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Experimental and Numerical investigation on the effect of CFRP straps with different orientation angles on the strength of the beam

Investigație experimentală și numerică asupra efectului benzilor CFRP cu unghiuri de orientare diferite asupra rezistenței fasciculului

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Abstract –
Now a days all the civil engineering structures are designed earthquake resistant to withstand the high intensity earthquakes that are occurring more frequently. But there is a need to strengthen the already existing structures to withstand for earthquakes. Usage of CFRP sheets is a technique to strengthen a structural member of a structure to withstand for natural occurring calamities.
This study presents the experimental and numerical investigation on the effect of CFRP sheets with varying angles of straps on the strength of the beam. The objective of this work is to explore the behaviour of RC beam strengthened with CFRP sheet and straps. Numerical analysis was carried out using software to represent the ultimate load vs deflection and ultimate load carrying capacity of the beam.
Comparison of experimental with numerical results exhibited, that beam strengthened with angled straps showed more effective in enhancing the deflections, failure modes and ultimate strength of the RC beam. The strength of CFRP straps with different orientations were analyzed and compared.

Key Words – *Unidirectional carbon fiber, epoxy, load versus, deflection graph, ultimate load carrying capacity.*

1. Introduction

Deterioration of old structure and replacing it with a new structure may lead to various disadvantages like financial, material, and labour cost, etc. Instead of deteriorating, strengthening of structure is the best solution. Retrofitting is required in many cases like poor construction, inferior material, unexpected loads, earthquakes, etc. Flexural and shear strengthening arrangement remains the best method in increasing the stiffness, ultimate strength and cracking behaviour of the RC beam [1]. Many researches have been conducted on the RC beams retrofitted with flexural and shear strengthening by CFRP sheets through experimental and numerical analysis. The analysis has showed that flexural and shear strengthening of beam would avoid the debonding failure, which provides good strength and ductility[2]. New techniques have emerged in recent times for increasing the flexural and shear strength of beams, Instead of bonding of CFRP externally they have made holes along the web of the beam and inserting the FRP material into the holes and filling the holes with grout to increasing the shear strength of the beam[3],Near surface mounted CFRP bars to enhance the overall load carrying capacity ,moment redistribution and ductility of the beam[4], Another anchoraging technique *i.e*, CFRP stitching along U-wrap is used for shear deficient beams it is new method for shear strengthening of beam[5], Another method for increasing the shear strength of the beam stands by using the shear deficient beam and using two schemes one is the externally bonded near surface mounted carbon fiber polymer u wrap strips and welded wire mesh and second strengthening scheme is CFRP u-wraps and horizontal CFRP strips of externally bonded to the beam[6]. Externally bonded reinforcement in groove (EBRIG) technique is used to enhance the shear capacity of the beam in this regard, as the spacing of stirrups increases the effective strains in the carbonfibre also increases ductility with increases in stirrups[7]. Experimental and numerical analysis has done to investigate the precracked and repaired beams and strengthened by CFRP sheets results indicated that improved load vs deflection curve and as the number of CFRP layers increases shear stresses rises[8]. A new improved anchorage technique by using steel pins,steel clamps and the initial compression induced by the clamps were investigated and found that steel clamps provide high strength[9]. The grade of steel plays a major role in the debonding of the fibre as the grade of steel increases the bond efficiency of CFRP laminates increased[10]. Combination of GFRP bars and CFRP sheets are used to increase the flexural performance of the beam. The test results revealed that central deflection and crack sizes are reduced considerably by increasing the number of CFRP layers and GFRP reinforcement ratio[21]. Debonding of CFRP is one of the problem but end self locking a technique to prevent the debonding of the CFRP from the beam, due to this intermediate crack debonding is subsequently reduced and an increase in the ultimate load and ductility is observed that ensuring failure of CFRP rupture or concrete crushing regardless of debonding[22]. Researchers have done on the flexural retrofitting of CFRP sheets bonded on the sofit of the beam. The main influence is bonding of CFRP to the sofit of the beam. Bonding plays a major role in the strengthening of structures. Bonding of cfrp sheets to the surface can be increased using different methodslike by improving the surface of the structure, by grooving method, by externally bonded reinforcement and externally bonded reinforcement on grooves or by anchored cfrp strips. Increasing the bonding delays the debonding and increases the ductility of the beam and also increases the ultimate load carrying capacity.[21,29,31,37]. A few studies also conducted on the length and thickness[19], concrete cover thickness[34] and effect of end anchorages[24] on the debonding failure and flexural strength of the beam. Externally bonded reinforcement is a basic strengthening technique applied for a existing damaged structure. The reason behind is high strength to weight ratio, stiffness and load carrying capacity.

Various parameters of this strengthening method have been investigated in the past years. The parameters include the effects of strengthened precracked beam[20], effect of strengthened shear failed beams[23] and also damaged concrete cover[34]. Special attention has been paid on the determination of type of resins they are rubber modified resin, cement based resin, bio based resin for bonding the CFRP to sofit of the beam[22,25,42].

From the above works it is clear that externally bonded carbon fiber sheets are currently being studied for strengthening of structural components. In this study carbon fiber is externally bonded to increase the flexural and shear strength of the beam. The effects of inclined straps on the load carrying capacity, crack patterns of the RC members loaded in four point bending test were specifically evaluated.

In earthquake prone area buildings get easily damaged due to high impact p,s,l waves, so retrofitting becomes a major factor for strengthening the structure. In the present work G+5 building is designed with different types of loadings i.e, dead load, live load, earthquake loads and building were analyzed for a critical section. The below figure shows the building plan of a G+5 and critical section.

