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Experimental and Numerical Comparative Study on RC Beam Flexurally Strengthened with CFRP Laminate.

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Abstract
In this article finite element model is prepared for reinforced concrete beam which is flexurally held together by means of carbon fiber reinforced polymer laminate. The 3D analysis is conducted using ABAQUS software and the results are investigated, where maximum load, deflection at mid span and strain characteristics of both reinforcement and concrete are analyzed numerically. Later these parameters are investigated experimentally in a similar way by keeping all the important conditions such as loading, reinforcement detailing, boundary condition etc. identical. This comparative assessment illustrates that, the using of CFRP has a significant advantage to improve flexure behavior of RC beams. Various types of failure mode such as deflection and stress for whole cross section and for only reinforcement are achieved from finite element analysis. In addition, typical deflection, stress and strain contours of a specified node are found for unstrengthen and CFRP strengthened beam. This article also represents both the reinforcement strain values and concrete strain values for strengthened and unstrengthen RC beams and found a precise similarity while comparing with finite element modelling results. Furthermore, in terms of ultimate load, the deviation in result is as narrow as 4% for flexurally strengthened reinforced concrete beam by CFRP laminate.

1. Introduction

Retrofitting of structures using Carbon Fiber Reinforced Polymer (CFRP) is an important option now-a-days in the field of structural maintenance as complete replacement of any damaged or age-old structures are very costly and tough (Al-Rousan and Abo-Msamh, 2019; Mofidi and Chaallal, 2011; W. Sun and Ghannoum, 2015; Tanarslan et al., 2017). Worldwide several research activities are carried out on the retrofitting of structures and different strengthening technique have been developed using verities of FRP materials. (Alam et al., 2015; Amin and Alam, 2014; Kim et al., 2008; Mostofinejad et al., 2019; Ombres and Verre, 2019). Among them, CFRP is found to be more advantageous because of its simplicity of connection, durability, high modulus of elasticity with high compressive and tensile strengths (Alam et al., 2015; Amaireh and Al-Tamimi, 2020; Pannirselvam et al, 2009; Siddiqui, 2009). Remarkable improvement also observed in several structural components including beams, slabs and columns. Using CFRP for flexural reinforcing of reinforced concrete beam is undoubtedly the best option in terms of flexural characteristics (Almusallam et al., 2013; Bocciarelli et al., 2013; Chahrour and Soudki, 2005; Dong et al., 2013; Elsanadedy et al., 2013; Koutas et al., 2013; Michels et al., 2013 Smith et al., 2013). In the existing literature, comparative studies on experimental and Finite Element Modeling (FEM) of flexurally reinforced RC beams are seldom found. However, the behavior of flexurally strengthened RC beam using CFRP is still ambiguous under various strengthening condition. (Teng et al., 2002) experimented on RC beams with Finite Element Analysis (FEA) for interfacial stresses strengthened with a bonded soffit plate. Fine mesh was used in their research for analyzing the stress point singularity in the plate. The author showed that the interfacial stress increases with a reduction in adhesive thickness. (Teng et al., 2002; Amaireh and Al-Tamimi, 2020) conducted a study on FEA using ABAQUS to analyze and assess the performance of RC beams strengthened with changed arrangements of CFRP compounds and found the performance of the beam was ineffective if more than three CFRP layers are used. (Amaireh and Al-Tamimi, 2020; Majid et al., 2020) numerically examined the reaction of CFRP

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strengthened RC beams and presented that the CFRP reinforcing method is successful in refining impact reaction of RC beams (Kadhim et al., 2020) and it also proven by many researches (Kabir et al., 2018; Lee et al., 2012; Wei Sun, 2018; J. Q. Yang et al., 2018). Though several researches have been conducted in this topic but it is confirm that a lot of comparative studies are compulsory to recognize the effects of numerous factors on the performance of the strengthened beams to advance the design guidelines (Teng et al., 2002).

