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AN EXPERIMENTAL STUDY ON RC CONTINUOUS BEAM STRENGTHENED BY USING FRP SHEET

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ABSTRACT

Strengthening structures using external bonding of advanced fiber reinforced polymer (FRP) composite is in its advent around the world from the past decade for it is more economically and technically effective and reliable substitute for the traditional structural engineering techniques in many applications as it possesses increased strength, light weight, corrosion free, high resistance to fatigue, simple and speedy installation and reduced change in structural geometry. Although in many of the practical implementations, RC beams are continuous in construction, the research work on FRP is seldom performed which is needed to be in focus for cheap and reliable substitutes for the exiting traditional techniques

As a part of current study, an experimental analysis is carried out on the behavioral attributes of continuous RC beams are subjected to static loading. These beams were reinforced with glass fiber reinforced polymer (GFRP) sheets which were externally bonded to the beams. To study the behavior of these strengthened beams, these are strengthened at different locations and with different arrangements.The observed results indicate that the flexural strength of RC beams can be consistently enhanced by attaching GFRP sheets to the tension face. Also, the epoxy bonded sheets enhanced the resistance to cracking of the beams by inhibiting the development of visible cracks and avoiding the increased crack widths at higher load levels.

KEYWORDS: continuous beam; flexural strengthening; GFRP; epoxy bonded sheets; external bonding.

INTRODUCTION

Around the world, a wide scope of research is currently being concerned about the use of fiber reinforced plastic encapsulations, laminates and sheets in the strengthening of reinforced concrete beams. Although several researches are being conducted on the strengthening of simply supported RCC beams using external plates or wraps, there is very less success results regarding this work on the behavior of strengthened RCC continuous beams. However, most of the design techniques were introduced for simply supported RCC beams with external FRP laminates [1]. A critical reviews regarding this concept shows that there is a need for the focus of researchers and engineers regarding the strengthening of negative moment region of continuous beams using FRP encapsulations.

MATERIALS AND METHODS

According to the existing literature,the experimental analysis compares the behavior of RC continuous beams strengthened with FRP plates with the non-strengthened beams (control beam) [4]-[9]show that, the use of FRP plates and sheets to strengthen the continuous beams is very much effective for minimizing the deflections and for increasing the load bearing capability. Aiello et al. [10] contrasts the continuous RC beams strengthened with carbon fibre reinforced polymers(CFRP) sheets at different values of negative and positive moment regions and traditional RC beams strengthened at both negative and positive moment regions. All beams were strengthened with a single CFRP layer. The control beams encounters a typical flexural behavior.The failure of the strengthened beams encapsulated with CFRP sheet is caused due to debonding of the CFRP sheet. It has been observed that when strengthening was was performed at both hogging and sagging regions, the ultimate load carrying capacity of the beam was the highest and about 22% of moment re-distribution was achieved. Grace et al. [11]analysed the effect of tri-axially woven ductilefabric providing ductile behaviors in RC continuous beams strengthened in flexure. They also concluded that, the beams strengthened with the fabric showed a greater ductility than those of strengthened with the carbon fiber layer. SoumyaSubhashree [12] tested fourteen symmetrical continuous (twospan) beams. The beams were grouped into two series. Each series had a different percentage of steel reinforcement. One beam from each series was not strengthened and was considered as a control beam, whereas all other beams were strengthened with different patterns of FRP sheets with externally bonded Glassfibre reinforced polymers (GFRP) sheets. The observational result was that the beam strengthened by U-shaped wrap , anchored by steel plate and bolt system, shows the highest ultimate load carrying capacity. The percentage increase of the load capacity of that beam was around 62percent.The load carrying capacity of beam which was strengthened by four layers of U-wrap in positive moment region was closer to the load capacity of beam strengthened by two layers U-wrap ,anchored by steel plate and bolt system. The percentage of increase in load carrying capacity of the beam was around 60percent. Usage of steel bolt and plate system is an efficient technique for anchoring the FRP sheet to avoid the debonding failure. Strengthening of continuous beam with U-wrap of FRP sheet is also an effective way to enhance the load carrying capacity.

