Finite Element Analysis of Concrete Beams Reinforced with Fibre Reinforced Polymer Bars

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***Abstract*—Fibre reinforced polymer (FRP) bars have become commercially available as reinforcement for concrete over the last decades. These bars have several important advantages over conventional reinforcing steel such as high tensile strength, light weight, non-corrosiveness, anti-fatigue, non-magnetic, electrical insulation, small creep deformation and specific gravity. All these advantages are the main reasons of their incorporation into the civil engineering structures. The FRP bars are generally made of glass, carbon and aramid fiber reinforced composites can be readily formed into complex shapes through the pultrusion manufacturing process in order to increase the strength. In this project behavior of concrete beams reinforced with Glass fibre reinforced polymer (GFRP) bars and carbon fibre reinforced polymer (CFRP) bars of different surface configurations by varying the reinforcement ratio are analyzed using non linear finite element analysis in ANSYS workbench 16.1. CFRP bars and GFRP bars of three different cross-sections are considered. Circular section without longitudinal ribs and with two and four longitudinal ribs. Total twenty eight beams of M25 grade concrete is modeled. Also found the ultimate load carrying capacity and deformation and studied the load deflection behavior of all the beams and comparison is done between the reinforced concrete beams. From ANSYS result, it is found that beam reinforced with CFRP bar of circular section with four longitudinal ribs of 4% reinforcement ratio increases the ultimate strength of the beam.**

Keywords—concrete beams; GFRP bars; CFRP bars; Finite element analysis; ANSYS

I.INTRODUCTION

An important feature of fibre reinforced polymer composites (FRP) is their extremely high corrosion resistance. This makes them suitable for use in structures subjected to severe environmental exposure. Applications for FRP bars as internal reinforcement in concrete structural members include parking garages, multi-storey buildings and industrial structures. In many of these applications provision of appropriate fire resistance is one of the major design requirements. Similar to other materials, the properties of Fiber Reinforced Polymer composite materials deteriorate when exposed to fire. One of the major concerns with using FRP reinforcing bars in building construction is their early loss of strength and stiffness at elevated temperatures. There is very little information in literature on the variation of strength and stiffness of FRP with temperature. Fiber reinforced polymer (FRP) reinforcement in the form of longitudinal and transverse reinforcement, are currently being developed for use in new buildings and bridges. The major driving force behind this development is the superior performance of FRPs in corrosive environments. FRP reinforcement has high strength-to-weight ratio, favorable fatigue strength, electro-magnetic transparency low relaxation characteristics when compared with steel reinforcement, offering a structurally sound alternative in most applications. However, FRP reinforcement shows linear stress-strain characteristics up to failure, without any ductility. This poses serious concerns about their applicability to earthquake resistant structures, where seismic energy is expected to be dissipated by inelasticity in members. Reinforced Concrete is a very common building material for the construction of facilities and structures. As complement to concrete's very limited tensile strength, steel reinforcement bar has been an effective and cost-efficient reinforcement. However, insufficient concrete cover, poor design or workmanship, and presence of large amounts of aggressive agents including environmental factors all can lead to cracking of the concrete and corrosion of the steel rebar. For many years, there have been many studies on this corrosion issue, and the interest in FRP (Fiber Reinforced Polymer) has arisen recently as prospective substitute for steel. Using pultrusion process FRP bars can be deformed into different shapes. Surface configurations of FRP bars effect the strength of concrete beams.

II.LITERATURE REVIEW

Nasr Z. Hassan.et.al (2017)[11]Finite element analysis has been used in order to study this problem. Fifty-seven beams analyzed using finite element program ANSYS V12. The analysis results compared with fifteen experimental beams had been done by Ibrahim. Study beams have opening width and height of dimensions 200x100 mm and 300x100 mm. The centerline of the opening is at distance of 225, 300, 350 and 400 mm from the near support. Strengthening of all beams with opening came out to six types of different scheme around the opening using fiber-reinforced polymer (FRP). Scheme 1 is vertical and horizontal carbon fiber sheets around the opening, scheme 2 is inclined at 45 carbon fiber sheets around the opening in addition to horizontal one, schemes 3 and 4 are same of schemes 1 and 2 respectively but with glass fiber sheets, while schemes 5 and 6 are same as schemes 3 and 4 respectively but with an additional strengthening at flexural area at the middle of the beam with U shape. The reinforced concrete beams were modeled in 'ANSYS V12' Program under statical load. The failure loads, crack pattern, strain progress, mode of failure and energy absorption were analyzed here in this study.

Ibrahim M. Metwally et.al (2015)[4] presents numerical investigation of twelve large scale concrete deep beams internally reinforced with GFRP bars without web reinforcement failed in shear which were experimentally tested and collected from literature. The collected specimens cover several parameters which usually influenced strength and behavior of deep beams as shear span/depth ratio, the reinforcement ratio, the effective depth, and the concrete strength. Concrete deep beams are generally analyzed using conventional methods such as empirical equations or strut and tie models. These methods however do not take into account the redistribution of forces resulting from non-linear materials' behaviors. To address this issue, non-linear finite element analysis that incorporates non-linear material behavior as ABAQUS package is used.