In order to build a safe structure, it is very significant to predict the load deformation behavior of flexurally strengthened RC structures (Chen et al., 2018; Wei Sun, 2018; J. Q. Yang et al., 2018). In this regard, the key goal of this research is fixed to compare the experimental and FEM simulation of strengthened and unstrengthen RC beams and is to predict the flexural strain characteristics of RC beam. Therefore, two RC beams have been experimentally and numerically investigated in this study to compare the flexure behaviors and to predict strain characteristics of reinforcement and concrete as well. One beam is flexurally strengthened with CFRP laminate and another one is kept unstrengthen. ABAQUS software is used for developing a three-dimensional nonlinear FEM for similar two RC beams. Reinforcement detailing, Loading, Boundary Condition and the other things are kept similar to what is used in experimental setup. However experimentally CFRP was attached with concrete using adhesive on the other hand tie constraint is used in FEM analysis to tie CFRP and concrete surface together. Different failure mode with respect to deflection and stress for entire cross section and for reinforcement bar only is obtained. Consequently, typical deflection, stress and strain contours of a same specified node are attained for unstrengthen and CFRP strengthened specimen. Lastly results found from numerical investigation are matched with experimental outcomes in terms of maximum load, mid-span deflection, concrete and reinforced bar strain characteristics.

2. Experimental program

2.1 Beam specimens

Two beams were set fort the experiment as represented in Fig.1. The dimensions of beams were 150 mm × 300 mm × 2300 mm. The beams were doubly reinforced.One beam is used as control specimen (ECB) and other one is flexurally strengthened with CFRP laminate which is outwardly bonded at the bottom surface of the beam (ESB). Both beams were analyzed using ABAQUS software to evaluate the reaction of reinforced concrete beams (MCB and MSB). The matrix of the beam specimen is shown in Table 1. The beams were designed for flexural failure to check the flexure behavior using CFRP laminate.

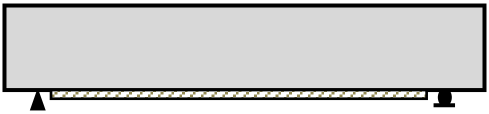
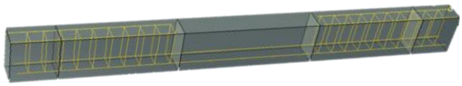
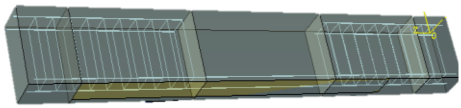
2.2 Materials specification

Generally, it is believed that the higher density of concrete contributes to the higher strength and lower porosity. However, the density depends on many factors such as aggregates to binder ratio, water to cement ratio, degree of compaction, etc. It is an important parameter for concrete as its different compositions for example binders, fine aggregates and coarse aggregates have different physical and mechanical properties. Here concrete having compressive strength of 28 MPa is used and steel having yield strength 560 MPa is used.

2.3 Flexural strengthening

For this study, flexural strengthening was done by CFRP laminate having a cross section of 80 mm × 1.2 mm. The 1650 mm long CFRP was attached at the lowest face (tension zone) of the beam for strengthening. For proper bonding, concrete surface was prepared using diamond cutter to acquire a uneven surface and to uncover the surface of the aggregate.

Table 1: Details of specimen

Group	Beam Specimen	Beam Details	CFRP	Beam Figure
Group 1	ECB	without CFRP	-	
	ESB	with CFRP	At the bottom	
Group 2	MCB	without CFRP (ABAQUS)	-	
	MSB	with CFRP (ABAQUS)	At the bottom	

2.4 Instrumentation

For testing of beams and to investigate the strain characteristics, electrical strain gauges were installed on the concrete surface, reinforcement bars, and CFRP laminate and all strain gauges were linked to data logger to collect the strain values. Linear variable differential transducers (LVDT) was used to detect the mid span deflection of beams. The beams were tested under two points loading. The feature of the test arrangement is shown in Fig. 1.

Figure 1: Instrumentation setup for flexural performance investigation

3. Numerical modeling in Abaqus

Three-dimensional nonlinear FEM was established in ABAQUS/CAE for concrete material. Modelling techniques used in this research are elaborately demonstrated in the subsequent subcategories.

3.1 Geometric modeling

Three-dimensional solid elements were engaged for RC beam having a mesh size of 10 mm. Mesh size was selected in a way so that there is an equilibrium between computational time and precision of results.

The reinforcement elements were inserted in the concrete by "embedded region "constraint option, where host region was concrete beam and embedded region was the steel reinforcement.