Previous FE studies of FRP-strengthened beams involve the use of refined FE meshes of two-dimensional plate/shell elements [13]-[16] or three-dimensional solid elements [17] using many commercial finite element packages. Using commercial numerical finite element package Abaqus, Obaidat et al. [18], suggested a 3D finite element model to analysis plate end interfacial debonding in retrofitted RC simple beams. Nonlinear cohesive bond model under mode-II conditions was used for the concrete–FRP interface. The high computational cost of structural response analyses based on FE models such as the ones referred above has prompted the development of purely numerical methods (not based on mechanics) for the analysis and design of FRP-strengthened RC structures [19]. Kadhim [20] focused on the behavior of the high strength concrete continuous beam strengthened with different CFRP sheet lengths, ANSYS program was used.The agreement between the results obtained from analysis and experimental date is good respect to load–deflection curve, ultimate strength, and the crack patterns. Full bond between RC beam and CFRP laminates was assumed besides neglecting the softening behavior of concrete either in compression or in tension. The length of CFRP sheet was changed in the negative and positive regions and the results showed that the ultimate strength of the beam was reached when the value of Lsheet/Lspan reaches 1.0. Using Near Surface Mounted (NSM) strengthening technique to strengthen reinforced concrete (RC) members using FRP composites is commonly spread in recent years. Hawileh [21] presented 3D nonlinear FE numerical model that can accurately predict the load-carrying capacity and response of RC beams strengthened with NSM FRP rods subjected to four-point bending loading. The developed FE model is created using the FE code ANSYS. The developed FE model considers the nonlinear constitutive material properties of concrete, yielding of steel reinforcement, cracking of the filler bonding materials, bond slip of the steel and NSM reinforcements with the adjacent concrete surfaces, and bond at the interface between the filling materials and concrete. The numerical FE simulations were compared with experimental measurement tested by other researchers. Overall, the predicted FE mid-span deflection responses agreed very well with the corresponding measured experimental tested data at all stages of flexural loading. Furthermore, the developed models were also capable of predicting the failure mode of the strengthened tested

FINITE ELEMENT MODELING

As shown in Fig. 1, there are three components in a strengthened beam for the present analysis model, i.e. reinforced concrete, FRP, and adhesive. The adhesive layer is modeled as contact layer generalized to handle cohesive forces in both the normal and tangential directions. Fig. 2 shows interfacial shear and normal stress distribution in the adhesive layers or in the cohesive zone. In the current study, a 21-node element is developed to represents the strengthened reinforced concrete beam as shown in Fig. 3. The reinforced concrete beam and FRP layer are modeled as beams with Euler-Bernoulli kinematics assumptions. Linear geometry due to small deformations and displacements is assumed. The cohesive zone model is utilized for determining the normal and tangential stiffness of the adhesive layer. Realistic nonlinear constitutive models are employed to represent the stress-strain behavior of concrete, reinforcing steel and bonded FRP.Perfect bond is assumed between the concrete and reinforcing steel. The model proposed in this study uses the constitutive laws of materials in the total form and not in the incremental form usually adopted in problems involving nonlinear analysis.