Maher A. Adam et.al (2015)[5] presents an experimental, numerical and analytical study of the flexural behavior of concrete beams reinforced with locally produced glass fiber reinforced polymers (GFRP) bars. A total of ten beams, measuring 120 mm wide 300 mm deep and 2800 mm long, were cast and tested up to failure under four-point bending. The main parameters were reinforcement material type (GFRP and steel), concrete compressive strength and reinforcement ratio. The mid-span deflection, crack width and GFRP reinforcement strains of the tested beams were recorded and compared. The test results revealed that the crack widths and mid-span deflection were significantly decreased by increasing the reinforcement ratio. The ultimate load increased by 47% and 97% as the reinforcement ratio increases. The recorded strain of GFRP reinforcement reached to 90% of the ultimate strains. A non-linear finite element analysis (NLFEA) was constructed to simulate the flexural behavior of tested beams, in terms of crack pattern and load deflection behavior. It can be considered a good agreement between the experimental and numerical results was achieved.

III. METHODOLOGY

This project is carried out on beams reinforced with FRP bars to determine the total deformation, and ultimate load obtained in the structure analytically using ANSYS workbench software package.

A.Review of Literature

Various literatures were studied and reviewed and the research gap was identified.

B.Research Gap Identification

In all the reviewed literatures concrete beams are reinforced with GFRP bars. Many research have been carried out related to FRP bars. Here, in this project, non-linear finite element method using the software ANSYS workbench is used to determine deformation and ultimate load capacity of twenty eight concrete beams of size 1500x200x250 mm reinforced with steel bars of circular cross section, glass fiber reinforced polymer (GFRP) bars and carbon fibre reinforced bars (CFRP) of circular section, circular section with two longitudinal ribs and circular section with four longitudinal ribs and with and without longitudinal ribs by varying reinforcement ratio (0.5%, 1%, 1.5% and 2%) will be modeled and analyzed using ANSYS software to determine the total deformation and ultimate load carrying capacity developed in the reinforced concrete beam and load deflection behavior of the different concrete beams modeled and is then compared among themselves to find the best cross section of bar to be used for reinforcement.

C.Validation

The validation on the referred paper, "Analytical and experimental flexural behavior of concrete beams reinforced with glass fiber reinforced polymers bars" is done.

D.Modeling

ANSYS Workbench 16.1 is used to model the concrete beams and 28 different models are considered. Concrete beams reinforced with reinforced with steel bars of circular cross section, glass fiber reinforced polymer (GFRP) bars and carbon fibre reinforced bars (CFRP) of circular section, circular section with two longitudinal ribs and circular section with four longitudinal ribs by varying the reinforcement ratio by 0.5%, 1%, 1.5% and 2% are modeled.

E.Analysis

After the modeling, analysis is carried out in ANSYS Workbench. Non-linear static analysis is carried out.

F.Comparison of parameters

The parameters such as ultimate load carrying capacity and corresponding deflection of different concrete beam models are compared.

G.Results and discussions

Ultimate load carrying capacity and deformation obtained for all the concrete beams are analyzed and discussed.

IV. MODELING AND ANALYSIS

Finite element analysis (FEA) includes modeling the beam, defining the element type for materials, real constant, material properties, meshing loading and boundary conditions. In order to accurately simulate the actual behavior of the concerned concrete beams, all its components such as concrete beam, steel bars, FRP bars and stirrups have to be modeled properly. Meanwhile, choosing the element types and mesh size are important as well in building the model to provide accurate results with reasonable computational time.

A.Finite element analysis

Finite element analysis is a numerical method for analyzing complex structural and thermal problems. Like homogeneous materials, composite materials can also be analyzed using pre- and post-processor facilities of ANSYS to study its behavior under different load condition. The displacements of the concrete structures are small compared to the dimensions of the structure and hence in the present study geometric nonlinearity is neglected. Since the concrete is a non-homogeneous material and behaves linearly over a small percentage of its strength, material non linearity is considered. With the aid of nonlinear finite element analysis, it is possible to study the behavior of concrete structures up to the ultimate load range. This leads to the optimum design of the concrete structures. The load - deformation relationships can be used to forecast the behavior of the structures.

B.Finite element analysis

The finite element approach a numerical method for solving differential equation generated by theories of mechanics such elasticity theory and strength of materials .The basis of a finite element method is the representation of the body or a structure by an assemblage of subdivisions called finite elements. This is usual done using numerical approximation in structural analysis is the finite element method(FEM). FEM is best understood from is practical application known as finite element analysis(FEA). FEA as applied in engineering is a computational tool for performing engineering analysis. Non linear analysis gives enhanced data of serviceability and ultimate strength.

C.ANSYS

ANSYS Workbench is used for modeling. ANSYS Workbench is a software environment for performing structural, thermal and electromagnetic analyses. For modeling concrete, ANSYS provides an element which replicates the behavior of concrete. The element also takes into account the non linear material properties of concrete as well as the non-linearity of large deflections. It also allows for the modeling of reinforcement within the elements. This capability is used to model the mesh. Concrete is modeled using 3 dimensional 8 noded solid element SOLID 65. Reinforcing bar is modeled using beam element BEAM 188. All calculations were made with FEM by creation of a friction interface between the composite rebar and concrete.

