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EFFECT OF LAP SPLICE LENGTH OF CFRP SHEETS WRAPPED TO REINFORCED CONCRETE BEAM UNDER FLEXURE

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Abstract: This paper investigates the performance of the lap length of CFRP sheets in strengthened RC beams to predict the ultimate load and deflection. A nonlinear 3D finite element model (FEM) subjected to a single point load is developed using ABAQUS. The behaviour of beams is described by evaluating their respective material models. The concrete-CFRP interface is represented by a cohesive zone model and the CFRP is modelled using a linear elastic isotropic model. Lap splicing of CFRP sheets is usually adopted for the transition of forces. Here, the CFRP is lapped for the length of 25mm, 50mm, and 75mm at mid-span and 1/3rd span of the beam. The numerical analysis aligns well with experimental findings in terms of load-deflection response when employing the cohesive bond model. The effect of the variation in the grade of concrete and the depth of the beam is also taken into account. It is observed that 50mm lap length sustains higher load-carrying capacity for the variation in the grade of concrete and depth of the beam. A 50mm lap length is found to be optimum.

***Index Terms* - Carbon fiber reinforced polymer (CFRP); Finite element model (FEM); Lap Length; ABAQUS.**

I. INTRODUCTION

Nowadays, Carbon Fiber Reinforced Polymer (CFRP) has gained extensive use in strengthening Reinforced Concrete (RC) beams. It significantly enhances flexural strength, diminishes crack development, and notably bolsters structural performance when compared to plain RC beams. Delamination of CFRP from the concrete is one such predictable failure mode for the strengthened beams usually occurs due to its inability to resist the high tensile stresses [1, 8]. When employing CFRP sheets for strengthening RC beams, a crucial aspect to consider is the lap splicing technique within the delamination process.

CFRP is extensively used to strengthen the structural elements and to upgrade the old structures since it is lightweight, high resistant to corrosion and good fatigue. CFRP is also used for its high strength to density ratio [8, 12]. Some of these advantages are: maintenance costs can be minimized and can be installed at the faster rate compared to the traditional materials. During the last two decades, there are many applications of CFRP in the retrofitting of bridges, buildings, and other structures to enhance the load carrying capacity of the structural elements. To understand the behaviour of the strengthened RC members and performance of CFRP, experimental, analytical and numerical studies are going on in many parts of the world [2, 3, 5, 8, 12,19,20]. Wrapping beams with CFRP on the tension side yields superior strength compared to applying CFRP on two parallel sides. Hence, it's preferred to use CFRP specifically on the tension side of the beam (as referenced in [8, 15]). The length of CFRP plays a crucial role in determining the ultimate load and behaviour of retrofitted beams that are strengthened using CFRP[18]. The cohesive model has been demonstrated through references [11, 13-14] to accurately depict the bond behaviour between CFRP and concrete. In reinforced concrete beams reinforced with CFRP plates, the presence of cracks is contingent upon the length of the CFRP plate. Most literature recommends ABAQUS for nonlinear analysis of CFRP-strengthened RC beams and exploring various parameters. The focus lies on CFRP types, dimensions, orientation, layer numbers, their effects on different factors, CFRP's impact on lap splice lengths, and modelling techniques. In finite element analysis, the glue is often modelled as perfectly compatible with CFRP nodes and concrete nodes due to observed lack of failure, accurately predicting load-displacement relations, ultimate load, and failure modes of the beam. Concrete damaged plasticity techniques showcase comprehensive representation of concrete's inelastic behaviour, encompassing tension-induced cracking and compression-induced crushing. Studies suggest a minor increase in loading capacity with an increase in bond length. Lap splicing of CFRP has received limited attention. Recent studies investigated lap lengths of CFRP at the beam's bottom. Yang et al. [17] delved into the fatigue performance of different lap-spliced CFRP lengths, revealing that 101.6-mm lap-spliced CFRP laminates endure over 2.0 million load cycles without compromising residual strength

