International Journal on Emerging Technologies **5**(2): 31-39(2014)

ISSN No. (Print) : 0975-8364
ISSN No. (Online) : 2249-3255

Finite Element Modeling of CFRP Retrofitted RC Beam-Column Joints

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(Received 05 August, 2014 Accepted 13 September, 2014)

ABSTRACT: In the past decades, earthquakes have confirmed that most of the damaged RC structures require major repair works. Retrofitting of the existing beam-column joints is a major challenge for the Civil Engineers. The finite element method (FEM) is now become a spike for validate and predicting and the physical performance of complex engineering structures. In the present study, the non linear behavior of RC beam-column joints using Finite Element Modeling under the static load has been carried out, to study the response and load carrying capacity of exterior RC beam-column joints using non-linear finite element analysis with software ATENA-3D. In the second part of the study and analysis FE model for the two layer of carbon fiber reinforced polymer (CFRP) retrofitted RC beam-column joint using finite element method with the same software ATENA-3D is presented. The CFRP element was provided in L-shape and at 45 degree orientation to the joint in two layers. The results show a significant improvement in the ultimate load carrying capacity percent along with an increase of percent in yield load and percent increase in stiffness of the CFRP retrofitted FE beam model, when compared to control FE beam model of such exterior beam-column joints.

Keywords: Finite Element Modeling, Exterior RC joints, Retrofitting, CFRP

I. INTRODUCTION

Strengthening of existing reinforced concrete structures has a major part of construction activity all over the world. The reinforced concrete structures in the urbanized world are frequently found to show signs of distress and go through damage, even before service life is above, due to several causes such as improper design, faulty construction, change of codal provisions, overloading, earthquakes, explosions, corrosion and fire. Beam- column joints in reinforced concrete framed structures are recognized as a very critical zone due to its importance in transferring the forces and bending moments between the beams and columns. In most cases, the structure design of the joint is usually neglected and the attention is restricted to provision of sufficient anchorage for the beam longitudinal reinforcement of the beams in the columns. Unsafe design and detailing within the joint region is dangerous for the entire structure, even though the structural members themselves may conform to the design requirements. Broad research has been carried out in the last few decades on the behavior of joints under different seismic conditions. The existing structures, due to changes in codal provisions, need immediate assessment to avoid collapse which can bring huge loss of human lives and economy that world has witnessed several times.

In the last few decades several attempts have been made in India and abroad to study these problems and to increase the life of the structures by suitable retrofitting and strengthening techniques. The various retrofitting techniques available, plate bonding is the most effective and convenient method of retrofitting. The present study is a part of the program to explore the potential of CFRP for its utilization in any non-engineered construction, and for improved performance in the event of an earthquake.

Various experimental studies have been conducted in recent years to strengthen flexural members by using different retrofitting techniques. D.D'Ayala et al. have conducted tests on different layout of FRP fabric and sheets bonded to R.C. beam-column joints. The tests all agreement on the effectiveness of the strengthening procedure to increase stiffness and ductility while increases in shear and flexural strength and in energy dissipation are highly dependent on proper confinement of concrete and anchorage of the wrapping. According to Pantelides *et al.* CFRP materials were used to strengthen an external beam-column in shear. The retrofitted specimen was wrapped with multiple layers of CFRP sheets. The joint shear capacity was increased by 25%. Xiong and Singh found that, under the testing of monotonic loading the beam- column joints ductility retrofitting has resulted insignificant improvement in ductility 24-35 percent increase in ultimate loading capacity.