D.Modeling

The model of 1500mm long with a cross section of 200 mmx250 mm is studied. Finite element model of the beam is shown in fig 1. Concrete beams reinforced with steel bar of circular section, GFRP bar of circular section with 2 and 4 longitudinal ribs and CFRP bar of circular section with 2 and 4 longitudinal ribs with reinforcement ratio 0.5%, 1%, 1.5% and 2% are modeled and analyzed using ANSYS workbench 16.1.

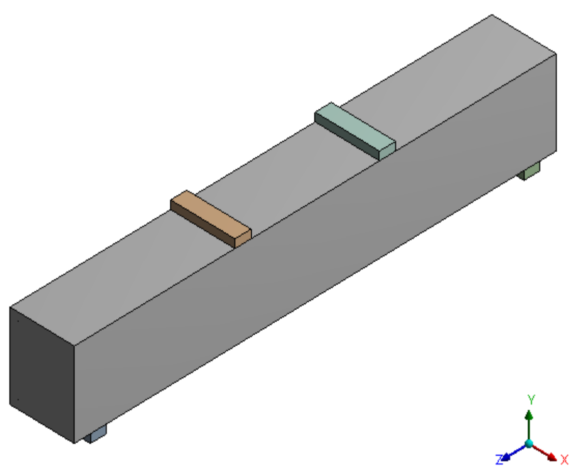

Fig. 1.ANSYS model of beam

Twenty eight models of concrete beams reinforced with steel bar of circular section, GFRP bar and CFRP bar of circular section with 2 and 4 longitudinal ribs with reinforcement ratio 0.5%, 1%, 1.5% and 2%considered are shown in table 1.

TABLE 1 TWENTY EIGHT MODELS CONSIDERED IN THIS PROJECT

No. of Models	Type of bar	Section	Reinforcement ratio
1	Steel	Circular section	0.5%
2	Steel		1%
3	Steel		1.5%
4	Steel		2%
5	GFRP	Circular section	0.5%
6	GFRP		1%
7	GFRP		1.5%
8	GFRP		2%
9	CFRP	Circular section	0.5%
10	CFRP		1%
11	CFRP		1.5%
12	CFRP		2%
13	GFRP	Circular section with 2 longitudinal ribs	0.5%
14	GFRP		1%
15	GFRP		1.5%
16	GFRP		2%
17	CFRP	Circular section with 2 longitudinal ribs	0.5%
18	CFRP		1%
19	CFRP		1.5%
20	CFRP		2%
21	GFRP	Circular section with 4 longitudinal ribs	0.5%
22	GFRP		1%
23	GFRP		1.5%
24	GFRP		2%
25	CFRP	Circular section with 4 longitudinal ribs	0.5%
26	CFRP		1%
27	CFRP		1.5%
28	CFRP		2%

E.Details of the specimen

Beam of size 1500x200x250mm is modeled. Flexural reinforcing bar is 6mm diameter and is spaced a 110mm c/c.

1)Material modeling

The material properties of the components considered are detailed in table 2, table 3 and table 4. In all cases, the ultimate strain of the concrete at failure was taken as 0.0035 and the Poisson's ratio of concrete taken is 0.15. A multi-linear isotropic stress-strain relation is used for modeling concrete material in compression. The Poisson's ratio was assumed to be 0.3 for steel reinforcement. For stirrups and loading plates, the stress-strain relation was considered linear.

a) Concrete

For concrete, ANSYS requires input data for material properties as shown in table 5.1 below. The grade of concrete (fck) is M25 and Fe415 grade of steel (fy) is used.

TABLE 2. PROPERTIES OF CONCRETE

Properties	Concrete
Modulus of elasticity, Ec	25000 MPa
Poisson's ratio, μ	0.15

b) Fibre reinforced polymer bars

The material properties assigned for the FRP materials- CFRP and GFRP bars used for the study.

TABLE 3. PROPERTIES OF CFRP AND GFRP

Properties	CFRP	GFRP
Modulus of elasticity	165000 MPa	21000 MPa
Tensile strength	2300 MPa	510 MPa
Poison's ratio, μ	0.3	0.26

c)Steel reinforcement

Elastic modulus and poisson's ratio for the steel reinforcement used in this FEM study are given in table 4.

TABLE 4. PROPERTIES OF STEEL

Properties	Steel
Young's modulus	200000 MPa
Poisson's ratio, μ	0.3

Steel plates were added at support locations and loading points in the finite element models to provide a more even stress distribution. An elastic modulus equal to 200,000 MPa and Poisson's ratio of 0.3 were used for the plates. The steel plates were assumed to be linear elastic materials. Structural steel grade of Fe250 is used.