This paper introduces a nonlinear 3D finite element model (FEM) aimed at predicting the ultimate load and deflection of CFRP-strengthened beams under a single point load. Validation against experimental data confirms the model's accuracy. The beams' behaviour is characterized using specific material models within the ABAQUS software. Strengthening the beam involves overlapping CFRP sheets at lengths of 25mm, 50mm, and 75mm, positioned either at the mid-span or 1/3rd span, a crucial aspect in standardized repair techniques. A thorough parametric study explores the impact of beam depth and concrete grade, varying the CFRP lap length for each depth and grade increment. Results indicate a substantial increase in load carrying capacity, particularly with an optimal CFRP lap length of 50mm, affirming the effectiveness of this strengthening approach.

The absence of standardized design protocols poses a challenge in externally strengthening structures using CFRP. Establishing a comprehensive comprehension of structures reinforced with CFRP is essential to formulate rational design guidelines. This research endeavors to enhance understanding regarding the impact of lap splicing on the load-carrying capacity and overall performance of strengthened beams. Its aim is to contribute valuable insights toward developing more informed design guidelines.

II. FINITE ELEMENT MODELLING

2.1 General

Finite element analysis is a numerical method that retains the intricacies of problems, such as varying shapes, boundary conditions, and loads, in their original form while providing approximate solutions. Its widespread attention in engineering stems from its versatility and adaptability as an analysis tool. In this study, Finite Element Analysis (FEA) is performed to model the nonlinear behaviour of the beams to validate the experimental test results. The FEM package ABAQUS [6] was used for the analysis. Two 3D FE models (one plain beam and one beam strengthened with CFRP) are developed as shown in Fig.2a and Fig.2b, and analyzed for validation purpose. Both models share an identical cross-section and are subjected to single point loads while being supported at their ends, following a simply supported configuration in the finite element analysis. The FE model measures 700mm in length, 150mm in width, and 150mm in depth, as depicted in Figure 1. CFRP strips, 150mm wide, 500mm long, and 1mm thick, are adhered to the underside of the beam, oriented along the axial direction of the beam, as illustrated in Figure 2b. Table 1 details the mechanical properties of the CFRP material. The CFRP sheets are overlapped at lengths of 25mm, 50mm, and 75mm, positioned either at the midspan or at the 1/3rd span of the beam, as shown in Figures 2c and 2d.