The development retrofitting hence demonstrated 154 - 172 percent increase in ultimate loading capacity**.** According to Nassif and Najm the addition of a thin layer of ferrocement to a concrete beam also enhances its ductility and cracking strength. The composite beams reinforced with square mesh exhibit better overall performance as compared to composite beams reinforced with hexagonal mesh. An increase in the number of layers leads to improvement in the cracking stiffness of the composite beams for both the cases. According to Anugeetha B. and Sheela S. the ultimate load carrying capacity of beams retrofitted with ferrocement having one, two and three layers of wire mesh increased by 6.25%, 50%, and 81.25 % and that of GFRP retrofitted beams with one, two and three layers increased by 50%, 68.75%, and 81.25 %, respectively. The beams retrofitted with one layer of GFRP in the flexural zone showed a higher strength-to-cost ratio. Hegger et al. conducted a nonlinear FE modeling to find the performance of beam-column joints using ATENA. It was observed that, was a good concord between the theoretical and experimental load-deflection curves for beam-column joints. Also, the FEM was able of individual between the failures types of the joints. Kachlakev et al. Finite Element technique is a dominant device with the opening of digital computers, which allow versatile analyses of reinforced concrete structures to be carried out in a regular mode. Though it is useful for obtaining the load deflection curves and its cracks with unlike loading situation.

II. EXPERIMENTAL PROGRAM

In the experimental program, five RC beam-column joints were cast using M-20 grade of concrete and Fe-415 steel grade as shown in Fig.1, using 1:1.43:2.97 with W/C 0.48. Testing arrangement of these joints is shown in Fig. 2. The cross-section of column was 225 mm x 125 mm with length of 1000 mm. The cantilever cross- section was 125 mm x 225 mm with a length of 500mm were used in the joints. 4-10Φ was used as longitudinal reinforcement in the columns, 6Φ lateral ties with spacing of 100mmc/c was provided in the columns. 2-10Φ used as tension reinforcement and 2-8Φ was used in compression reinforcement. Three specimens were used as control specimens and two specimens were stressed up to ultimate load. The average ultimate load of control joints was taken as an ultimate stress level. These joints then retrofitted using two layers of CFRP (carbon fiber reinforced polymer) as shown in Fig. 3. The retrofitted beam-column joints again tested and recorded the results in the form of load and deflection and crack patterns (Singh *et al.*,).

Fig. 1

Fig. 2.

Fig. 3.

Material Properties: The I.S.456:2000 stress-strain relationship was used for the purpose.

The basic material properties used are as follows:
Modulus of elasticity of steel, Es = 2.1×10^5MPa
Modulus of elasticity of concrete, E_C = 26429.81 MPa

Ultimate strain in bending, ε_{cu} = 0.0035
Characteristic strength of concrete, f_{ck} = 20 MPa
Yield stress for steel, f_y = 415 MPa

Geometry of Beam-Column Joint
Height of the column = 1000mm
Length of the cantilever = 500mm
Cross section of the column = 225 x 125mm
Cross section of the cantilever beam = 125 x 225mm

The loading conditions are shown in Fig. 2.

III. FEM OF BEAM-COLUMN JOINT

In this paper, reinforced concrete unretrofitted and retrofitted BC joints using FEM with the static loading has been presented. It shows the load variation deflection variation, cracks on the investigational results. ATENA software was used for the FE analysis. All aspects of materials in tension and compression are considered in report. The Stress-Strain relationship used is as per I.S.456:2000. The basic properties of various materials used for modeling are reported in Table 1.

Table 1

Sr. No.	Characteristics	Value
1.	Modulus of Elasticity of steel, E_s	2.1×10^5MPa
2.	Modulus of Elasticity of concrete, E_C	26429.81 MPa
3.	Characteristic strength of concrete, f_{ck}	20 MPa
4.	Yield stress for steel, f_y	415 MPa
5.	Ultimate strain in bending, ε_{cu}	0.0035

A. Modeling of Concrete

Solid brick element having minimum 8 and maximum 20 nodes is taken for concrete element in modeling of concrete used in ATENA (Fig. 4)**.** This element having three degree of freedom (X,Y,Z) directions at each node. It is also capable of plastic deformation and cracking in same directions (Cervenka Vladimir, ATENA theory manual).