2) Finite element type and mesh

To obtain an accurate simulation of the actual behavior of the concrete beam, the elements composing the finite element model had to be chosen properly. The mesh size is carefully selected to obtain high accuracy of results with reasonable computational time. Meshed view is shown in fig. 2. The aspect ratio of the used solid elements was kept as possible within the recommended range between 1 and 3. Both material and geometric non- linearity were considered in the analysis. Concrete is modeled using 3 dimensional 8 noded solid element 65. Reinforcing bar is modeled using beam element BEAM 188.

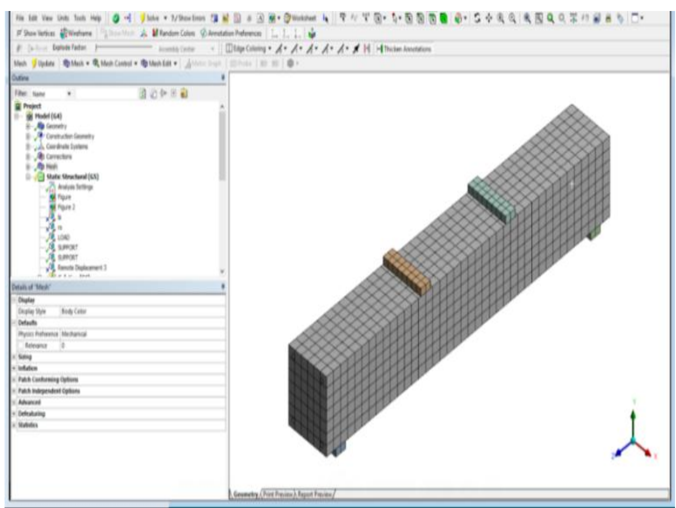

Fig. 2.Meshed view

3) Loading and boundary condition

Two point loading is applied to the concrete beam. Modeling of boundary condition are must in ANSYS analysis and the most critical aspect in achieving sensible, reliable data from a finite element method. Therefore simply supported beam is taken for analysis. Loading and supports are shown in fig 3.

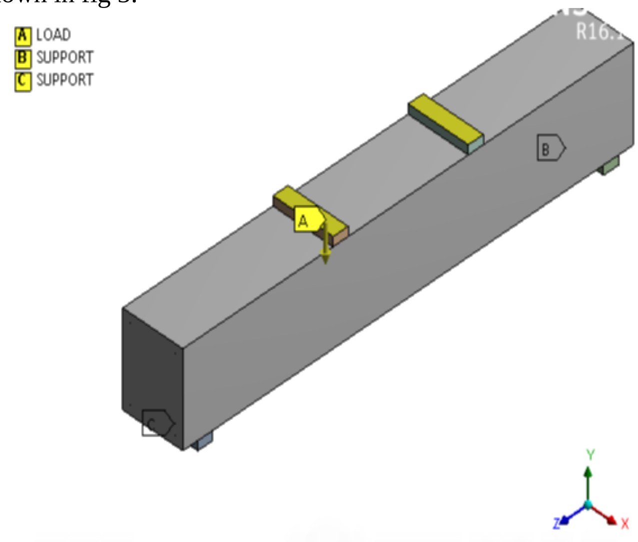

Fig. 3.Loading and supports

F. Modeling of concrete beams reinforced with CFRP and GFRP bars of circular section with two longitudinal ribs.

Concrete beams reinforced with steel bar of circular section, GFRP bar of circular section with 2 longitudinal ribs and CFRP bar of circular section with 2 longitudinal ribs with reinforcement ratio 0.5%, 1%, 1.5% and 2% . Reinforcement ratio is the ratio of the area of bar provided to the area of section of beam. Bar modeled with two longitudinal ribs is shown in fig. 4. Both CFRP and GFRP bar are modeled with four longitudinal ribs. Height of the rib provided is 4mm and width is 2.5mm.

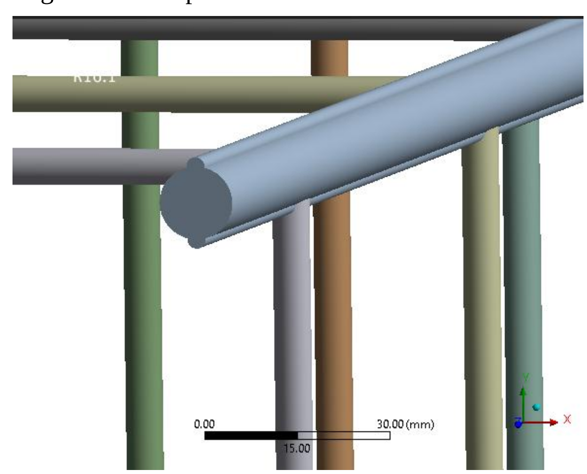

Fig. 4.Bar of circular section with 2 longitudinal ribs

G. Modeling of concrete beams reinforced with CFRP and GFRP bars of circular section with four longitudinal ribs.

Concrete beams reinforced with steel bar of circular section, GFRP bar of circular section with 4 longitudinal ribs and CFRP bar of circular section with 4 longitudinal ribs with reinforcement ratio 0.5%, 1%, 1.5% and 2% . Bar modeled with four longitudinal ribs is shown in fig. 5. Both CFRP and GFRP bar are modeled with four longitudinal ribs. Height of the rib provided is 4mm and width is 2.5mm.