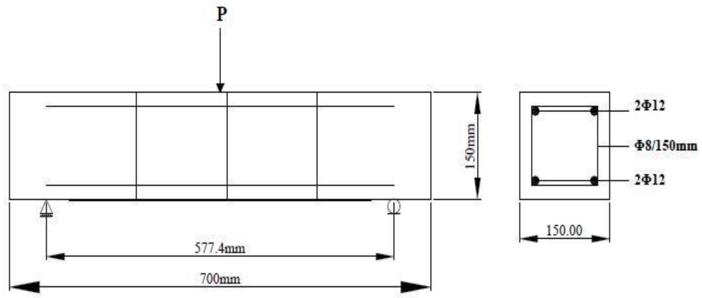

Fig.1: Geometry, reinforcement and load of the beam

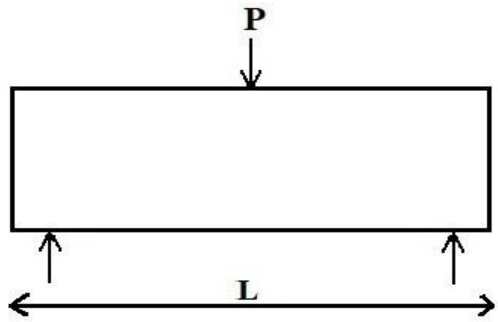

Fig.2a: RC Beam without wrap

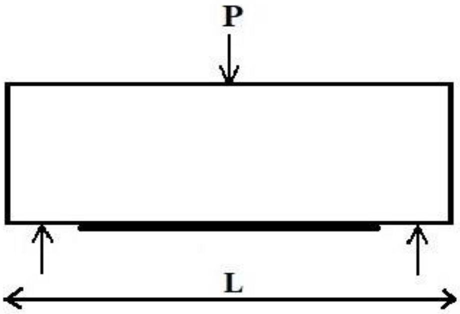

Fig.2b: RC Beam wrapped with CFRP

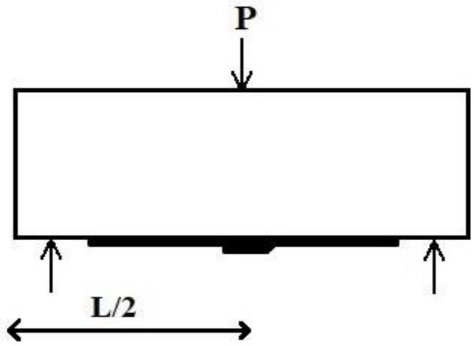

Fig. 2c : RC Beam wrapped with CFRP and lapped at mid span of beam

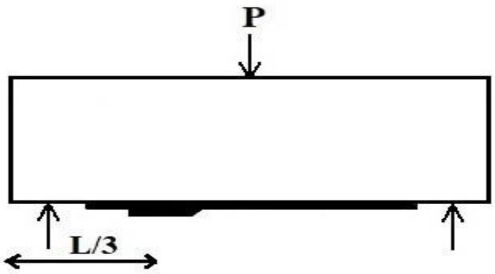

Fig. 2d : RC Beam wrapped with CFRP and lapped at 1/3rd span of beam

Table 1 : Properties of Materials for FE analysis

Materials	Parameters	
Steel	ρ_s (kg/m^3)	7850
	E_s (GPa)	210
	f_y (MPa)	500
	υ	0.3
Concrete	ρ_c (kg/m^3)	2400
	υ	0.2
CFRP	E_{CFRP} (GPa)	540
	$G^C{}_n$ (N/mm)	0.9
	$G^C{}_t = G^C{}_s$ (N/mm)	0.09
	$\tau^0{}_s = \tau^0{}_t$ (MPa)	1.5
	υ	0.3
	η	1.45

Geometric modeling is pivotal in finite element modeling, and selecting the right element type is crucial for accurately simulating a structure's physical behavior. In this particular study, the CFRP layer is represented using 4-node plane stress elements (CPS4R). Concrete, on the other hand, is modeled using 8-node linear brick elements with reduced integration and hourglass control (C3D8R). Steel components are represented using truss elements. Each of these instances is created separately and then assembled to effectively simulate the behavior of an RC beam strengthened with CFRP.

2.2 FE meshing and contact modelling

Selecting an appropriate mesh size in Finite Element (FE) modeling is crucial, especially when simulating high strain rate loading events. In this particular FE modeling, various mesh sizes have been employed to expedite the conventional computation time. A moderately sized mesh has been chosen for modeling both concrete and CFRP. However, during simulation, there have been instances of excessive deformation observed in both the CFRP and concrete components.

The interaction between concrete and CFRP is simulated using a cohesive zone model, specifically employing a bilinear traction-separation law. This cohesive zone model characterizes the interface behavior and damage evolution. The evolution of interface damage is quantified in terms of energy release, as outlined in reference [8]. The dependence of fracture energy on the mode mix is determined by the Benzaggah-Kenane fracture criterion [8]. When the critical fracture energies for deformation along the first and second shear directions are equivalent, the Benzaggah-Kenane fracture criterion is applicable. The values utilized in this tudy are detailed in Table 1. For the interaction between CFRP-CFRP during lapping, a tie constraint is employed, effectively bonding the two surfaces together.

2.3 Material Model

The materials used for modelling the RC beam involve concrete, steel bars and CFRP. The constitutive models available in the ABAQUS material library are used to model the material behavior. The input parameters and their corresponding models are discussed briefly.

2.3.1 CFRP

The CFRP material is presumed to behave as linear elastic isotropic until it reaches failure. Given that the composite primarily experiences stress along the fiber direction, the modulus in that specific direction is more pertinent [12]. As a result, an isotropic model for CFRP is deemed appropriate for this study. The mechanical properties of unidirectional CFRP are explicitly detailed in Table 1.