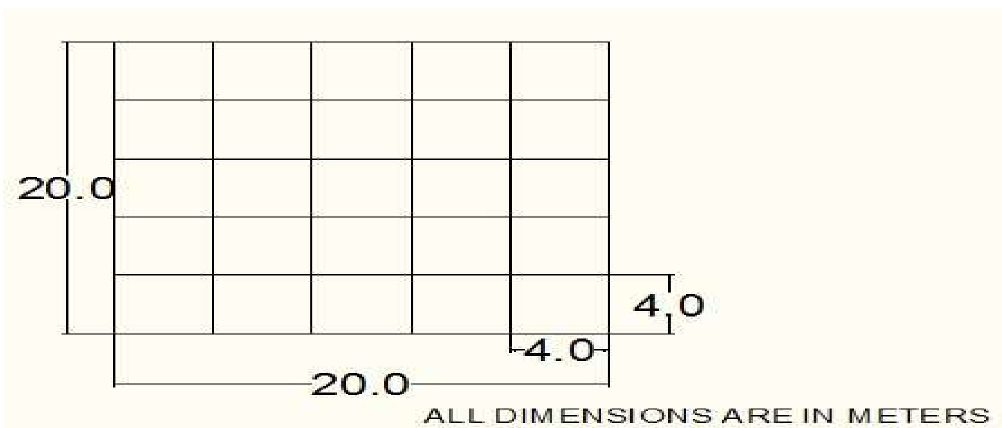

Fig:-1 Plan of building

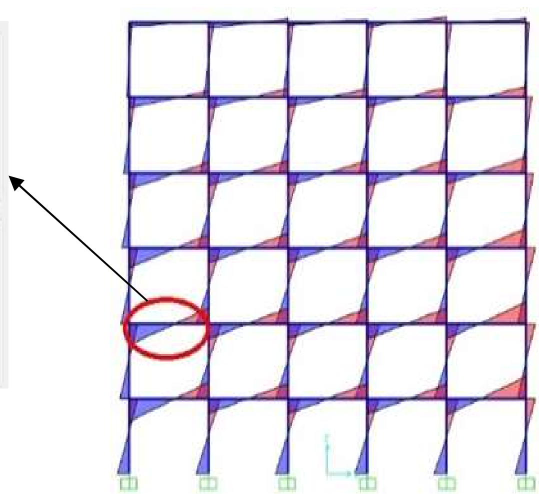

Fig:-2 Critical section

From the critical section, beam is derived and it is consized to suit the lab conditions. After consizing, the beam is as shown in the figure below.

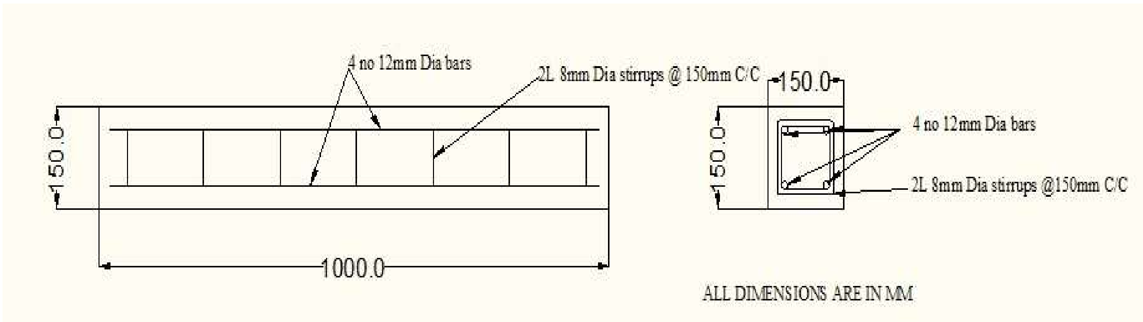

Fig:-3 Geometric dimensions of beam

2. Material Properties

A. Concrete

OPC grade53 cement confirming to IS 12269-1987 was used in the study. Fine aggregate locally available and crushed angular coarse aggregate passing 20mm sieve have been used. Tests are conducted on the materials as per IS standards. The mix proportions have been calculated according to the design mix as per IS 10262-2009 in order to achieve the 25N/mm^2. Calculated mix proportions are with a W/C ratio of 0.5 with a slump of 100mm. Six cubes were casted using the mix proportions and the results are tabulated below.

Table:1

Test results of concrete cube

Compressive strength of concrete cube (MPa)	Sample 1		Sample 2		Sample 3	
Days	7	28	7	28	7	28
M25 mix(N/mm^2)	18.6	32.8	20.3	34.5	19.6	33.2

B. Reinforcement

Fe500 HYSD 12mm &8mm dia bars having characteristic strength of 500 MPa were used and three samples have been tested in universal testing machine. 12mm dia bars used as longitudinal reinforcement and 8mm dia bars as stirrups.

C. CFRP and Epoxy

Different types of fiber reinforced polymer are available in market and carbon fiber reinforced polymer is one of them. Carbon fiber of 230 GSM have been used in the project and it is used as externally bonded reinforcement. Epoxy is used to bond the cfrp to the surface of the concrete. Epoxy named Araldite has been used in this work. The properties of carbon fiber and araldite epoxy are supplied by the manufacturer are summarized in Table 2&3.