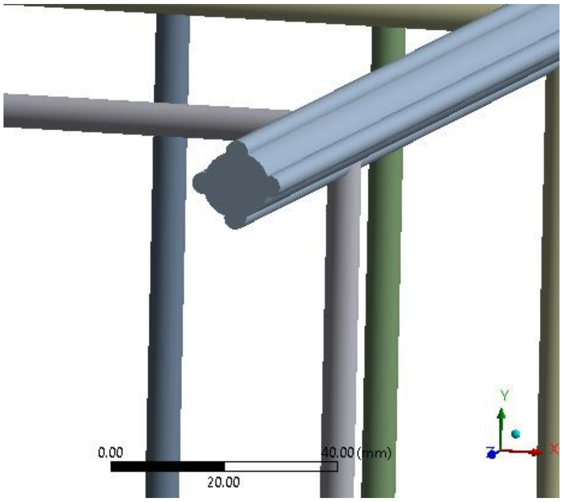

Fig. 5.Bar of circular section with 4 longitudinal ribs.

H. Analysis

The structure is modeled using ANSYS workbench 16.1. ANSYS Workbench provides superior CAD connectivity, meshing and an easy framework to perform design optimization. After analysis, the results are drawn and graphs have been potted in Microsoft Excel using chart tools option.

V.RESULT AND DISCUSSION

Analysis of concrete beams reinforced with steel bar of circular section with reinforcement ratio 2% is done. When the load is applied, the obtained deflected shape of the concrete beam is shown in fig. 6.

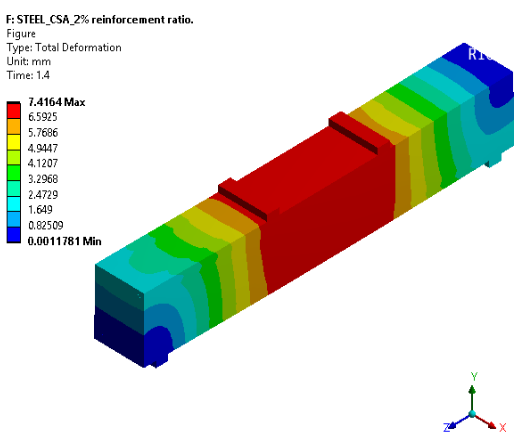

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Fig. 6.Deformation developed in concrete beam reinforced with steel bar of circular section with reinforcement ratio 2%.

Analysis of concrete beams reinforced with GFRP bar of circular cross section with 4 ribs of reinforcement ratio 2% is done. When the load is applied, the obtained deflected shape of the concrete beam is shown in fig. 7.

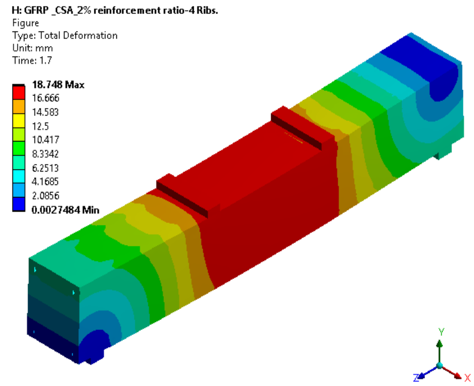

Fig. 7.Deformation developed in concrete beam reinforced with GFRP bar of circular cross section with 4 ribs of reinforcement ratio 2%.

Analysis of concrete beam reinforced with CFRP bar of circular cross section with 4 ribs of reinforcement ratio 2% is done. When the load is applied, the obtained deflected shape of the concrete beam is showed in fig. 8.

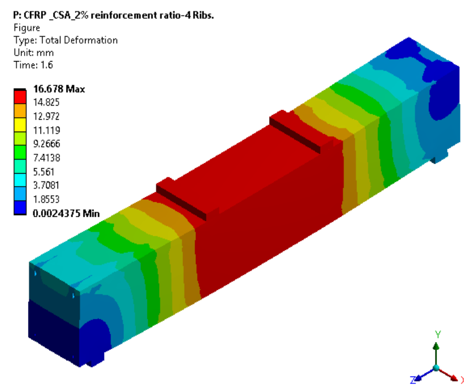

Fig 8.Deformation developed in concrete beam reinforced with CFRP bar of circular cross section with 4 ribs of reinforcement ratio 2%.

The load v/s deflection graph plotted for the beams reinforced with steel bars of 0.5%, 1%, 1.5% and 2% is shown in fig. 9.