3.2 Material modeling

In this model two material property was given. Modulus of elasticity and Poisson's ratio. Modulus of elasticity of 30 GPa with Poisson's ratio of 0.2 were used for concrete. For Steel modulus of elasticity is 21 GPa and Poisson's ratio is 0.33. For CFRP, the modulus of elasticity was 170000.

3.3 The bond between CFRP and concrete surface

Tie constraints were used for modelling bond area in the middle of strengthening CFRP and the concrete surface of the beam. By using tie constraints, it was ensured that the translational degrees of freedom are guarded. In this circumstance, CFRP operated as the master surface and the concrete surface of the beam represented the slave surface.

3.4 Boundary conditions and loading

Mechanical displacement/rotation boundary condition available in ABAQUS/CAE was used in this model. To replicate simply supported condition, the support of the RC beams was incorporated in a way that one side was pinned by restricting its movement on y and z directions and the remaining side was made roller support by limiting its movement on y direction. The supports were located at 150 mm from the edge of the beam.

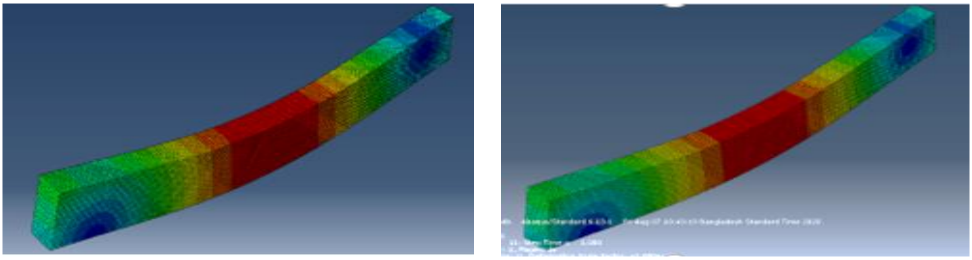
Flexural failure was replicated by using four-point loading as same as the experimental tests. Two-point loads on RC beams was simulated by pressure load like real loading in laboratory. In ABAQUS, the load is given consistently to reflect the actual load increase scenery.

3.5 Solution Algorithm

To solve the nonlinear equations, a suitable incremental iterative technique was adopted. The vertical loads were given as pressure load to replicate the loading condition of the laboratory. Static, general step was implemented having initial arc length increment as 0.01, whereas the minimum and maximum arc length increments were 1E-005 and 0.1 respectively. Total arc length was estimated as 1. Convergence was successfully achieved at the end of each load step using this procedure.

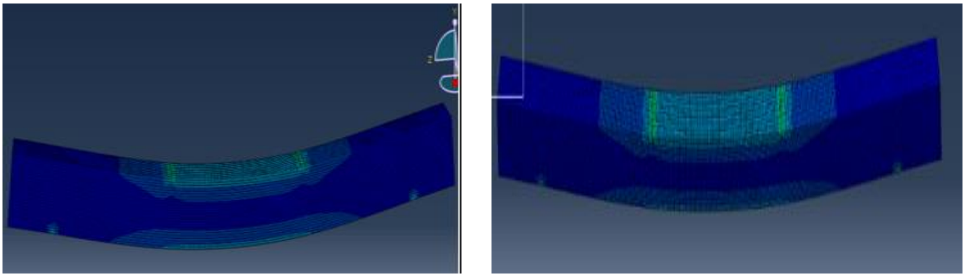
3.6 Numerical failure mode

Fig.2 shows the deformation pattern of both strengthened and unstrengthen beam where maximum deformations in the form of U are observed at the center of the beam. Fig.3 shows the stress in entire cross section of beam where stress distribution in the form of S, Mises at various points of beam section is also visible. Fig.4 and Fig.5 respectively represents the deflection (U) and stress distribution (S, Mises) of beam reinforcement for both strengthened and unstrengthen beams.