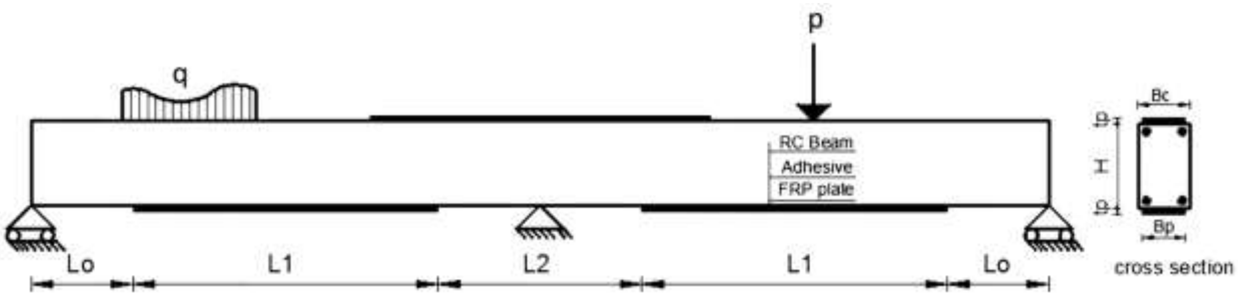


Figure 1.RC beam bonded with FRP plate

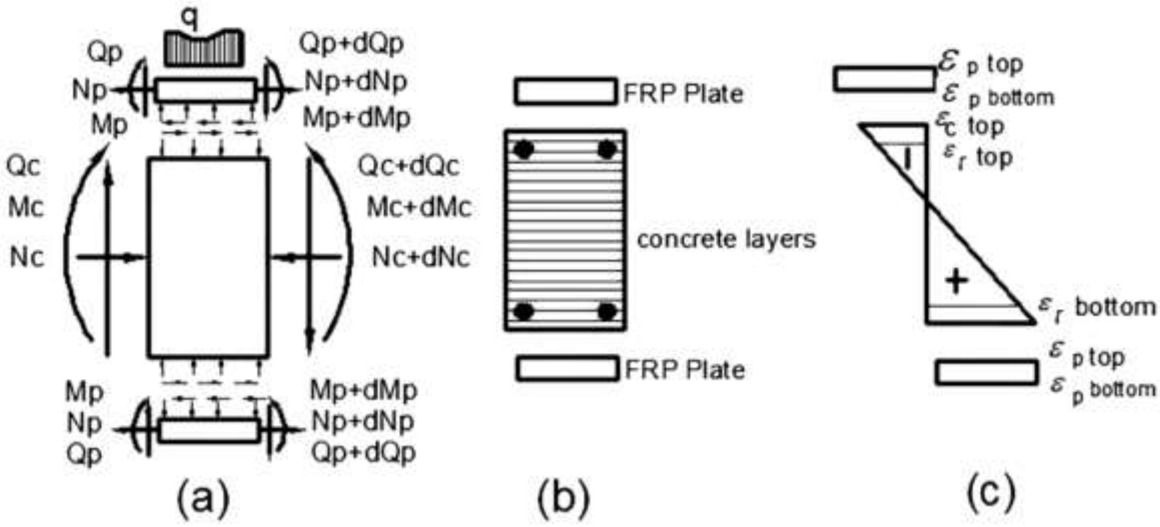


Figure 2. (a) Differential element along span; (b) general cross section geometry and layer discretization; and (c) strain distribution