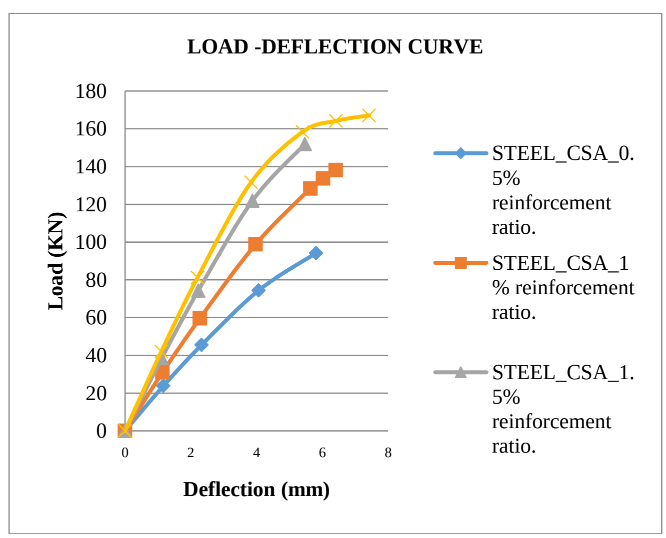

Fig. 9.load v/s deflection

From figure 9 it is clear that beam reinforced with steel bar of 2% reinforcement ratio undergoes less deflection compared to beams reinforced with steel bar of reinforcement ratio 0.5%, 1% and 1.5%.

The load v/s deflection graph is plotted for the beam reinforced with GFRP bar of circular cross section with 4 ribs of reinforcement ratio 0.5%, 1%, 1.5% and 2% is shown in fig 10.

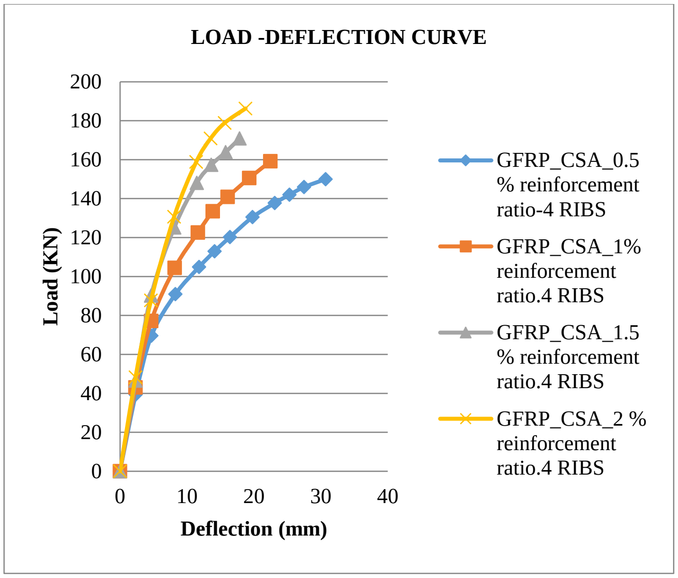

Fig. 10.load v/s deflection

From figure 10 it is clear that beam reinforced wih GFRP bar of cross section with 4 longitudinal ribs of reinforcement ratio 2% undergoes less deflection compared to other beams.

The load v/s deflection graph is plotted for the beam reinforced with CFRP bar of circular cross section with 4 ribs of reinforcement ratio 0.5%, 1%, 1.5% and 2% is shown in fig. 11.

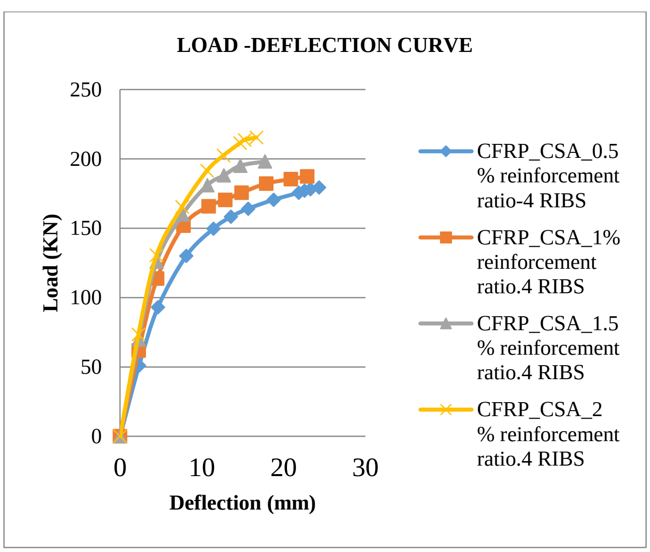

Fig. 11.load v/s deflection

From figure 11 it is clear that beam reinforced wih CFRP bar of cross section with 4 longitudinal ribs of reinforcement ratio 2% undergoes less deflection compared to other beams.

A. Comparison of results

Comparison of ultimate load obtained the concrete beams reinforced with steel bar of circular section and the concrete beams reinforced with GFRP and CFRP bars of circular section, circular section with 2 longiudinal ribs and circular section with 4 longiudinal ribs of reinforcement ratio 0.5%, 1%, 1.5% and 2% is shown in table 5.