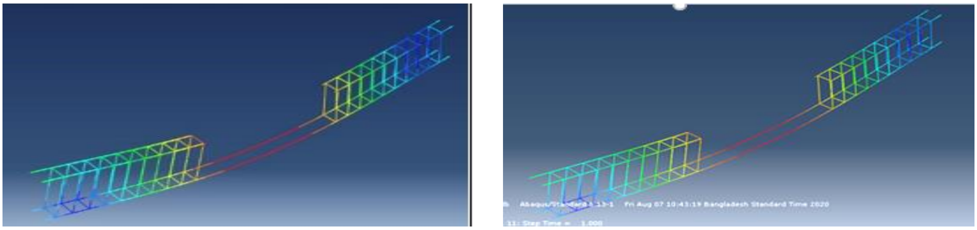
(a) (b)

Figure 2: Deflection of entire section of beam (a) without CFRP (b) with CFRP



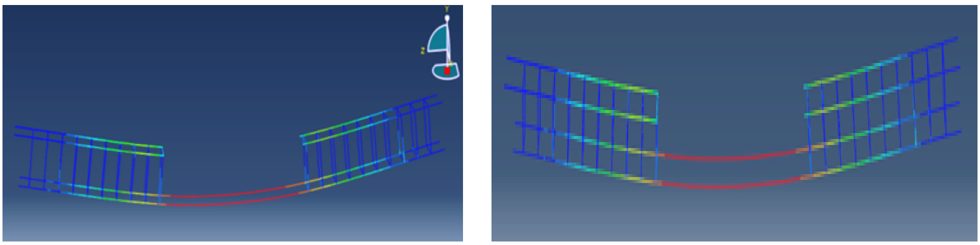
(a) (b)

Figure 3: Stress in entire section of beam (a) without CFRP (b) with CFRP



(a) (b)

Figure 4: Deflection of reinforcement of beam (a) without CFRP (b) with CFRP

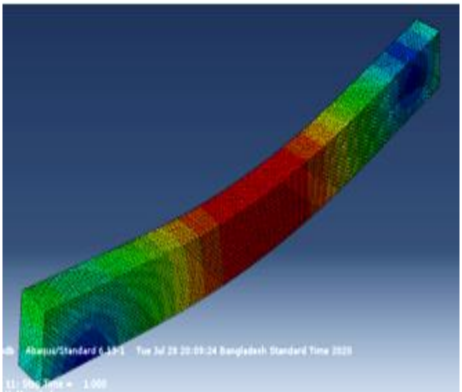


(a) (b)

Figure 5: Stress in reinforcement of beam (a) without CFRP (b) with CFRP

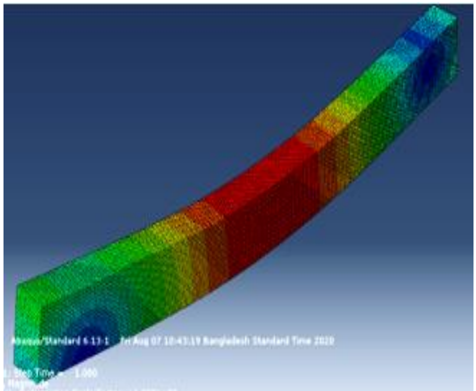
3.7 Contouring

Characteristic deflection contours, stress contours and strain contours of a same specified node (ID-10143) for the unstrengthen specimen and CFRP strengthened beam are presented in Figure 6 to Figure 8, where various magnitudes of U and different deflection coordinates are obtained for beam (part-1 instance).



Part Instance	Node ID	Orig. Coords	Def. Coords	Attached elements	U, Magnitude
BEAMPART-1	10143	115.385, 0, 1159.93	120.564, -114.324, 1146.21	38976, 39001, 40726, 40751	115.261

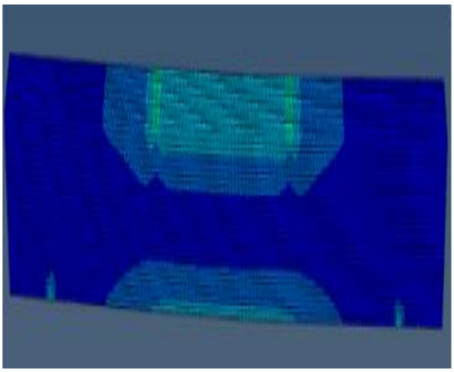
(a)