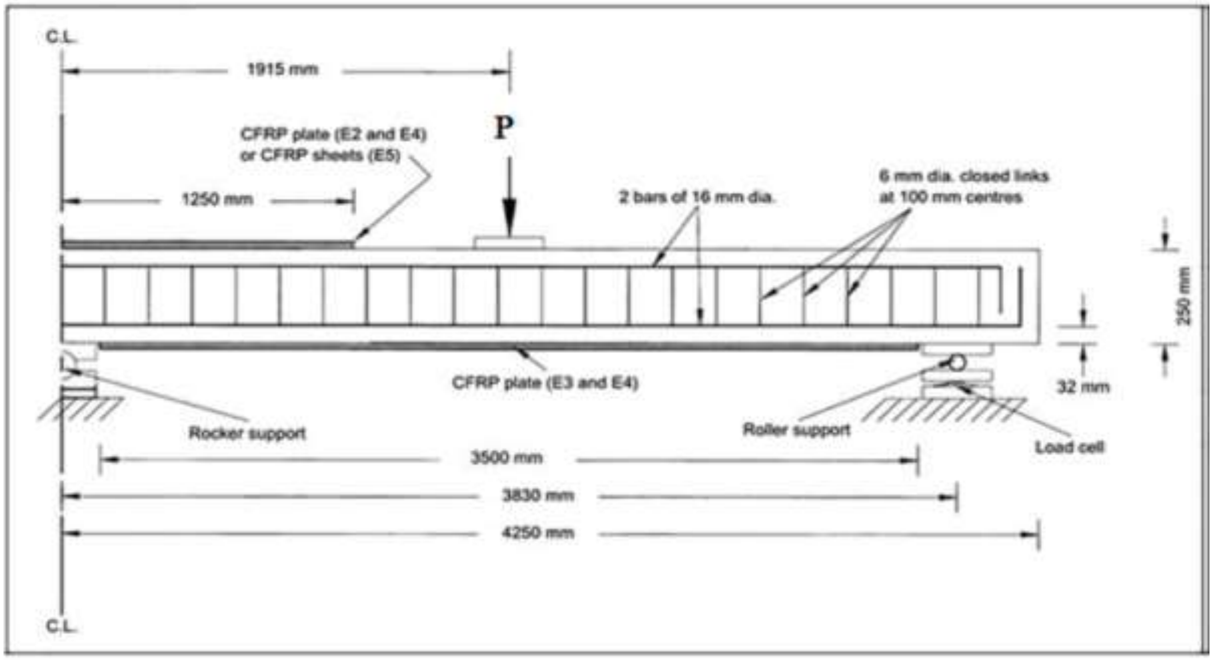


Figure 4. Geometric properties of the specimens tested in [6]

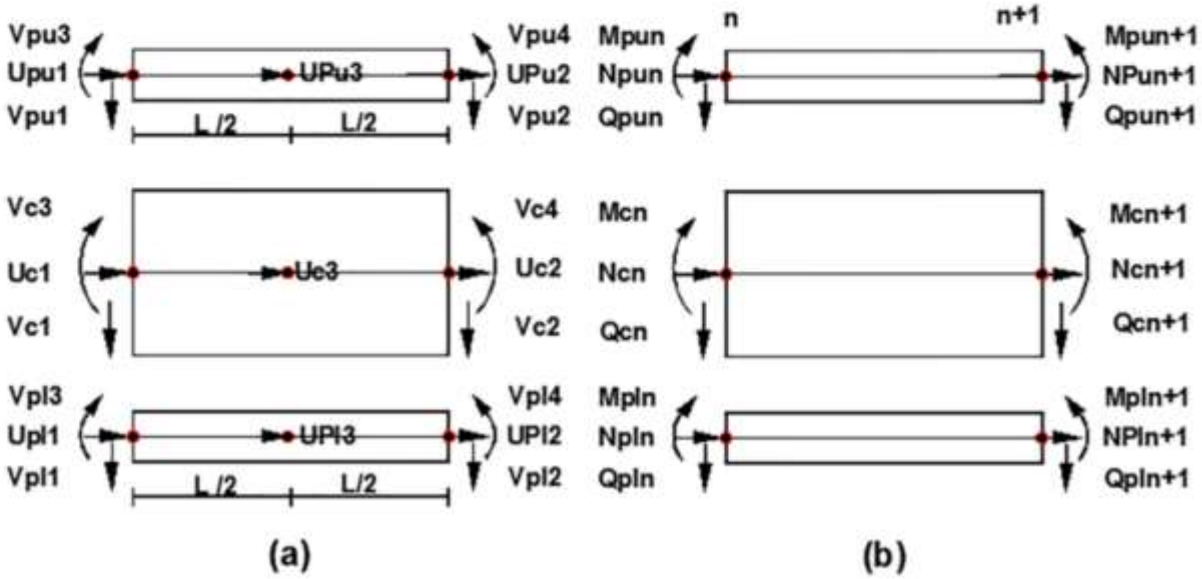


Figure 3. The developed finite element: (a) nodal degrees of freedom; (b)nodal forces