Modeling of Reinforcement: In Finite Element modeling, discrete or smeared type of reinforcement used. In the present work discrete modeling of reinforcement has been used. Bar elements are used In ATENA for the modeling of steel. It is having the same degrees of freedom as concrete. The behavior of the element shown in Fig. 5. The initial part is elastic modulus of steel E_s and later one is the plasticity of the steel modulus E_{sh}. In case of perfect plasticity E_{sh} =0. Limit strain ε_L represents limited ductility of steel (Cervenka Vladimir, ATENA theory manual).

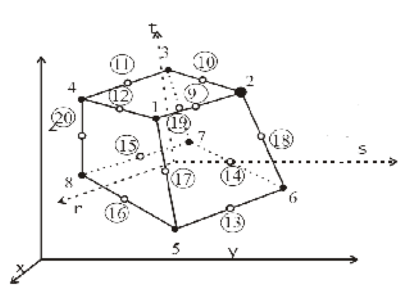

Fig. 4.

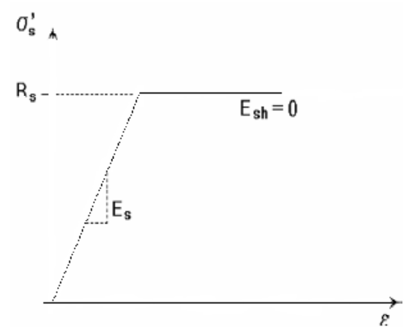

Fig. 5.

Modeling of CFRP: The CFRP is modeled as a shell element in ATENA. It is having 20 nodes isoparametric brick element as shown in Fig. 6. It is having five degree of freedom in every node with three displacements and two rotations. The three degrees of freedom are same as concrete and steel with x, y displacement of a bottom node degrees of freedom. The two nodes are placed on the ordinary to mid-surface passing through the original mid-surface element node (Cervenka Vladimir, ATENA theory manual).

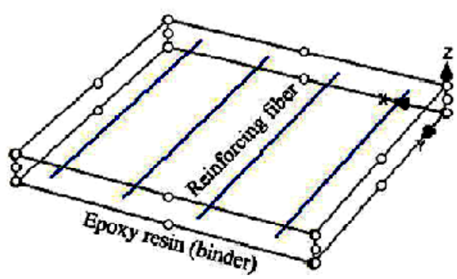

Fig. 6.

IV. MATERIAL PROPERTIES IN FEM

A. Material Properties of RC Beam-Column Joint

Concrete: Concrete element was modeled with 3D nonlinear cementitious2 The physical properties of Concrete element are shown in Table 2. Which are calculated as per IS code 456:2000 for ATENA.

Steel Bars: Fe-415 of 10mm, 8mm, diameter are used as main steel while 6mm diameter bars are used in stirrups. The properties of these bars are shown in Table 3.

Table 2

Properties	**Values**
Elastic Modulus (Fresh Concrete)	26429.81 MPa
Possion Ratio	0.2
Tensile Strength	3.130 MPa
Compressive Strength	20MPa
Specific Material Weight	0.024MN/mE+3
Coefficient of Thermal Expension	1E-05
Fixed Crack Model Coefficient	1

Table 3

Properties	Values
Elastic Modulus	$2.1x10^5$MPa
Yield Strength	415MPa
Specific Material Weight	0.0785MN/m E+3
Coefficient of Thermal Expansion	1.2E-05 1/K

Steel Plate for Loading: In ATENA**,** the function of the steel plate is for loading. Here, the property of steel plate is similar to the steel bars.

The Fe-415 was used for steel plate in ATENA, Fig. 7 – Fig. 9 shows the modeling beam-column joint in ATENA.