Part Instance	Node ID	Orig. Coords	Def. Coords	Attached elements	U, Magnitude
BEAMPART-1	10143	115.385, 0, 115!	117.385, -113.912, 1146.64	38976, 39001, 40726, 40751	114.703

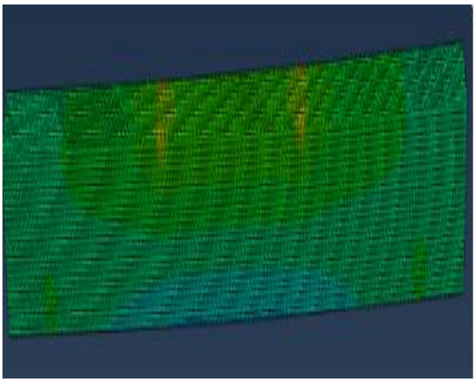
(b)

Figure 6: Typical deflection contour for (a) unstrenghthen specimen and (b) CFRP strengthened specimen



Orig.Coords	Def.Coords	S,Mises
115.3,0,1159.9	115.5,-6.6	65.41

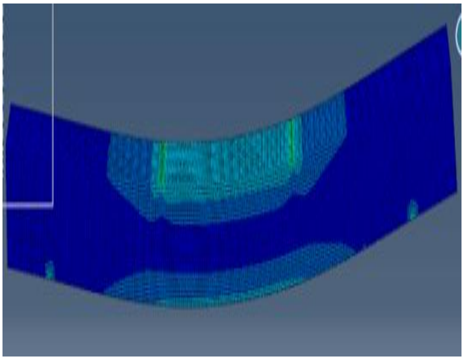
(a)



Orig.Coords	Def.Coords	LE,LE11
115.3,0,1159.9	115.5,-6.6	0.00043

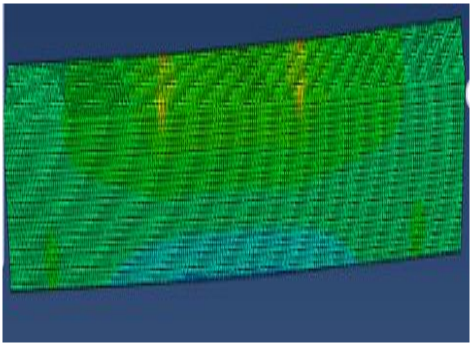
(b)

Figure 7: Typical stress and strain contour for unstrenghthen specimen



Orig.Coords	Def.Coords	S,Mises
115.3,0,1159.9	117.3,-113.9,1146.4	1135.8

(a)



Orig.Coords	Def.Coords	LE,LE11
115.3,0,1159.9	117.3,-113.9,1146.4	0.00759

(b)

Figure 8: Typical stress and strain contour for CFRP strengthened specimen

4. Results and Discussion

Along with the experimental study, both beams were numerically investigated using Abaqus software. Then the comparison results between experimental and numerical analysis are presented in this study. After investigating the failure pattern of beam in experimental study it is observed that the unstrengthen control beam (ECB) failed in flexure as it was designed to fail by flexure mode, on the other hand the beam strengthened with CFRP (ESB) failed due to the detachment of the externally bonded CFRP laminate at plate interface as presented in Fig.1. From the experimental study, extensive data on ultimate failure load, mid-span deflection and maximum flexure strain values are presented inTable 2. Similarly, from the numerical analysis ultimate failure load, mid-span deflection and maximum flexure strain are presented inTable 2. It is detected from Table 2 that, for the numerical analysis the mid span deflection was higher than the experimental values by 35% for unstrengthen and 64% for strengthened beam. The reason of getting higher deflection values at numerical analysis can be that, detachment failure was not observed in FEM. But in terms of ultimate load, both have shown almost similar type of result as variation is only 4% for both unstrengthen and strengthened beam which actually validates the FEM result with the experimental result.