2.3.2 Steel

The steel material was assumed to exhibit elastic-perfectly plastic behavior and possess identical characteristics in tension and compression. The steel reinforcement configuration aligns with the representation in Fig. 1. The bond between the steel reinforcement and concrete was assumed to be perfectly bonded. Table 1 outlines the mechanical properties of the steel utilized for analysis purposes.

2.3.3 Concrete

The concrete behavior is modeled using the Concrete Damage Plasticity model available in the material library [6]. This model incorporates two failure modes: tensile cracking and compressive crushing. In uniaxial tension, the stress-strain response follows a linear elastic pattern until reaching the failure stress value. The stress-strain relationships for concrete under uniaxial tension and compression. Establishing the tensile cracking necessitates the elastic parameters Ec and fct. Assuming a compressive strength fc' of 20 MPa, Ec and fct were computed using equations from references [8, 12]:

$$E_c = 4700\sqrt{f_c'} = 21000 MPa \quad ---- (1) \qquad f_{ct} = 0.33\sqrt{f_c'} = 1.5\ MPa \quad -----(2)$$

III. Validation of Finite Element Model

Validating the simulation results derived from the developed FE models (Fig.3) involves a comparison with experimental data. The comparison primarily focuses on load carrying capacity and deflection to ascertain the accuracy and reliability of the simulation outcomes. This validation process ensures that the numerical models effectively replicate the real-world behavior observed in experimental tests. Good matching between the experimental results and FEA results in terms of load-deflection curves for RC Beams strengthened with CFRP as shown in Fig.4. The FE results are found to be 90% closer to the experimental results. Table 2 shows the comparison of experimental results and FEA results and ratios of load carrying capacity and deflection are presented. The ratios obtained are less than 1. The RC beam of 700 x 150 x 150mm is wrapped with CFRP at the bottom of the beam and is subjected to single point load. The length, breadth and thickness of CFRP is taken as 577.4mm, 150mm and 1mm respectively. Further, the CFRP is lapped for the length of 25mm, 50mm and 75mm. The observed trend in both FEA and experimental results, where load carrying capacity increases for 0mm, 25mm, and 50mm lap lengths but decreases for a 75mm lap length, suggests a possible reason behind this behavior. As the lapping length of CFRP increases, it potentially lowers the tensile stress in the CFRP while simultaneously elevating the tensile stress in the concrete. This shift in stress distribution could lead to the occurrence of debonding, indicating potential failure of the CFRP at the bottom of the beam. This behavior likely signifies a critical point in the failure mechanism associated with lap lengths and their impact on load-carrying capacity.

