centre point deflection for RC beam subjected to three different live loads using non-linear FEM. The deflection values are compared for different FRPs. with the steel reinforcement bars. Figure 8 shows the load point deflection for RC beam subjected to three live loads using non-linear FEM. The centre point deflection values are more than the load point deflection. In case of non-linear FEM the magnitude of deflection is more than linear FEM.

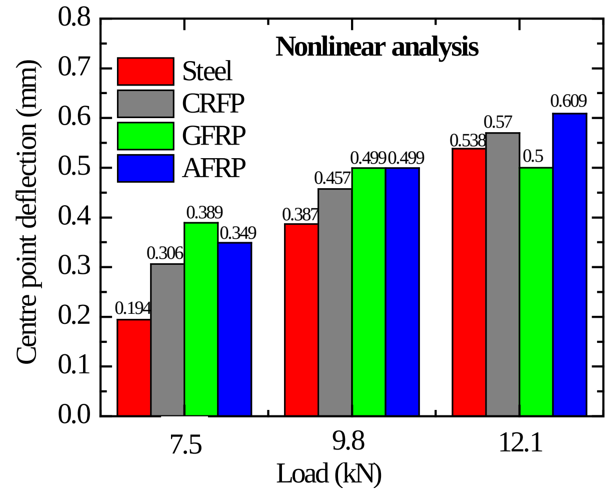


Figure 7: Load Vs centre point deflection for non-linear FEM.

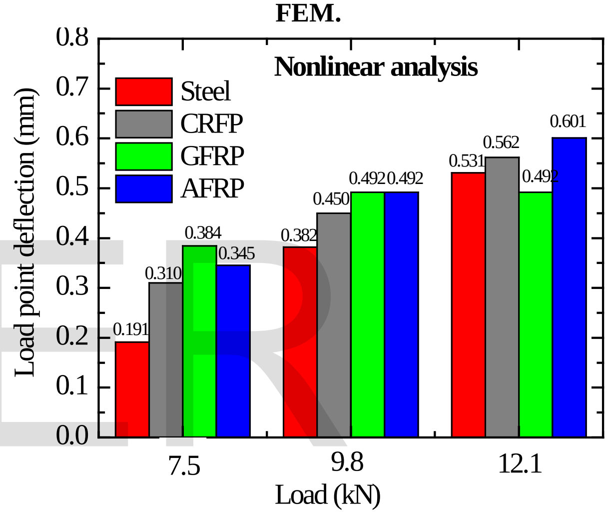


Figure 8: Load Vs load point deflection for non-linear FEM.

V. CONCLUSIONS

The flexural performance reinforced concrete (RC) beams reinforced with carbon FRP, glass FRP aramid FRP and steel bars are investigated using linear and non-linear FEM. Static responses of all the beams are evaluated in terms of strength, deflection and compositeness between FRP bars and concrete. From the present study the following conclusions are arrived:

(a) The results of deflection of RC beam using FEM are in good agreement with the theoretical results.
(b) In case of CFRP, GFRP and AFRP the ultimate load bearing capacity of the beam is significantly increased as per codal provisions.
(c) In case of beams with FRPs the deflection values are almost same as steel reinforcement beam but the percentage of reinforcement ratio is comparatively less. For the same load CFRP and AFRP bars requires 10% to 33% less reinforcement ratio as compared to steel

reinforcement bars. And also for the same load GFRP requires greater reinforcement ratio as compared to steel.

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