TABLE 5 ULTIMATE LOAD COMPARISON BETWEEN THE CONCRETE BEAMS

Type of bar	Reinfor-cement ratio	Section of bar	Ultimate load (N)	% increase in ultimate load
Steel Bar	0.5%	Circular section	94177	
	1%		138080	46.6
	1.5%		151920	61.3
	2%		167110	77.4
GFRP bar	0.5%		133620	
	1%		145850	9.15
	1.5%		152830	14.4
	2%		159070	19.05
CFRP bar	0.5%		162080	
	1%		172080	6.17
	1.5%		183950	13.5
	2%		194710	20.13
GFRP bar	0.5%	Circular section with 2 ribs	142460	
	1%		149590	5.04
	1.5%		157930	10.86
	2%		169650	19.09
CFRP bar	0.5%		174600	
	1%		185320	6.14
	1.5%		195890	12.19
	2%		202460	15.96
GFRP bar	0.5%	Circular section with 4 ribs	150000	
	1%		159150	6.1
	1.5%		170900	13.93
	2%		186260	24.17
CFRP bar	0.5%		179350	
	1%		187290	4.43
	1.5%		198060	10.43
	2%		215420	20.11
GFRP bar	2%	Circular section	159070	
		Circular section with 2 ribs	169650	6.65
		Circular section with 4 ribs	186260	17.09
CFRP bar	2%	Circular section	194710	
		Circular section with 2 ribs	202460	3.98
		Circular section with 4 ribs	215420	10.64
GFRP bar	2%	Circular section	159070	
		Circular section with 2 ribs	169650	6.65
CFRP bar	2%	Circular section	194710	
		Circular section with 2 ribs	204460	5.01
GFRP bar	2%	Circular section	159070	
CFRP bar			194710	22.4

GFRP bar	2%	Circular section with 2 ribs	169650	
CFRP bar			204460	20.52
GFRP bar	2%	Circular section with 4 ribs	186260	
CFRP bar			215420	15.65

Deflection v/s reinforcement ratio is plotted for the concrete beams reinforced with GFRP bars of circular section, circular section with 2 longitudinal ribs and 4 longitudinal ribs is shown in figure 12.

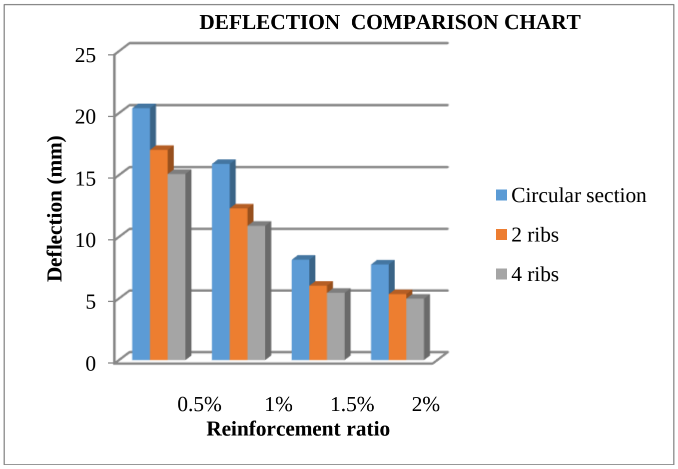

Fig. 12.Deflection comparison chart for concrete beams reinforced with GFRP bars of circular section, circular section with 2 longitudinal ribs and 4 longitudinal ribs.

From figure 12 it is clear that as the reinforcement ratio increases, there is decrease in deflection. Concrete beams reinforced with GFRP bars of circular section with 4 longitudinal ribs with 2% reinforcement ratio has less deflecion compared to other beams.

Ultimate load v/s reinforcement ratio is plotted for the concrete beams reinforced with GFRP bars of circular section, circular section with 2 longitudinal ribs and 4 longitudinal ribs is shown in figure 13.

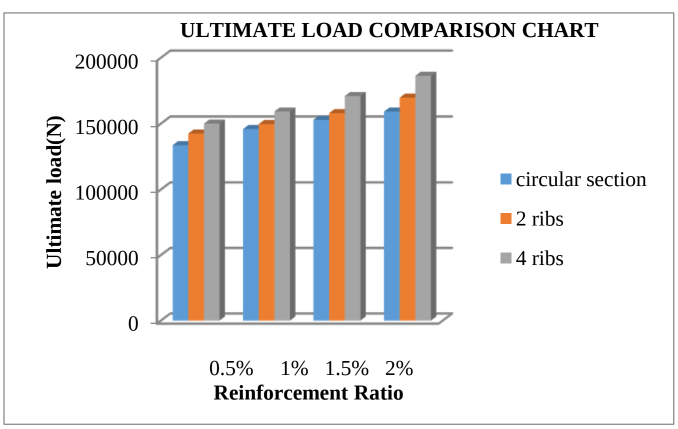

Fig. 13.Ultimate load comparison chart for concrete beams reinforced with GFRP bars of circular section, circular section with 2 longitudinal ribs and 4 longitudinal ribs.

From figure 13 it is clear that as the reinforcement ratio increases, there is increase in ultimate load carrying capacity of concrete beams. Concrete beams reinforced with GFRP bars of circular section with 4 longitudinal ribs of 2% reinforcement ratio has higher ultimate load carrying capacity compared to other beams.