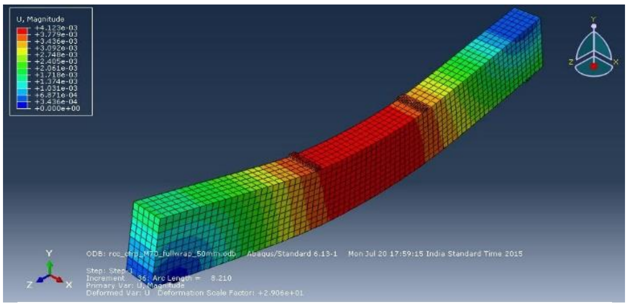

Fig..3: FEA of CFRP wrap beam deformation

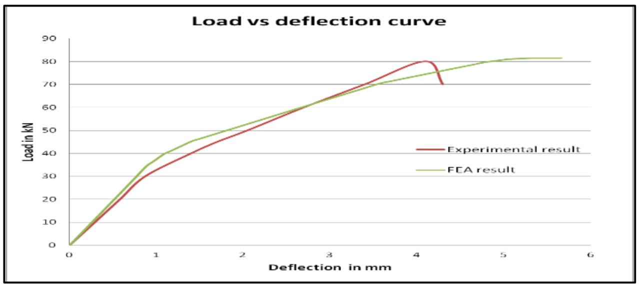

Fig..4: Comparison of experimental and FEA

Table 2: Comparison between experimental results and FE analysis

RC Beam strengthened with CFRP	Ultimate load (kN)		Maximum Deflection (mm)		P_{test}/P_F	δ_{test}/δ
	P_{test}	P_{FEA}	δ_{test}	δ_{FEA}		
0mm	72.36	80.76	4.70	5.2	0.90	0.91
25mm	75.36	86.39	13.80	14.25	0.87	0.96
50mm	82.11	90.84	6.30	6.98	0.91	0.90
75mm	73.02	79.41	9.60	10.4	0.91	0.92

PARAMETRIC STUDY

4.1 Effect of lap length of CFRP on depth of beam

Considering the variation in depth of beam, here 0mm, 25mm, 50mm and 75mm lap lengths is done for the RC beam of M20, M30, M40 and M50 grade of concrete and the load vs. lap length of CFRP graph is plotted as shown in Fig.5 and Fig.6 with beam designation mentioned in Table 5 and it is observed that load carrying capacity increases as lap length on beam increases for all depths of beam. Therefore, 50mm lap length sustains higher load carrying capacity than all other lap lengths. The percentage load carrying capacity of all lap lengths compared with the plain beam, 0mm lap length and 50mm lap length are given in Table 3, for RC beam of M20, M30, M40 and M50 grade of concrete. Based on the observed trends and outcomes, it's reasonable to conclude that a lap length of 50mm appears to be optimal for achieving the ultimate strength in CFRP laminates. Therefore, for lapping performed both at the mid-span and at 1/3rd span of the beam, a 50mm lap length is deemed sufficient to achieve the desired level of strength in the CFRP. This finding suggests that this specific lap length effectively balances stress distribution and prevents debonding, resulting in optimal load-carrying capacity.

4.2 Effect of lap length of CFRP on grade of concrete

The load vs lap length of CFRP graph is plotted by considering the variation in grade of concrete (M20, M30, M40 and M50) as shown in Fig.5 and Fig.6 with beam designation mentioned in Table 5 for the RC beam of 200mm, 300mm, 400mm and 500mm depth. The lap lengths considered for CFRP are 0mm, 25mm, 50mm and 75mm. It is observed that load carrying capacity increases as lap length on beam increases for all grades of concrete. Therefore, 50mm lap length sustains higher load than all other lap lengths. The percentage load carrying capacity of all lap lengths compared with the plain beam, 0mm lap length and 50mm lap length are given in Table 4, for RC beam of 200mm, 300mm, 400mm and 500mm depth. Absolutely, based on the trends observed and the results obtained, it's conclusive that a lap length of 50mm has proven sufficient to attain the ultimate strength in CFRP laminates. Consequently, for both mid-span and 1/3rd span lapping of the beam, a 50mm lap length emerges as the optimum choice for achieving the desired strength in the CFRP. This finding underscores the significance of this specific lap length in ensuring optimal load-bearing capacity while maintaining structural integrity.