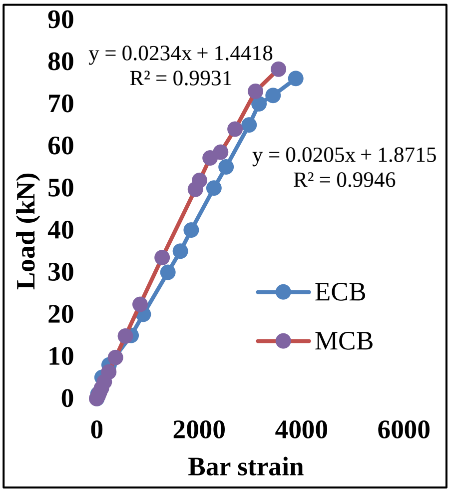
Then the experimental and numerical results have been compared with the previous experimental and numerical research where same type CFRP has been used and presented inTable 2. Both experimental and numerical data has been collected from the research conducted by(Amaireh and Al-Tamimi, 2020).In their research, experimental mid-span deflections were 21 mm and 33 mm for unstrengthened and strengthened beam respectively whereas in this research it is found 8.58 mm and 7.02 mm respectively. In their numerical research which was also conducted by ABAQUS software(Amaireh and Al-Tamimi, 2020) mid-span deflections were 27 mm and 30.3 mm for unstrengthened and strengthened beam respectively whereas in this research it is found 11.57 mm and 11.52 mm respectively. Therefore, it can be concluded that they have got higher mid-span deflection for strengthened beam than unstrengthened beam in both experimental and numerical study whereas in this study higher mid-span deflection value was found for unstrengthened beam in both experimental and numerical study. In their research, experimental ultimate loads were 50 kN and 120 kN for unstrengthened and strengthened beam respectively whereas in this research it is found 81 kN and 114 kN respectively. Hence, it is reflected that higher ultimate load is found for strengthened beam than unstrengthened beam in their investigation as well as in current research. In their numerical research ultimate load was 118 kN for strengthened beam. No data is found for unstrengthened beam.

Table 2: Comparison of experimental and numerical results (strengthened and unstrengthen beams) with previous research

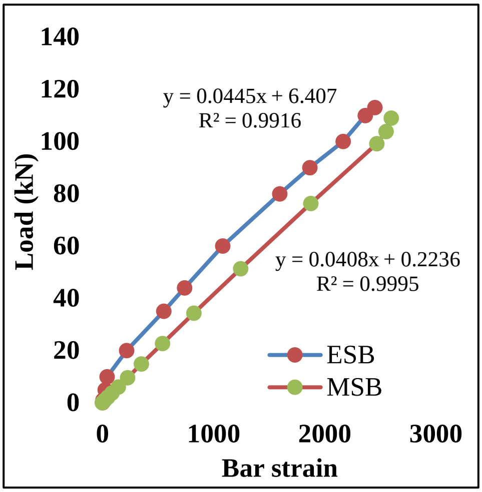
Beam Specimens	Mid-span Deflection (mm)				Ultimate Load (kN)				Max flexure Strain			
									Bar		Concrete	
	Exp.	FEM	Exp. (Amaireh and Al-Tamimi, 2020)	FEM (Amaireh and Al-Tamimi, 2020)	Exp.	FEM	Exp. (Amaireh and Al-Tamimi, 2020)	FEM (Amaireh and Al-Tamimi, 2020)	Exp.	FEM	Exp.	FEM
Unstrengthen beam	8.58	11.57	21	27	81	78	50	-	3885	3550	2700	2820.5
Strengthened beam	7.02	11.52	33	30.3	114	109	120	118	2453	2563.3	2634	3500.6

The reinforcement bar strain data for the unstrengthen and strengthened beams exhibited similar pattern when compared between numerical and experimental results as variation is 9% for unstrengthen and 4% for strengthened beam shown in Fig.9a and Fig.9b. This result also validates the FEM result in comparison with experimental result. The bar strain values linearly increase with the increase of loads on the beams. A linear regression analysis has been done to establish relationship between load and reinforcement strain. Coefficient of determination R^2 has been found as 0.99 for both ECB and MCB for the unstrenthened beam which is the best result. R^2 value is found as 0.99 again for both ESB and MSB for the strenthened beam.