III. CONSTITUTIVE ELEMENTS OF MATERIALS USED FOR ANALYSIS

A layered model approach was followed during the development of the proposed finite element for the concrete beam cross section. The cross section was divided into a finite number of layers. The layered model approach is relevant for the formulation of this type of complex elements due to (i) the difference between the properties of beam reinforcement and concrete; and (ii) the dissimilarity between the behavior of concrete in tension and compression. For concrete in compression, the stress- strain relationship suggested by [22] is adopted. This relationship is characterized by linear-elastic behavior up to 40% of the maximum strength. Beyond the elastic limit, an elastic- plastic with final softening branch is assumed. For concrete in tension, linear-elastic behavior is considered up to the cracking phenomenon, which occurs when the tensilestrength is reached. The tension stiffness of concrete between cracks due the presence of reinforcement is taken into account by the nonlinear softening law proposed by [23]. Compared to the case of concrete without reinforcement, the tensile stress does not vanish for large strain, but it tends to a positive value that depends on the percentage of reinforcement in the concrete beam. For reinforcement steel, an elasticplastic with small hardening law typically used for structural steel has been assumed.The FRP is modeled with linear elasticbrittle behavior in tension and zero-strength and stiffness in compression.Due to its simplicity, cohesive zone modeling is largely used for behavior of adhesive layers. The energy release rates in mode-I (GI) and mode-II (GII) are identified as the areas under the respective cohesive laws integrated up to the current values of stresses. The total energy release rate is the sum of G_I and G_{II}. Different approaches have been used in the literature for cohesive zone modeling of interfaces under mixed-mode conditions: In uncoupled cohesive zone approach, cohesive laws in the normal and tangential directions are independent from each other. In coupled cohesive zone approach, cohesive laws in the normal and tangential directions are linked to each other, typically by means of a coupling parameter.

In the current study, uncoupled cohesive laws are considered both in the normal and tangential directions.This choice is made to enable the use of different values for the mode-I and mode-II interfacial fracture energies, in agreement with the experimental evidence. The cohesive laws implemented herein are bilinear. This simple shape is able to capture the three characteristic parameters of the interface, i.e., the fracture energies (areas underneath the curves), the cohesive strengths, and the linear-elastic properties (slopes of the curves in the ascending branch). Following the approach given by [24], the energy release rates in mode-Iand mode-IIare identified as the areas under the respective cohesive laws integrated up to the current values of normal and tangential displacements and the simplest possible mixed-mode failure criterion . The mode-mixities can be estimated directly from the numerical predictions by examining the value of G_{II}/G_I for a crack-tip cohesive zone element just before it fails. The above cohesive models have been implemented into a 21-node composite element proposed by the current study, and generalized to handle cohesive forces in both the normal and tangential directions. Also, all the above constitutive equations of materials for concrete in tension or compression, reinforcement, and FRP have been implemented in that element.

EXPERIMENTAL VALIDATION

A. PREDICTION OF ULTIMATE LOAD- CARRYING CAPACITY

The proposed FE model is evaluated through a comparison between the experimentally measured and the numerically predicted load-carrying capacity of the two spansymmetrical continuousbeams included in the experimental database. The geometric properties of the specimens and the most important mechanical properties of the used materials, including both reference (i.e., non-strengthened) and FRP-strengthened beams as in [6], [7], and [12]and mostly obtained through steel coupon and FRP tensile tests or concrete compression tests. Table I and Table IIshow a comparison between the experimental ultimate load capacity, P_{exp},ultimate negative bending moment, M^{--}_{exp} ,and ultimate positive bending momentM^{+}_{exp} at failure of test specimens and the predicted FE ultimate load capacity P_{FE}, ultimate negative bending moment, M^{--}_{FE} ,and ultimate positive bending moment M^{+}_{FE} obtained by UNFEM at failure of test specimens. The ratio between the predicted and the experimental ultimate load capacity ranges from 0.93 to 1.17. The ratio between the predicted and the experimental ultimate negative bending moment ranges from 0.84 to 1.18. The ratio between the predicted and the experimental ultimate positive bending moment ranges from 0.83 to 1.16. The agreement between the experimental results and the predicted results is very good for the reference beams and the strengthened beams.