Fig:-4 uni-directional carbon fiber sheet

Table:-2

Properties of carbon fiber

Thickness (mm)	Tensile strength (MPa)	Elastic modulus (GPa)	Cracking ductility(%)	Weight of carbon fiber (g/m^2)
0.112	4900	230	1.5%	230

Table:-3

Properties of epoxy

Tensile strength (MPa)	Tensile modulus (MPa)	Cracking ductility(%)	Elastic modulus (MPa)	Specific gravity (g/cm^3)
64	3700	3.4	3200	1.17

D. Specimen details

The dimensions of the beam were 150mm wide by 150 mm deep by 1000mm long. The reinforcement consist of 12mm at top and bottom, shear reinforcement of 8mm bars as stirrups shown in fig.3. Table 3 shows the 5 RC beams strengthened with the coupled shear and flexure in the form of sheets and straps. One beam CS was kept without retrofitting for comparison. The rest of the beams were divided into four categories A,B,C,D. In A series the beam was retrofitted with CFRP sheets and the straps are inclined at 30^0. In series B t4e beams are retrofitted with CFRP sheets and straps are inclined at 45^0, In series C straps are inclined at 60^0, and In series D straps are perpendicular to the longitudinal direction.

Table - 4

Series	FRP provided	Orientation of strap(^{0})	Number of layers
A1,A2,A3	Sheet+Strap	30	1,2,3
B1, B2, B3	Sheet+Strap	45	1,2,3
C1, C2, C3	Sheet+Strap	60	1,2,3
D, D2, D3	Sheet+Strap	90	1,2,3

E. Sample preparation and test setup

The surface of the beam was cleaned and the epoxy spread on the bottom surface of the beam and then the CFRP sheet was placed on the epoxy and it was pressed with roller for uniformity and excess epoxy removed, next the epoxy is applied on where the straps to be laid and the CFRP straps are spread on the epoxy applied surface and the process is continued for the remaining layers. All the beams were simply supported over a span of 1000mm and tested under four-point loading. The load was applied using a hydraulic servo of 600Kn capacity with a loading of 5kN/min.

F. Testing of beams

Five beams were casted and cured for 28 days. Out of five beams, one beam kept as control specimen and rest of the four specimens were strengthened with unidirectional carbon fiber having thickness of 0.112mm. Universal testing machine (UTM) is used for testing of beams. The strengthened beams are showed in the figures 5,6,7 with four point bending test which consist of beam supported on the two steel roller bearing 150 mm from the end of the beam remaining portion is divided into equal parts and test is conducted. The deflections of the beam were recorded.

3. Experimental Procedure

- Analysing the G+5 structure using software to find the critical section.
- Finding the physical properties of materials like aggregate, cement etc.,
- Calculation of Mix Design for Concrete.
- Casting the beam.
- Applying CFRP Straps in different angles with 1,2,3 Layers.
- Testing the beams using Universal Testing Machine with 3 point loading to find the deflections.
- By using Finite element analysis software the beam is analysed with and without FRP straps.
- Results are compared with analytical and numerical approaches.

4. Results of Tested Beams

A. Orientation of angle at 30^o:-

Fig:-5 1 layer

Fig:-6 2 layer

Fig:-7 3 layer

Specimen A_1 :-

The beam strengthened with one layer CFRP sheet with 30^{o} angles during testing showed combination of shear cracks and delamination of strap. For this beam an ultimate load of 168.45kN and corresponding mid span deflection of 6.13mm was achieved. It achieved strength of 90.3% greater than the control specimen.

Specimen A_2 :-

The beam strengthened with 2 layers CFRP sheets with 30^{o} angle exhibited concrete crushing at top of the beam. For this beam an ultimate load of 209.64kN and a corresponding mid span deflection of 7.19mm. The strength achieved was 121.14% more than the control specimen.

Specimen A_3 :-

The beam strengthened with 3 layers CFRP sheets with 30^{o} angle exhibited concrete crushing at top of the beam. For this beam an ultimate load of 219.69kN with a corresponding mid span deflection of 9.04mm. The strength achieved was 148.24% more than the control specimen.

B. Orientation of angle at 45^{o}:-

Fig:-8 1 layer

Fig:-9 2 layer

Fig:-10 3 layer

Specimen B_1 :-

The beam strengthened with one layer CFRP sheet with 45^{o} angles during testing showed combination of shear cracks and delamination of strap. For this beam an ultimate load of 181.11kN and corresponding mid span deflection of 6.7mm was achieved. It achieved a strength of 104.64% more than the control specimen.

Specimen B_2 :-

The beam strengthened with 2 layers CFRP sheets with 45° angle exhibited shear cracks and concrete crushing at top of the beam. For this beam an ultimate load of 199.4kN and a corresponding mid span deflection of 8.76mm was recorded and the strength achieved 125.31% more than the control specimen.

Specimen B_3 :-

The beam strengthened with 3 layers CFRP sheets with 45° angle exhibited concrete crushing at top of the beam. For this beam an ultimate load of 214.11kN with a corresponding mid span deflection of 9.3mm. The strength achieved was 141.93% more than the control specimen.

C. Orientation of angle at 60°:-

Fig:-11 1 layer

Fig:-12 2 layer

Fig:-13 3 layer

Specimen C_1 :-

The beam strengthened with one layer CFRP sheet with 60° angles showed combination of shear cracks and delamination of strap. For this beam an ultimate load of 190.68kN and corresponding mid span deflection of 6.78mm was achieved. It recorded a strength of 115.46% more than the control specimen.