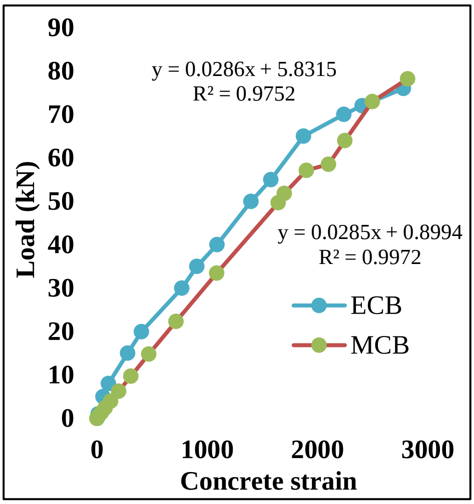
Load vs concrete strain relationships for both unstrengthen and strengthened beams are shown in Fig.9c and Fig.9d respectively. In terms of concrete strain, the experimental unstrengthen beam (ECB) and FEM unstrengthen beam (MCB) has shown almost similar values with similar graph. Both ESB and MSB shows rapid upsurge when reaches to its ultimate load as shown in Fig.9c. This is because of the total failure of concrete during loading at its ultimate load. However, in Fig.9d, the experimental strengthened beam (ESB) has shown almost 30% lower strain than the FEM strengthened beam (MSB). This is because experimentally CFRP was attached with concrete using adhesive which displays higher bonding behavior than FEM which leads to lower concrete strain for experimental beam. Similar linear regression analysis has been done to establish relationship between load and concrete strain. Coefficient of determination R^2 has been found as 0.97 and 0.99 for ECB and MCB respectively for the unstrenthened beam which is excellent result. R^2 value is found as 0.99 for both ESB and MSB for the strenthened beam.



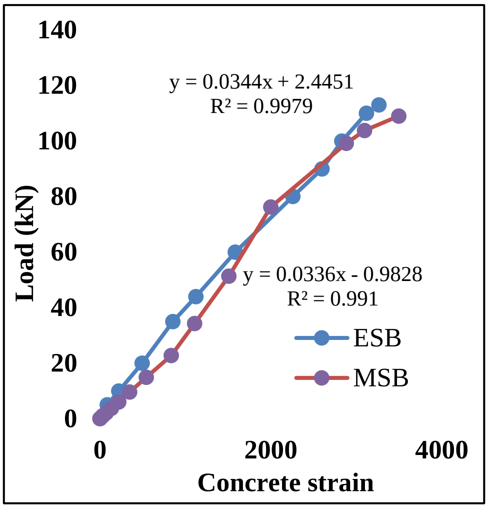
(a)



(b)



(c)



(d)

Fig. 9: Analytical and experimental data of load vs bar strain for (a) unstrengthen beam and (b) strengthened beam; load vs concrete strain for (c) unstrengthen beam and (d) strengthened beam

5. Conclusion

In this study, two types of beams were experimentally investigated and both of them were numerically analyzed to check the flexure behavior. The summery of the findings are presented below.

In terms of ultimate load, both experimental and numerical analysis have shown almost similar type of result as variation is only 4% for both unstrengthen and strengthened beam.

It is detected that, for the numerical analysis the mid span deflection was higher than the experimental values by 35% for unstrengthen and 64% for strengthened beam.

The reinforcement bar strain data for the unstrengthen and strengthened beams exhibited similar pattern when compared between numerical and experimental results as variation is 9% for unstrengthen and 4% for strengthened beam.

In terms of concrete strain the experimental strengthened beam has shown almost 30% lower strain than the FEM strengthened beam. This is because in FEA, bonding between concrete and CFRP is analyzed by tie constraint method while practically CFRP was attached with concrete using adhesive.

Author contributions

The study conceptualization, numerical analysis in software was performed by A. Basit. Previous researches were reviewed by T. Ehsan. Experimental analysis was performed by T. Ehsan. A. Basit completed the drafting and editing of the paper.

Conflict of interest

The authors declare no potential conflict of interest regarding the publication of this work. In addition, the ethical issues including plagiarism, informed consent, misconduct, data fabrication and, or falsification, double publication and, or submission, and redundancy have been completely witnessed by the authors.

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Highlights

- In this research, two types of beams (unstrengthen and strengthen with CFRP) were investigated experimentally and numerically to check the flexure behavior.
- Results obtained from numerical investigation are compared with experimental outcomes in terms of ultimate load, mid-span deflection, concrete and reinforced bar strain characteristics.