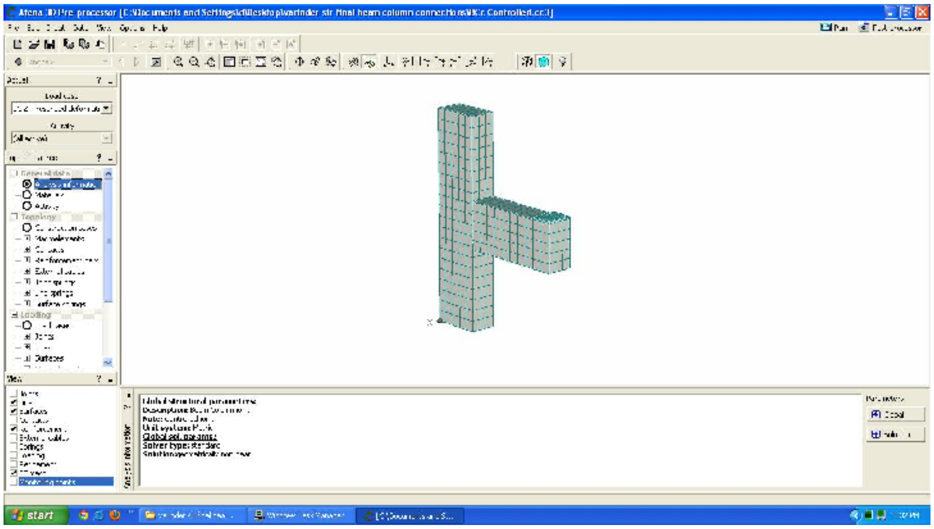

Fig. 7.

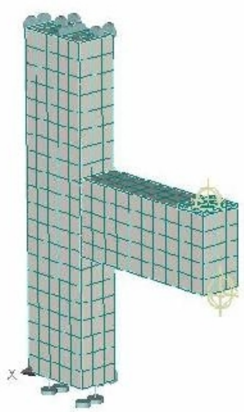

Fig. 8.

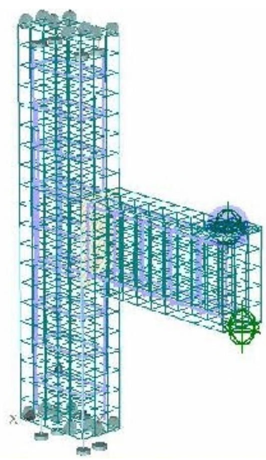

Fig. 9.

B. Material Properties of Retrofitted Beam-Column Joint

The concrete element was the same as previous modeling of the concrete. Damage level 0.5 was assumed at final crack and elastic modulus was assumed to be 0.5 of first value after the repair. The further values of concrete are incorporated corresponding to 0.5E in the jacketed model. The yield value is taken 210Mpa instead of 415 MPa, as the steel already has yielded to its yield point (Kumari and Kwatra). The material properties of epoxy are shown in Table 4.

Table 4

Properties	Values
Elastic Modulus	3465 MPa
Possion Ratio	0.2
Yield Strength	53 MPa
Specific Material Weight	2.300E-02
Coefficient of Thermal Expansion	1.200E-05 1/K

C. Carbon Fiber Reinforced Polymer

3D isotropic element was used for the retrofitting of the CFRP sheets. The method for modeling of wire mesh wrapping in CFRP retrofitting and retrofitted sample are shown in Fig. 10 and Fig. 11.

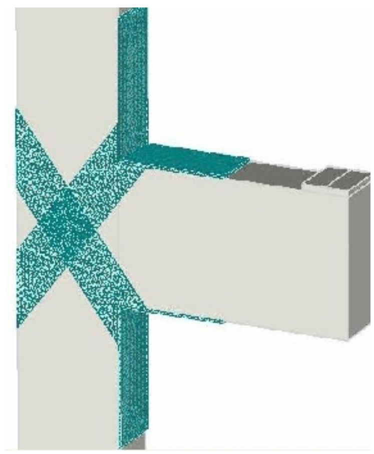

Fig. 10.