Specimen C_2:-

The beam strengthened with 2 layers CFRP sheets with 60° angle exhibited shear cracks and concrete crushing at top of the beam. For this beam an ultimate load of 200.1kN and a corresponding mid span deflection of 7.98mm. The strength achieved was 126.1% mare than the control specimen.

Specimen C_3:-

The beam strengthened with 3 layers CFRP sheets with 60° angle exhibited concrete crushing at top of the beam. For this beam an ultimate load of 224.58kN with a corresponding mid span deflection of 9.08mm. the strength achieved was 153.76% more than the control specimen.

D. Orientation of angle at 90°:-

Table No:-5

Results of the Specimens

Specimen	Load at first crack(kN)	Ultimate load(kN)	Ultimate deflection(mm)	Ductility index	Shear strength(kN)	Contribution of CFRP(kN)
CS	31.2	88.5	4.83	1.16	44.25	0
A_1	45.34	168.45	6.14	1.27	84.23	79.95
A_2	56.54	209.64	7.19	1.48	104.82	121.14
A_3	63.46	219.69	9.04	1.87	109.845	131.19
B_1	47.76	181.11	6.7	1.38	90.5	92.61
B_2	52.1	199.4	8.76	1.81	99.7	110.9
B_3	68.91	214.11	9.3	1.92	107.05	125.61
C_1	49.47	190.68	6.78	1.40	95.35	102.18
C_2	53.81	200.1	7.98	1.65	100.05	111.6
C_3	71.2	224.58	9.08	1.87	112.3	136.08
D_1	43.07	172.37	7.87	1.62	86.185	83.87
D_2	47.53	179.82	7.17	1.48	89.91	91.32
D_3	49.16	187.37	6.65	1.37	93.68	98.87

Fig:-14 1 layer

Fig:-15 2 layer

Fig:-16 3 layer

Specimen D_1:- The beam strengthened with one layer CFRP sheet with 90° angles showed combination of delamination of straps, shear cracks and concrete crushing. For this beam an ultimate load of 172.37kN and corresponding mid span deflection of 7.87mm was achieved. It recorded a strength of 90.64% more than the control specimen.

Specimen D_2:- The beam strengthened with 2 layers CFRP sheets with 90° angle exhibited delamination of straps, shear cracks and concrete crushing at top of the beam. For this beam an ultimate load of 179.82kN and a corresponding mid span deflection of 7.17mm. The strength achieved was 103.19% mare than the control specimen.

Specimen D_3:- The beam strengthened with 3 layers CFRP sheets with 90° angle exhibited concrete crushing at top of the beam. For this beam an ultimate load of 187.34kN with a corresponding mid span deflection of 6.65mm. the strength achieved was 111.68% more than the control specimen.

5. Finite Element Modelling

In the finite element analysis a tool named Ansys17.0 is used for nonlinear model to analyse the retrofitted beam. The element, Solid 65 used for concrete model as it has capable of cracking in tension, crushing in compression, plastic deformation and creep. The important property of this solid65 element is it can handle nonlinear material properties. Element, Link8 used for steel model in reinforced concrete. The purpose of using this element is as it has the capability of handling plastic deformation. Solid45 was used for 3-D modeling of adhesive. This element had features of plasticity, creep, swelling, stress stiffening, large deflections and large strain capabilities. Solid46, the element used for reinforced fiber polymer sheets with number of layers. CONTA174 and TARGE170 are used for bonding of CFRP to concrete. CONTA174 is generally used for rigid-flexible and flexible-flexible contact analysis.

Properties of materials in modelling:-

A. Concrete and steel reinforcement

Linear stress strain analysis is used to model the concrete and steel reinforcement. The properties of the materials are shown in the Table:-6. The properties of steel much easier than the properties of concrete.

Table :-6

Properties of concrete and steel

Material	Material property	value
Concrete	Compressive strength @28days (MPa)	31.25
	Tensile strength(MPa)	2.1
	Modulus of elasticity (GPa)	25
	Poissons ratio	0.2
	Shear coefficient for open crack	0.2
	Shear coefficient for closed crack	0.8
Steel reinforcement	Modulus of elasticity (GPa)	210
	Poissons ratio	0.3
	Ultimate stress (MPa)	500

B. CFRP sheets and Epoxy:-

The properties of these materials are given by the manufacturer and same properties are used in the analysis. The properties are mentioned below in Table no:-7.

Table:-7

Properties of CC and Epoxy

Material	Material property	Value
CFRP	Elastic modulus (GPa)	230
	Poissons ratio	0.3
	Layer thickness(mm)	0.112
	Layer number	1,2,3
Epoxy	Elastic modulus (MPa)	3200
	Poissons ratio	0.3
	Tensile strength(MPa)	30
	Layer thickness	1
	Layer number	1,2,3

Beam modelling:-

Figure 17 shows the finite element model of RC beam element where solid 65 is the property defined for RC beam in Ansys software with support and loading conditions. Longitudinal reinforcement and stirrups are shown in fig18. Discrete method, element link180 is used in the modelling. The interface between the concrete-epoxy-CFRP is assumed to be perfect bonding as shown in the fig.19.