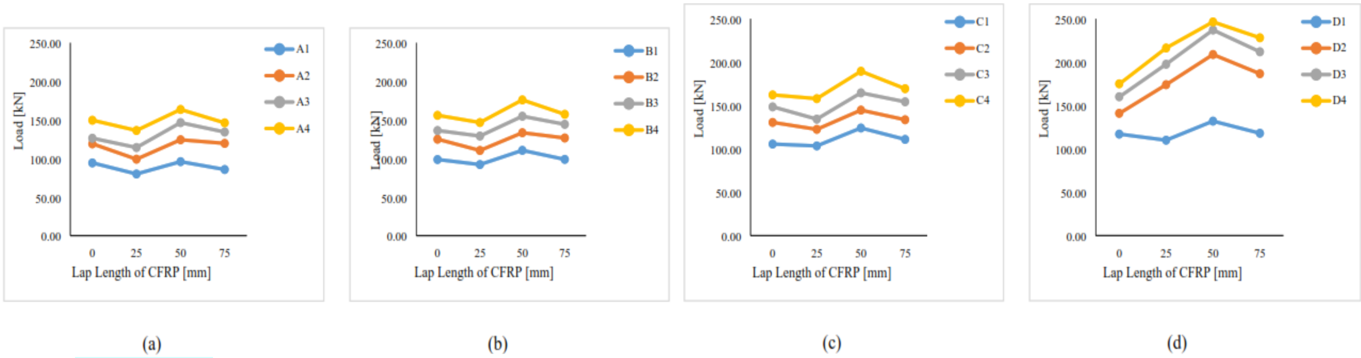

Fig.5: Load vs Lap Length of CFRP for lapping done at mid-span of beam

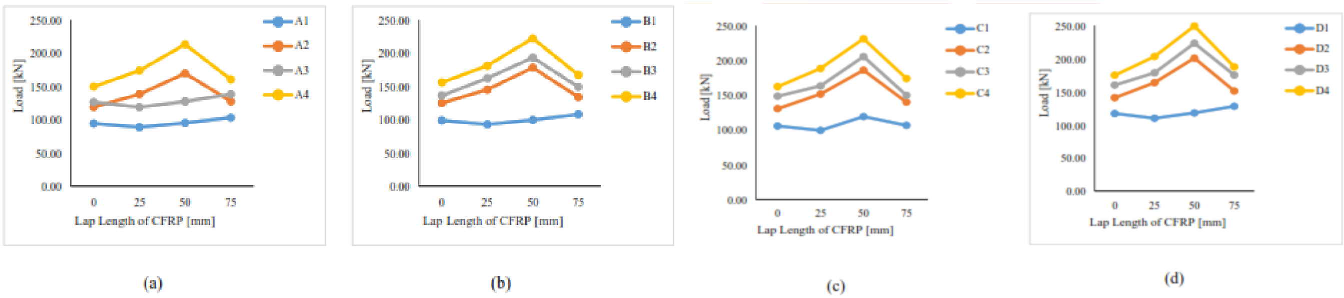

Fig.6: Load vs Lap Length of CFRP for lapping done at 1/3rd span of beam

Table 3: Percentage of load capacity for 50mm lap length, no lap CFRP wrapped and without wrap plain RC beam with different depths of beam for position of lapping at mid span of the beam.

Depth of Beam (mm)	Load increase in percentage (%)											
	M20			M30			M40			M50		
	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)
200	23.3	21.46	1.74	23.88	29.24	12.08	12.25	44.59	17.57	23.12	48.17	18.92
300	15.18	18.13	4.48	17.36	31.12	6.76	19.28	39.25	10.88	36.94	61.77	48.1
400	12.56	27.8	16.04	13.41	34.36	19.62	21.95	46.35	21.52	43.05	64.4	52.3
500	22.17	24.30	9.38	16.23	41.89	12.84	26.84	49.11	16.81	51.26	65.5	40.8

(1) with wrap (no lap) vs without wrap (plain beam), (2) 50mm lap vs without wrap (plain beam), (3) 50mm lap vs with wrap (no lap)

Table 4: Percentage of load capacity for 50mm lap length, no lap CFRP wrapped and without wrap plain RC beam with different depths of beam for position of lapping at 1/3rd span of the

Depth of Beam (mm)	Load increase in percentage (%)											
	M20			M30			M40			M50		
	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)
200	22.7	24.46	2.85	21.87	27.24	14.8	15.25	42.59	19.57	25.12	46.17	19.92
300	14.29	19.13	1.48	18.36	29.12	8.76	17.28	37.25	13.87	38.94	63.77	49.1
400	11.56	25.8	17.04	15.41	31.36	21.62	19.95	48.35	23.52	41.05	65.4	53.3
500	23.17	26.30	11.38	18.23	42.89	14.84	25.84	47.11	17.81	53.26	67.5	41.8