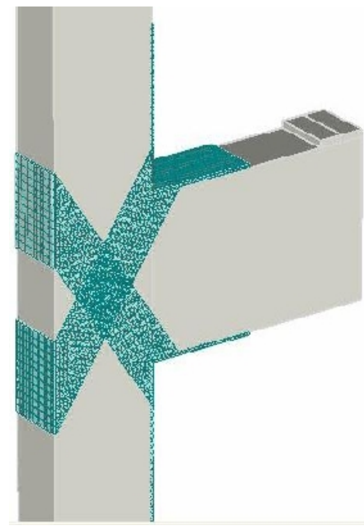

Fig. 11.

V. RESULTS AND DISCUSSION

Finite element analysis of BC joints was completed in two parts, in the first part finite element analysis of joints was done to obtain the ultimate load, deflection at ultimate load, cracks and LD curves for of control joint (without retrofit), in the second part of finite element analysis joints was analyzed to obtain the same for CFRP jacketed with two layers of fiber at ultimate loading. The FEM results are compared with experimental results.

A. Finite Element Analysis of Beam-Column Joints

FE analysis of joints under incremental loading was done with the software ATENA. The load was applied till failure of the joint. The results were recorded in post processing part of ATENA. The LD data at every step was recorded and the cracks and behavior of the control joint shown in Fig. 12. The FEM results are compared with experimental results in the form of LD curves. Analysis and testing was done upto ultimate load and was observed 24.85kN shows 9.56% variation from experimental value, 18.91 mm deflection was observed at free end of the beam. But, it was observed 22.68kN with deflection of 23.24mm in the experimental values , also 22.76 kN yield load observed, in comparison to 20kN in the experimental value (Singh *et.al.,*). The cracks of finite element modeled joint shown in Fig. 12 and Fig. 13. The various cracks at end of all steps are shown in Fig. 12-Fig. 13 at ultimate load of 24.85kN**.** In the case of CFRP jacketed beam- column joints, it was seen from the FEM and graphs that CFRP jacketed finite element model of joint, shows the increase in the ultimate load carrying capacity. The load carrying ability increased from 24.83kN [experimental value, Singh V et.al] to 26.94kN shows 8.5 % variation from experimental value, for CFRP two layer retrofitted joints of finite element model. The deflection of finite element model for CFRP two layer retrofitted models reduced to 19.25 as compared to 22.00mm [Singh V et.al] for two layers CFRP retrofitted joint, also 22.95 kN yield load observed, in comparison to 23kN in the experimental value (Singh *et.al.,*).

In finite element model of two layers CFRP jacketed joints there was no cracks in the jacketed portion of the joints. CFRP jacketed joints showed less deflection at higher loads as comparison to experimental values. The finite element model of CFRP jacketed joints disastrous due to cracks in the un- jacketed portion only. Figure- 14 and Figure -15 shows the cracks and stresses in CFRP retrofitted finite element model beam-column joint. A comparison of experimental and FEM values shown in Fig.16 Fig. 17.

VI. CONCLUSIONS

The following major conclusions are drawn;

1. The experimental study shows that the CFRP retrofitted joints showed an increase in ultimate load carrying capacity of 9.47% as compared to control joint specimens, shows the usefulness of CFRP for retrofitting but in the FEM analysis, finite element models of CFRP retrofitted joint showed this increase 18.78%, as compared to control sample at ultimate loading.
2. The experimental study shows that the CFRP retrofitted joints showed an increase in yield load 15 %, as compared to control joint. but in the FEM analysis, finite element models of CFRP retrofitted joint showed this increase 14.75%, as compared to control sample at ultimate loading which is approximately same as in the experimental results.
3. The experimental study shows that the CFRP retrofitted joints showed an increase in stiffness of CFRP jacketed joints with 15.46%, as compared to control joint. but in the FEM analysis, finite element models of CFRP retrofitted joint showed this increase 43.29%, as compared to control sample at ultimate loading.
4. In the comparison of the results obtained from FEM with ATENA and that from the experimental analysis shows that the FEM with ATENA results are approximately similar to the experimental results for the carbon fiber reinforced polymers.