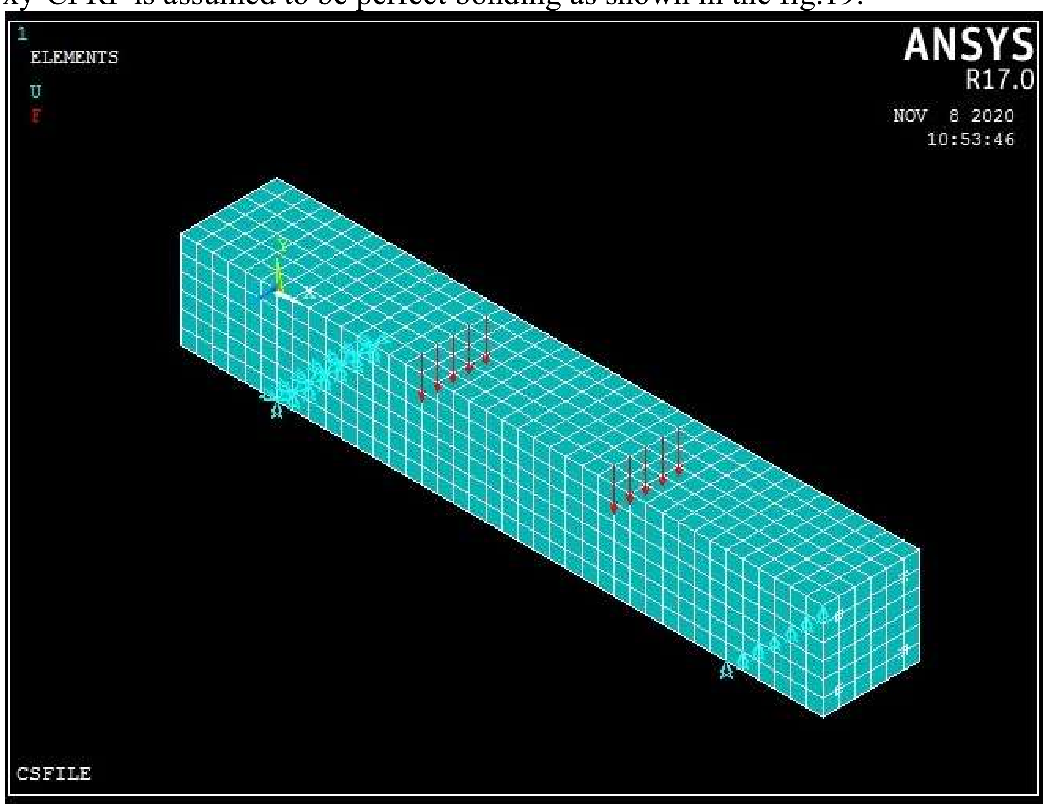

Fig:-17 Full beam model with boundary and loading conditions

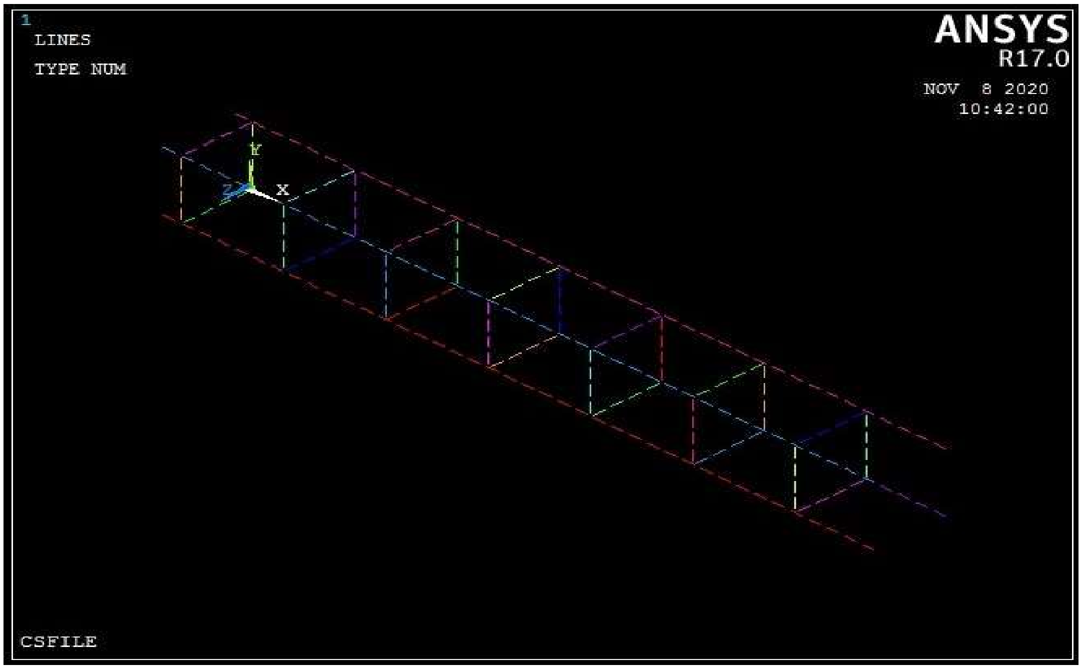

Fig:-18 Longitudinal reinforcement and stirrups in FE model

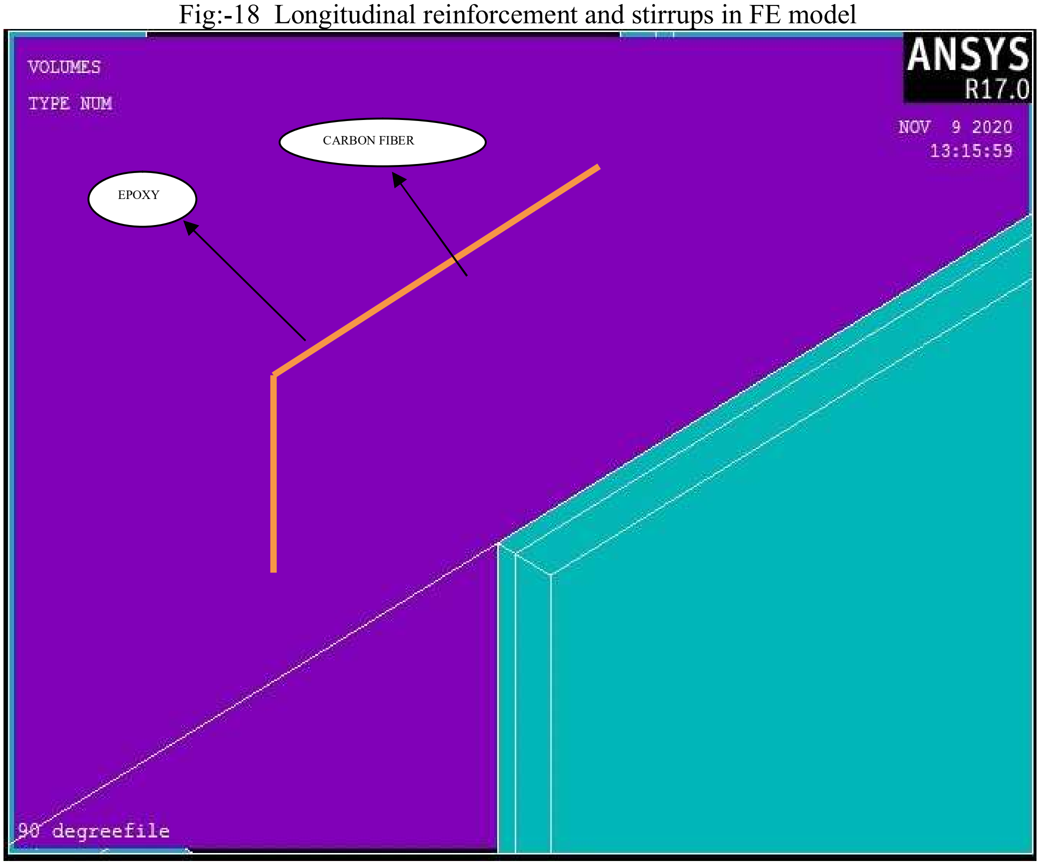

Fig:- 19 Modelling of single layered CFRP sheet and epoxy

6. Results

The comparison of experimental and numerical results of load vs deflection of control specimen and 12 strengthened beams are showed in fig 20-25. A noticeable agreement between experimental and numerical analysis is observed. The FE