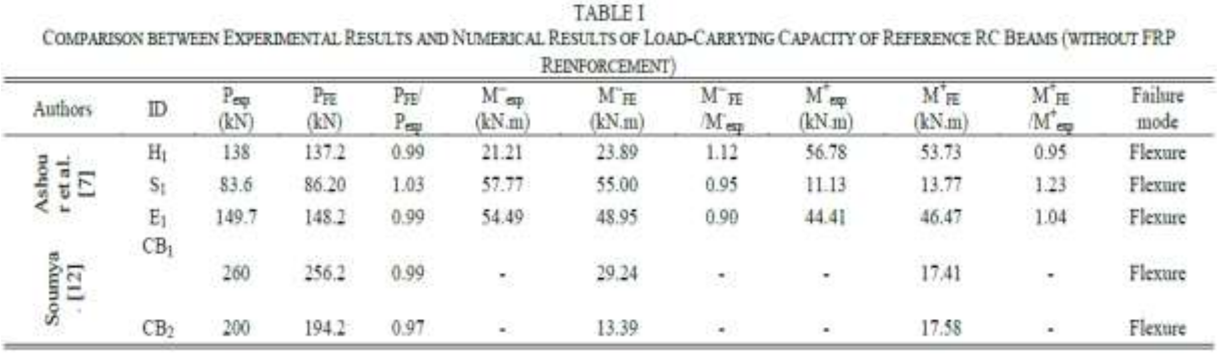
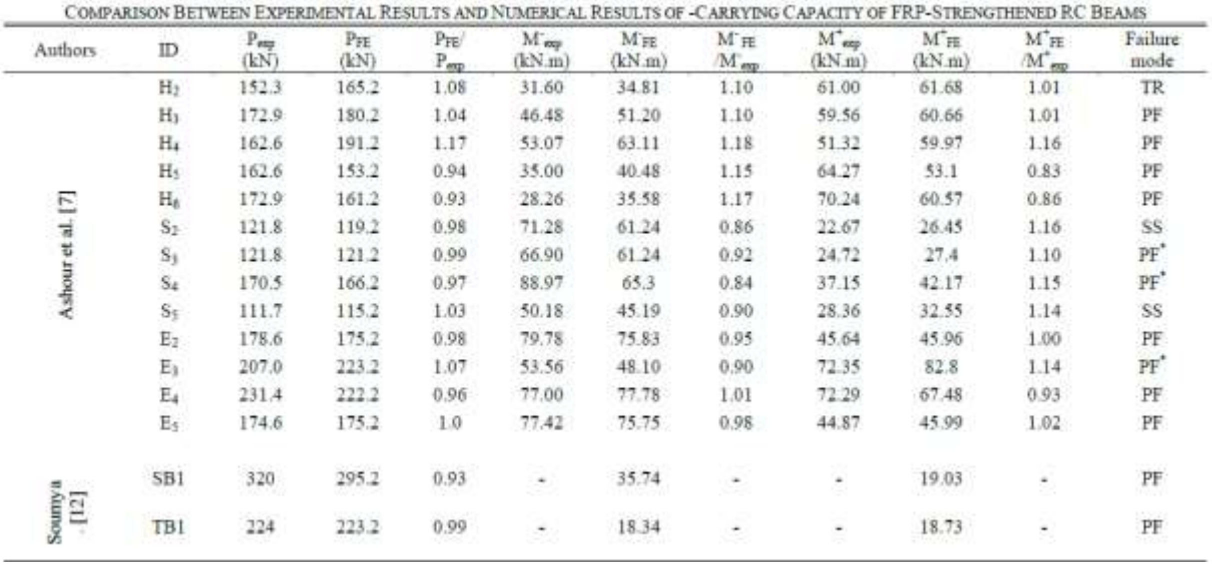