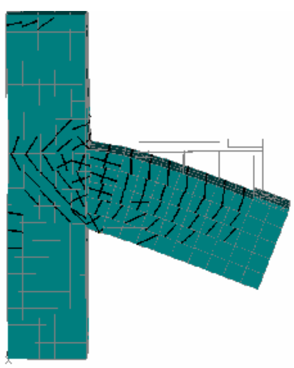

Fig. 12.

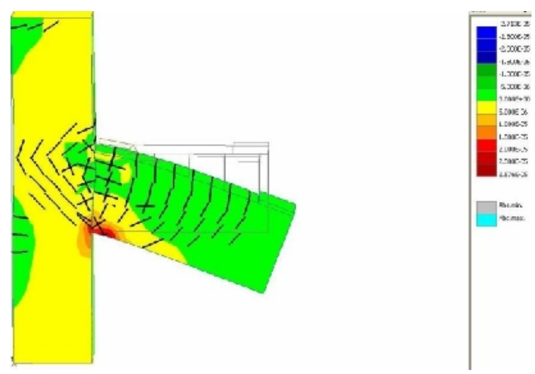

Fig. 13.

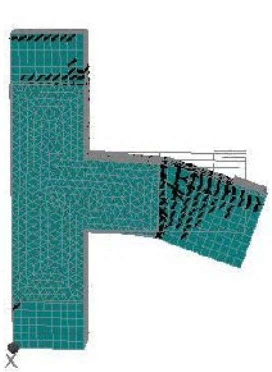

Fig. 14.

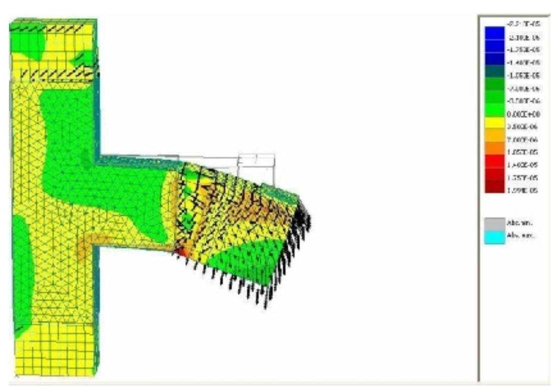

Fig. 15.

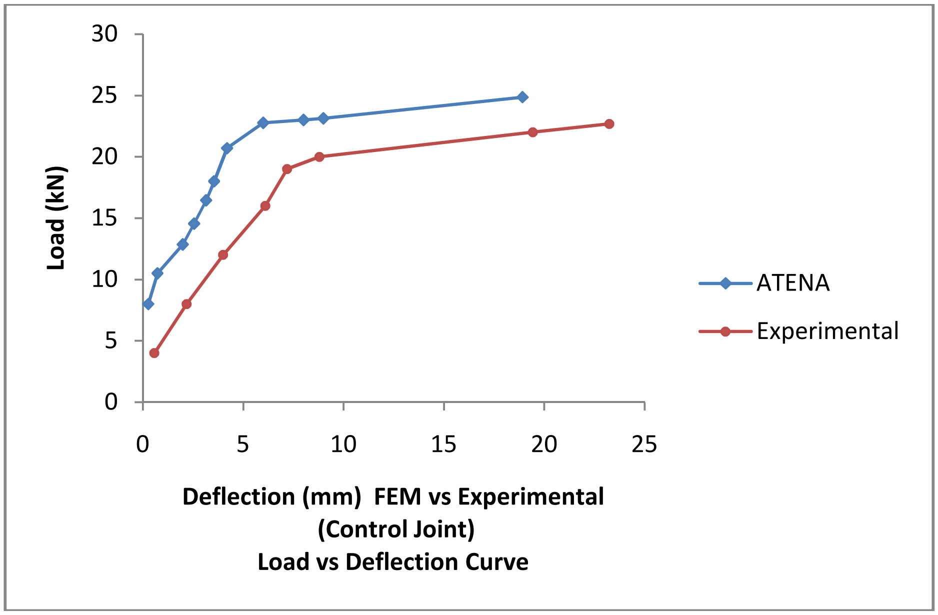

Fig. 16. Comparison Un-Retrofitted Experimental vs FEM (Load vs Deflection Curves).