beams are considered to be strong and slightly stiffer than real one. Because a perfect bond is considered between the concrete and reinforcement in the FE analysis.

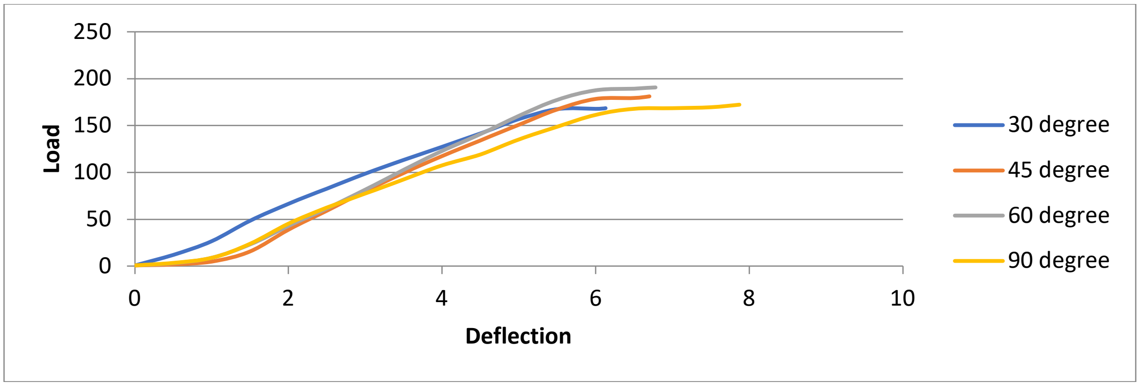

Fig:-20 Experimental Load vs Deflection graph for 1 layer CFRP

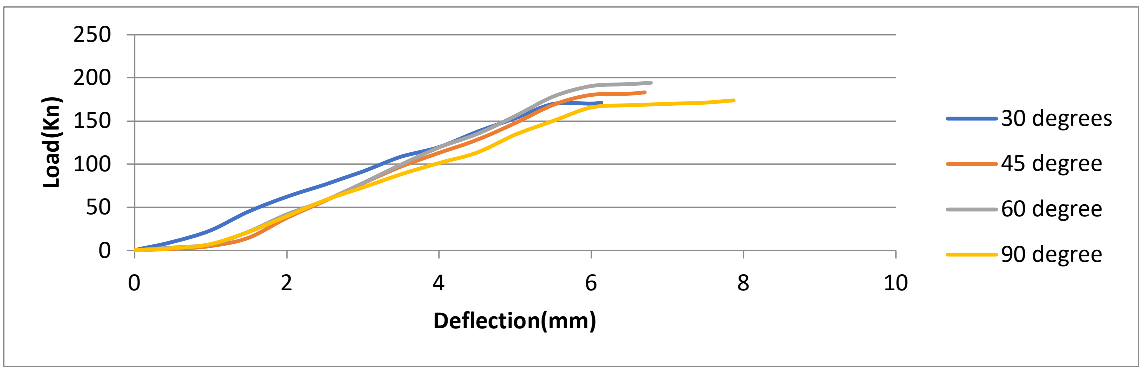

Fig:- 21 Numerical Load vs Deflection graph for 1 layer CFRP

Fig 20 and 21 resemblance the experimental and numerical values of specimens A1,B1,C1,D1 out of which specimen C1 obtaied the highest load 194.42kN with a deflection of 6.88mm