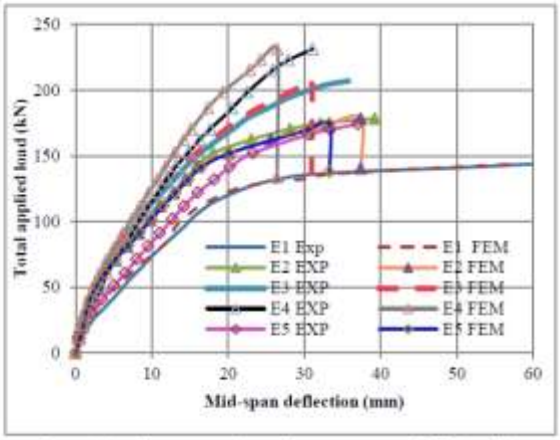
TABLE I
COMPARISON BETWEEN EXPERIMENTAL RESULTS AND NUMERICAL RESULTS OF LOAD-CARRYING CAPACITY OF REFERENCE RC BEAMS (WITHOUT FRP REINFORCEMENT)

Authors	ID	P_{exp} (kN)	P_{FE} (kN)	P_{FE}/P_{exp}	M^{-}_{exp} (kN.m)	M^{-}_{FE} (kN.m)	M^{-}_{FE}/M^{-}_{exp}	M^{+}_{exp} (kN.m)	M^{+}_{FE} (kN.m)	M^{+}_{FE}/M^{+}_{exp}	Failure mode
Ashour et al. [7]	H_1	138	137.2	0.99	21.21	23.89	1.12	56.78	53.73	0.95	Flexure
	S_1	83.6	86.20	1.03	57.77	55.00	0.95	11.13	13.77	1.23	Flexure
	E_1	149.7	148.2	0.99	54.49	48.95	0.90	44.41	46.47	1.04	Flexure
Soumya [12]	CB_1	260	256.2	0.99	-	29.24	-	-	17.41	-	Flexure
	CB_2	200	194.2	0.97	-	13.39	-	-	17.58	-	Flexure