Deflection v/s reinforcement ratio is plotted for the concrete beams reinforced with CFRP bars of circular section, circular section with 2 longitudinal ribs and 4 longitudinal ribs is shown in figure 14.

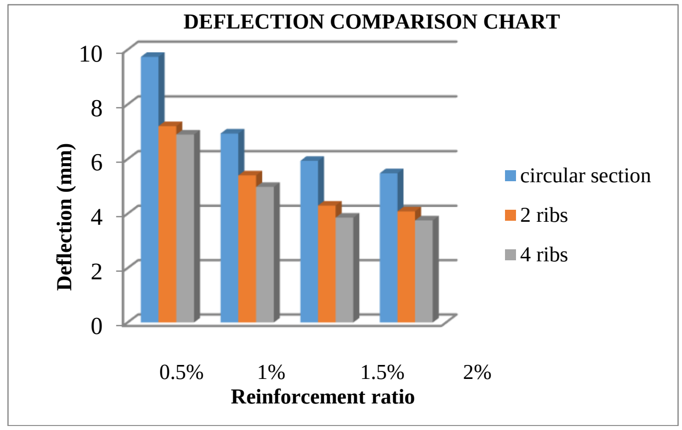

Fig. 14.Deflection comparison chart for concrete beams reinforced with CFRP bars of circular section, circular section with 2 longitudinal ribs and 4 longitudinal ribs.

From figure 14 it is clear that as the reinforcement ratio increases, there is decrease in deflection. Concrete beams reinforced with CFRP bars of circular section with 4 longitudinal ribs with 2% reinforcement ratio undergoes less deflection compared to other beams.

Ultimate load v/s reinforcement ratio is plotted for the concrete beams reinforced with CFRP bars of circular section, circular section with 2 longitudinal ribs and 4 longitudinal ribs is shown in figure 15.

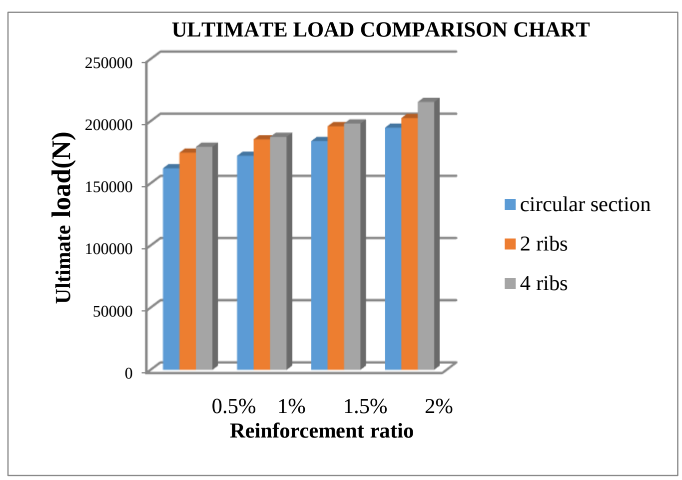

Fig. 15.Ultimate load comparison chart for concrete beams reinforced with CFRP bars of circular section, circular section with 2 longitudinal ribs and 4 longitudinal ribs.

From figure 15 it is clear that as the reinforcement ratio increases, there is increase in ultimate load carrying capacity of concrete beams. Concrete beams reinforced with CFRP bars of circular section with 4 longitudinal ribs with 2% reinforcement ratio has higher ultimate load carrying capacity.

VI.CONCLUSIONS

The following conclusions are obtained.

1. As the reinforcement ratio increases from 0.5% to 2%, ultimate load carrying capacity increases and deflection decreases.

2. Beam reinforced with CFRP bar of circular section with 4 ribs of 2% reinforcement ratio has highest load carrying capacity and lowest deflection.

3. Ultimate load is increased about 77.4% and deflection is reduced by 64.84% for the concrete beam reinforced with steel bar of circular section with 2% reinforcement ratio.

4. Ultimate load is increased about 24.17% and deflection is reduced by 66.93% for the concrete beam reinforced with GFRP bar of circular section with 4 longitudinal ribs of 2% reinforcementratio.

5. Ultimate load is increased about 20.11% and deflection is reduced by 43.44% for the concrete beam reinforced with CFRP bar of circular section with 4 longitudinal ribs of 2% reinforcement ratio.

6. Concrete beam reinforced with GFRP bars of circular section, circular section with 2 ribs and circular section with 4 ribs of reinforcement ratio 2% are compared. While comparing ultimate load is increased about 17.09% and deflection was reduced by 35.68% for the concrete beams reinforced with GFRP bar of circular section with 4 longitudinal ribs.

7. Concrete beam reinforced with CFRP bars of circular section, circular section with 2 ribs and circular section with 4 ribs of reinforcement ratio 2% are compared. While comparing ultimate load is increased about 10.64% and deflection was reduced by 45.30% for the concrete beams reinforced with CFRP bar of circular section with 4 longitudinal ribs.

8. From these results, concrete beams reinforced with bars of circular cross section with 4 longitudinal ribs gives the highest ultimate load. So it is the best surface configuration than the bar with circular section and circular section with 2 longitudinal ribs.

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