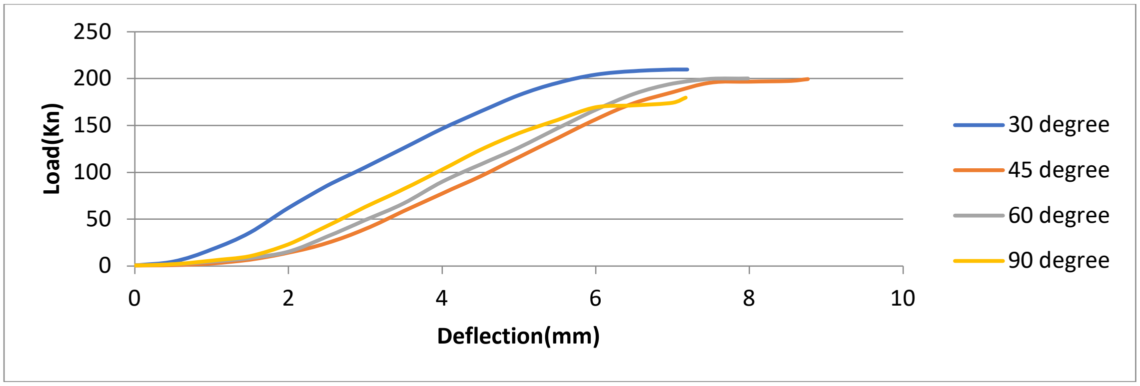

Fig:-22 Experimental Load vs Deflection graph for 2 layer CFRP

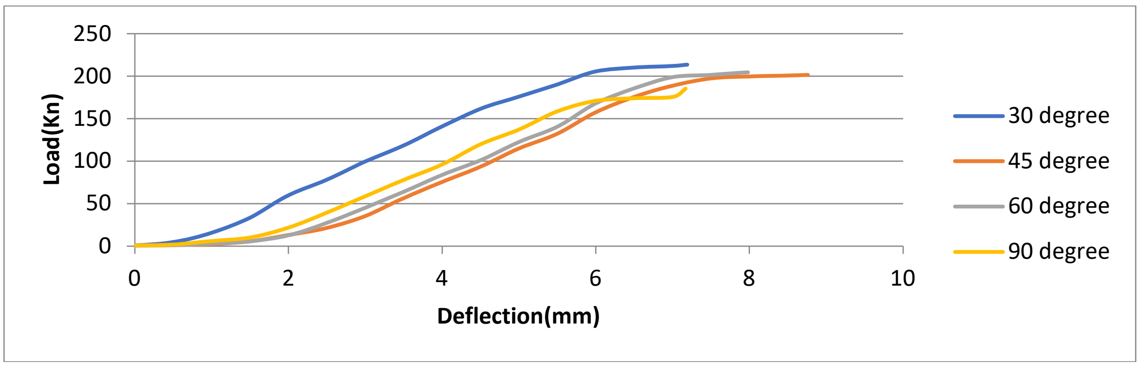

Fig:-23 Numerical Load vs Deflection graph for 2 layer CFRP

Fig 22 and 23 resemblance the experimental and numerical values of specimens A2,B2,C2,D2 out of which specimen A2 obtaied the highest load 213.58kN with a deflection of 7.19mm which is similar to the experimental values.