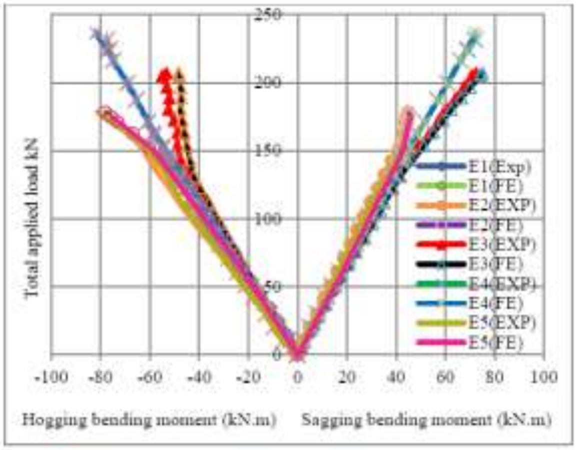


COMPARISON BETWEEN EXPERIMENTAL RESULTS AND NUMERICAL RESULTS OF -CARRYING CAPACITY OF FRP-STRENGTHENED RC BEAMS

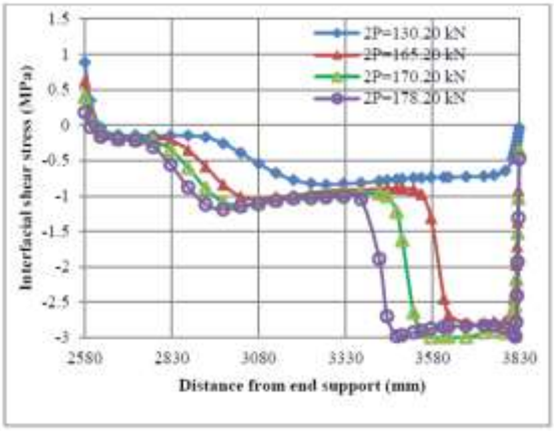
Authors	ID	P_{exp} (kN)	P_{FE} (kN)	P_{FE}/P_{exp}	M^{-}_{exp} (kN.m)	M^{-}_{FE} (kN.m)	M^{-}_{FE}/M^{-}_{exp}	M^{+}_{exp} (kN.m)	M^{+}_{FE} (kN.m)	M^{+}_{FE}/M^{+}_{exp}	Failure mode
Ashour et al. [7]	H_2	152.3	165.2	1.08	31.60	34.81	1.10	61.00	61.68	1.01	TR
	H_3	172.9	180.2	1.04	46.48	51.20	1.10	59.56	60.66	1.01	PF
	H_4	162.6	191.2	1.17	53.07	63.11	1.18	51.32	59.97	1.16	PF
	H_5	162.6	153.2	0.94	35.00	40.48	1.15	64.27	53.1	0.83	PF
	H_6	172.9	161.2	0.93	28.26	35.58	1.17	70.24	60.57	0.86	PF
	S_2	121.8	119.2	0.98	71.28	61.24	0.86	22.67	26.45	1.16	SS
	S_3	121.8	121.2	0.99	66.90	61.24	0.92	24.72	27.4	1.10	PF^{*}
	S_4	170.5	166.2	0.97	88.97	65.3	0.84	37.15	42.17	1.15	PF^{*}
	S_5	111.7	115.2	1.03	50.18	45.19	0.90	28.36	32.55	1.14	SS
	E_2	178.6	175.2	0.98	79.78	75.83	0.95	45.64	45.96	1.00	PF
	E_3	207.0	223.2	1.07	53.56	48.10	0.90	72.35	82.8	1.14	PF^{*}
	E_4	231.4	222.2	0.96	77.00	77.78	1.01	72.29	67.48	0.93	PF
	E_5	174.6	175.2	1.0	77.42	75.75	0.98	44.87	45.99	1.02	PF
Soumya [12]	SB1	320	295.2	0.93	-	35.74	-	-	19.03	-	PF
	TB1	224	223.2	0.99	-	18.34	-	-	18.73	-	PF



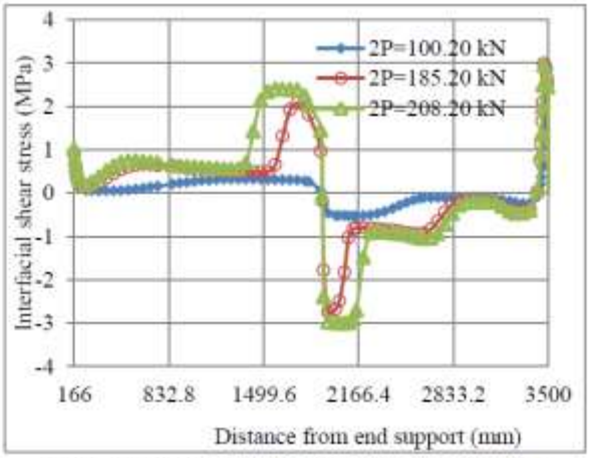
Comparison between experimental measurement and FE simulation



Comparison between experimental measurement and FE results of the hogging and sagging bending moments for the tests



Interfacial shear stress of the adhesive layer of upper FRP plate of beam E2 at different loads till failure



Interfacial shear stress of the adhesive layer of lower FRP plate of beam E3 at different loads till failure

CONCLUSION

The research work presented in this paper develops a new structural construction material substite able to simulate the mechanical behavior of FRP-strengthened RC continuous beams utilizing realistic nonlinear constitutive relations for each strengthened beam components. The interfacial shear and normal stresses in the adhesive layer are presented using analytical uncoupled cohesive zone model based on nonlinear fracture mechanics. The following are advantages of using the proposed concept: (i) accurately predict the ultimate load of FRP-strengthened RC beams, (ii) provides a sound mechanical description and interpretation for failure modes of FRP-strengthened RC beams, (iii) allows reducing the complexity and computational cost of FE analyses based on existing FE models, and (iv) simulates the structural response of the considered structural systems with accuracy satisfactory for practical applications.

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