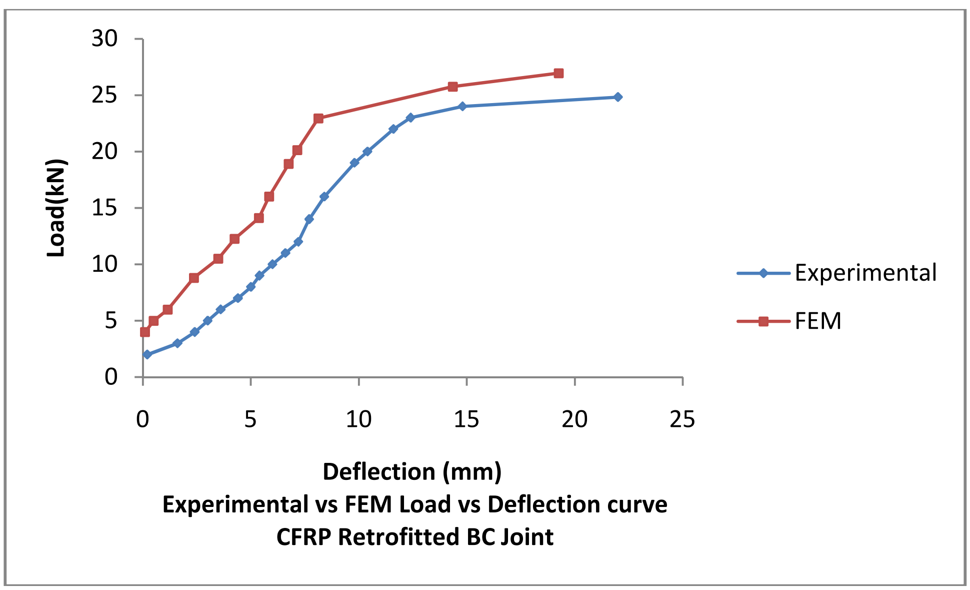

Fig. 17. Comparison CFRP Retrofitted Experimental vs FEM (Load vs Deflection Curves).

Table 5: Comparison of Experimental vs Finite Element Modeling for Ultimate load, Yield load, First crack load, Ductility Ratio and Energy absorption.

S.No.	Analysis Type	Sample Type	First Crack Load (kN)	Yield Load (kN)	Pu (kN)	Percentage Variation			Δ_{CR} (mm)	Δ_Y (mm)	Δ_U (mm)	Ductility ratio (Δu/ Δy)	Stiffness P_u / Δ_U kN/mm	Energy Absorption (KN.mm) ***
						P_{cr}	P_y	P_u						
1	Experimental	URS	6.85	20	22.68	-	-	-	1.58	8.38	23.24	2.77	0.97	412.70
2	FEM	URS	8.46	22.76	24.85				0.30	6.00	18.91	3.15	1.31	375.60
3	Experimental	CFRP-RS	8.98	23.00	24.83	31.09	15	9.47	5.35	12.40	22.00	1.77	1.12	371.49
4	FEM	CFRP-RS	9.35	22.95	26.94	36.49	14.75	18.78	2.80	8.12	19.25	2.37	1.39	370.80

P_{CR} – first crack load, P_Y – yield load, P_U – ultimate load; URS- un-retrofitted Sample; CFRP-RS Carbon Fiber Retrofitted Sample
ΔCR – deflection at first crack, ΔY – deflection at yield point, ΔU – deflection at ultimate load;
*** Area Under load deflection graph using tri-linear curves

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