4.3 Deflection

The deflection vs lap length of CFRP graph is plotted for RC beam of M50 grade of concrete with 200mm depth as shown in Fig.7. Here we observe that the deflection of RC beam is higher by 3.86% for 50mm lap length when the lapping of CFRP sheet is done at the mid-span of the beam. But when the lapping is done at the 1/3rd span of beam, the deflection of beam is reduced by 10% for 50mm lap length. Hence, it is found that 50mm lap length CFRP wrapped RC beam is more stiffer than the RC beam with no wrap and RC beam with no lap and also lapping of CFRP done at 1/3rd span of the beam makes the more stiffer than the lapping of CFRP done at mid-span of the beam.

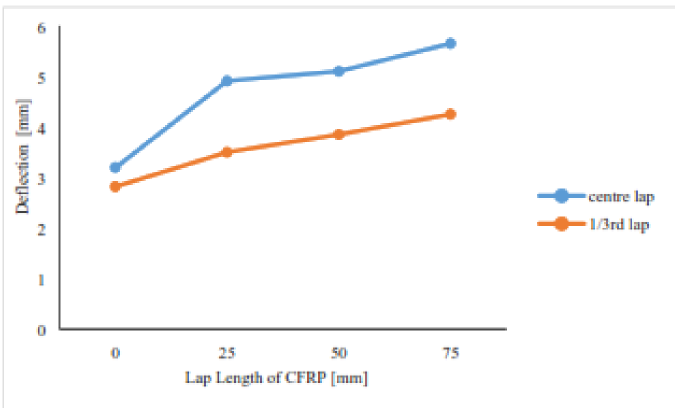

Fig..7: Deflection vs Lap Length of CFRP

IV. Conclusions

The paper explores the impact of CFRP lap length in reinforced concrete beams through Finite Element Analysis (FEA). It showcases the viability of employing CFRP sheets on the tension face of reinforced concrete beams. Utilizing ABAQUS for finite element analysis demonstrates the tool's precision in predicting load carrying capacity, load deformation, and the progression of cracking behavior, mirroring the outcomes observed in experimental tests. This highlights the efficacy and reliability of FEA, specifically conducted through ABAQUS, in simulating and understanding the behavior of CFRP-strengthened concrete structures.

Following are the key conclusions drawn from the present study:

- The strong correlation between experimental and FEA outcomes affirms the efficacy of FE simulations in accurately determining the ideal lap length of CFRP in reinforced concrete beams under a singular point load. The use of a cohesive bond model effectively represents the bond behavior between CFRP and concrete in these simulations.
- Comparing CFRP-wrapped RC beams to plain RC beams reveals higher load carrying capacity and reduced deflection across all concrete grades and beam depths. The load capacity increases by 10% to 15% with each rise in concrete grade and by 5% to 20% with each increment in beam depth.

Consequently, CFRP-wrapped beams consistently outperform plain RC beams, regardless of concrete grade or beam depth, when lapping occurs at both mid-span and 1/3rd span positions.

- For CFRP-wrapped RC beams, whether lapped at the mid-span or 1/3rd span, a 50mm lap length demonstrates a notably superior increase in load carrying capacity. The RC beam wrapped with 50mm lap length of CFRP is more stiffer in comparison with the RC beam with no wrap and RC beam with no lap and also lapping of CFRP done at 1/3rd span of the beam makes the more stiffer than the lapping of CFRP done at mid-span of the beam. Hence, 50mm is the optimum lap length of CFRP sheet.
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Table 5: Beam Designation

Beam	Grade of Concrete	length(mm)	width(mm)	height(mm)
A1	M20	700	150	200
A2	M20	700	150	300
A3	M20	700	150	400
A4	M20	700	150	500
B1	M30	700	150	200
B2	M30	700	150	300
B3	M30	700	150	400
B4	M30	700	150	500
C1	M40	700	150	200
C2	M40	700	150	300
C3	M40	700	150	400
C4	M40	700	150	500
D1	M50	700	150	200
D2	M50	700	150	300
D3	M50	700	150	400
D4	M50	700	150	500

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