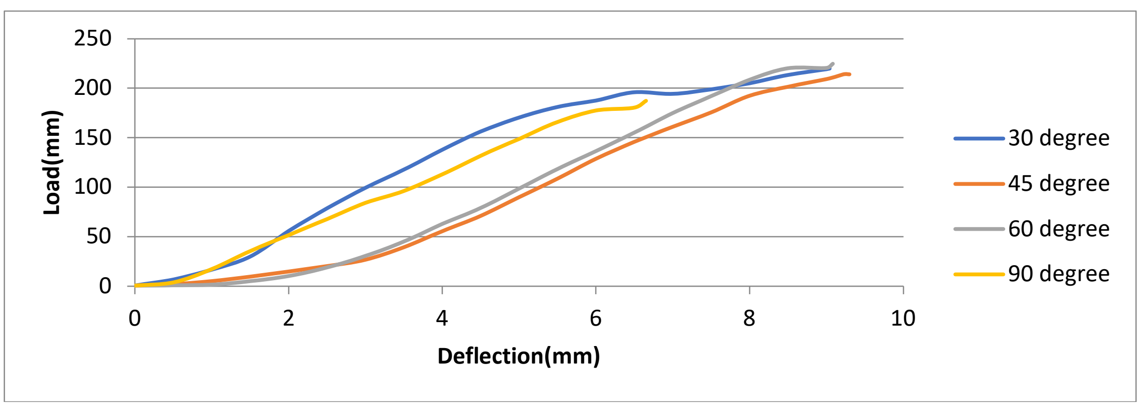

Fig:-24 Experimental Load vs Deflection graph for 3 layer CFRP

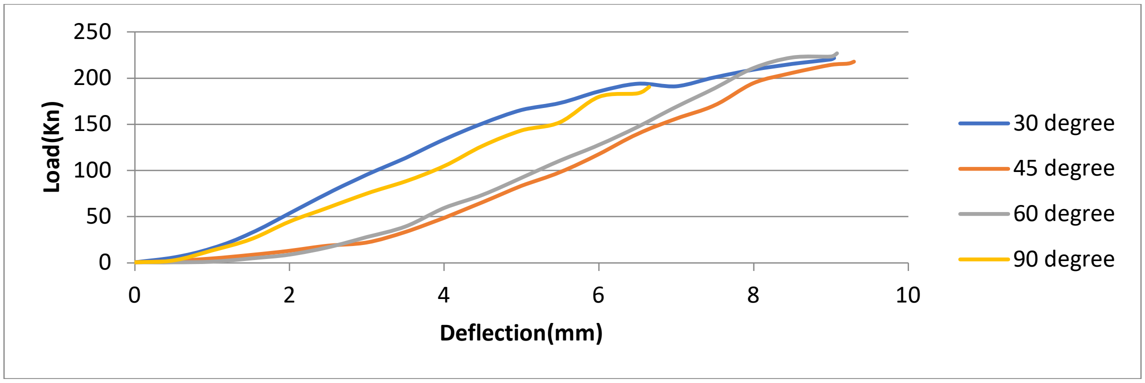

Fig:-25 Numerical Load vs Deflection graph for 3 layer CFRP

Fig 24 and 25 resemblance the experimental and numerical values of specimens A3,B3,C3,D3 out of which specimen C3 obtaied the highest load 226.74kN with a deflection of 9.08mm

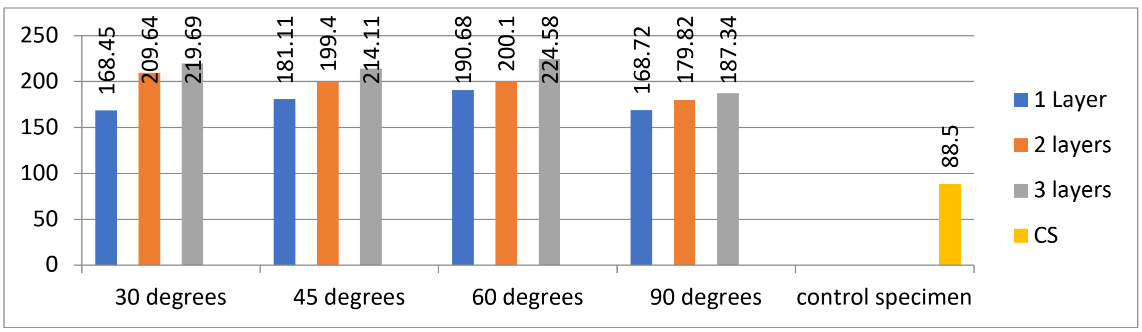

Fig:-26 comparison of ultimate load capacity

Retrofitting method will enhance the strength of the beam. By observing the ultimate load carrying capacity of the control specimen and strengthened beams it is clear that strengthened beams has more ultimate load carrying capacity, retrofitted beam *ie,* strap orientation 60^{O} with three layers beam had a strength of 224.58 kN. The ultimate load carrying capacity of the beam increased by 153.76% when compared to control specimen. It registered the highest load carrying capacity than the other strengthened beams.

All the retrofitted specimen have gained a strength of more than 100% than control specimen, except strap orientation of 30^{O} and 90^{O} with 1 layer showed less than 100% strength than control specimen . Among the four sets of strap orientations i.e, 30^{O},45^{O},60^{O},90^{O} of retrofitted beams, the beam retrofitted with strap orientation of 30^{O} with 1 layer beam exhibited the least load carrying capacity with the value of 168.45 KN, which is 90.3% greater than the ultimate load carrying capacity of control specimen.

7.Conclusions

The experimental and numerical results of the control specimen and four strengthened beams in flexure and shear by CFRP sheets and straps are presented below.

From the results of the strengthened beams the following conclusions are drawn

- The beam strengthened with flexural sheet with orientation angle of 30^o with 3 layers of CFRPshowed the highest load carrying capacity than other strengthened beams .
- From the experimental and numerical comparison,it clearly indicated that the specimen C_3 is better than the other strengthened beams
- To avoid the debonding failure of flexural sheet, utilization of straps act as anchorages to the flexural sheet and it acts as a working technique to keep intact the CFRP sheet to the beam.
- When compared with the control specimen the strengthened beams attains 90.3% to 153.76% of ultimate load carrying capacity respectively.
- The longitudinal sheet provided at the sofit of the beam had increased the flexural strength of the beam due to that flexural cracks are minimised.
- The presence of CFRP inclined straps also minimised the shear cracks while increasing the thickness.
- It was observed that the inclination of the straps upto 60^O are opposite to the shear crack formation so the holding capacity of the beam to minimise shear cracks also increased due to the ultimate load carrying capacity of the beam had increased.
- As the straps are perpendicular the beam withstands more displacement than the other beams but the ultimate load carrying capacity was slightly less than the other retrofitted beams.
- It was found that wrapping of CFRP straps around the three sides of the beam registered more effective in improving ultimate load carrying capacity, flexural strength and deflections of the beam.
- The beams retrofitted with single layer was failed with shear cracks and delamination of straps.
- The beams retrofitted with 3 layers had failed in concrete crushing at top of the beam.

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