International Journal of Scientific & Engineering Research Volume 10, Issue 5, May-2019
ISSN 2229-5518

Strengthening Steel Beams Using CFRP Subjected to Impact Loads

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Abstract— Over the past few years, retrofitting structures using carbon fiber reinforced polymer (CFRP) has been gaining a lot of importance due to its effectiveness. Some structures need to be replaced if they exceed their design period because of deterioration and certain other structures may have some errors during design or construction phase. These kind of structures need to be strengthened for ensuring better performance and quality. The flexural strengthening using CFRP has been traditionally associated with concrete and steel structures. In steel structures, most researches have been conducted when these are subjected to static and fatigue loads and very less studies exist when these are subjected to dynamic loads. This paper presents the numerical analysis of the flexural strengthening phenomenon when steel beams are externally bonded with CFRP and subjected to impact loads. The objective of this research is to determine the effectiveness of CFRP in reducing the failure of existing square hollow section steel beams when the beams are subjected to impact loads. The finite element software ANSYS 16.1 is used for the dynamic analysis. The parameters considered in the study are the number of layers and the thickness of CFRP and also the pattern in which CFRP is bonded onto the beam.

Index Terms— ANSYS; CFRP; dynamic analysis; flexural strengthening; impact; retrofitting; square hollow beams

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1 INTRODUCTION

Steel strucutres can be subjected to impact loads induced by a variety of sources (e.g., vehicle, barge, rock-fall, debris, and bombing). Impact loading is characterised by its large amplitude within a short duration, causing strain-rate effects in the materials (e.g., concrete and steel) and inertia effects in the structures. These effects can lead to significantly different behavior of steel structures under impact loading compared with that under static loading.

Carbon fiber reinforced polymer (CFRP) or carbon composite is an extremely strong and light fiber reinforced plastic which contains carbon fiber. CFRPs are expensive to produce, but are commonly used wherever high strength to weight ratio and stiffness (rigidity) are required, such as aerospace, ships, automotive, civil engineering and an increasing number of consumer and technical applications. Thermostat resin, such as epoxy and thermoset or thermoplastic polymers like polyester, vinyl ester, or nylon are most commonly used as binding polymers. [1]

CFRPs are composite materials which consists of two parts: a matrix and reinforcement. Carbon fiber is the reinforcement which provides strength and rigidity measured by stress and elastic modulus respectively. Unlike isotropic materials like steel and aluminium, CFRP has directional strength properties. Therefore, CFRP is an orthotropic material, with elastic constants varying in both longitudinal and transverse directions.

2 LITERATURE REVIEW

Because of CFRP's highly favorable characteristics and properties, they have been traditionally adopted for the purpose of strengthening both concrete and concrete structures and structural components. A large body of research on CFRP-strengthened steel members under various load conditions has been undertaken in the last few years (Colombi et.al. 2006; Deng et.al. 2007). [5] Additionally, in some of this research, design guidelines for CFRP-strengthened steel members under static loads have been proposed (Zhao et.al. 2011, Moy et.al. 2001, Schnerch et. al. 2007). One important load condition that should also be considered in design situations is impact load, which can be caused by several kinds of events such vehicular or ship collisions or debris.

Al-Zubaidy et al. 2012 - Several studies have been aimed at investigating the effect of impact load on FRP-strengthened steel members. Among these studies, Al-Zubaidy et al. 2012 tested a series of CFRP sheet-steel double strap joints at various dynamic (3.35 m/s, 4.43 m/s, and 5 m/s) and quasi-static (3.34×10^5 m/s) tensile loading speeds. [3]

Zhao et.al. 2007 - Various types of joints are often utilized to investigate the bond between steel plates and CFRP sheets (Zhao et.al. 2007). Double strap joints are made of two steel plates and one (or more) CFRP ply on each side of the joint. It was found that the bond strength of double strap joints achieved greater increases under impact loading compared to the quasi-static loading rate. [7]

Al-Mosawe et al. 2016 - Similarly, the bond strength of CFRP plate-steel double strap joints has also been investigated for the same quasi-static and dynamic tensile loading rates mentioned previously (Al-Mosawe et al. 2016). The tests results showed a significant increase in the load-carrying capacity for the joints tested under high loading rates compared to those tested under quasi-static loading. The preceding two groups of studies showed that the bond strength between CFRP and

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steel, which is the weak point in the case of CFRP-strengthened members, was improved under higher loading rates. This conclusion was the motivation to study the use of the CFRP-strengthening technique in the enhancement of steel structural members vulnerable to impact load.

Khadim et. al 2019 - In the study of Khadim et.al, a total of five specimens were tested under impact load using a purpose-built test rig. Various CFRP thicknesses and lengths were investigated. Finally, the effect of varying the impact energy generated by two velocities (4.43 m/s and 6.26 m/s) and masses (91 kg and 182 kg) was examined experimentally. They also provided a numerical analysis in which different masses with different velocitites have been used to provide impact loads. And the effect of changing CFRP distribution by a constant volume, i.e, with same thickness to width ratios of CFRPs have been studied. [6]

3 OBJECTIVE, SCOPE AND METHODOLOGY

3.1 Objective

To numerically study the behavior of CFRP strengthened steel SHS beam subjected to impact loading. To study the effectiveness of CFRP in preventing the failure of steel beams by adopting different number of layers and also by changing the pattern in CFRP is bonded.

3.2 Scope

This study deals with the flexural behavior of CFRP strengthened beams subject to impact loads only.

3.3 Methodology

The methodology of the study is as follows: Validate the results in the literature using ANSYS workbench 16.1 software. Study the effectiveness of CFRP in preventing the failure of the beams by conducting a parametric study by varying the pattern in which CFRP is bonded to the faces of the beam and by increasing the number of layers of CFRP.

4 MODELLING

4.1. Description of the Experimental Model

The experimental results are obtained from the experiment conducted by Khadim et al. 2019. Four specimens strengthened with CFRP and one unstrengthened specimen were prepared and tested under a constant kinetic energy. The SHS steel beams were of size 40 mm x 40 mm x 3 mm. The kinetic energy was derived from a 91 kg mass dropped from a 1.0 m height. No axial pre-compression force was applied across the test series. Boundary conditions of the tested beams was both ends having rotational and translational restraint except at one end, which had freedom in axial translation only (Fig. 1). The impact was applied using an indenter made from high strength steel. The indenter head was carefully rounded to avoid local failure in the specimens.

4.2 Finite element model

The validation of the steel SHS beam is to be done using ANSYS workbench 16.1. In the model, the measured cross-section dimensions of the test specimen were used.

4.3.1 Geometry modelling

The model of the slab specimen was developed with the help of design modeller in ANSYS workbench. Fig. 2 shows the FE model of the specimen considered. FE model consists of a steel SHS beam wrapped with CFRP, and an impactor at a height of 1.0 m.

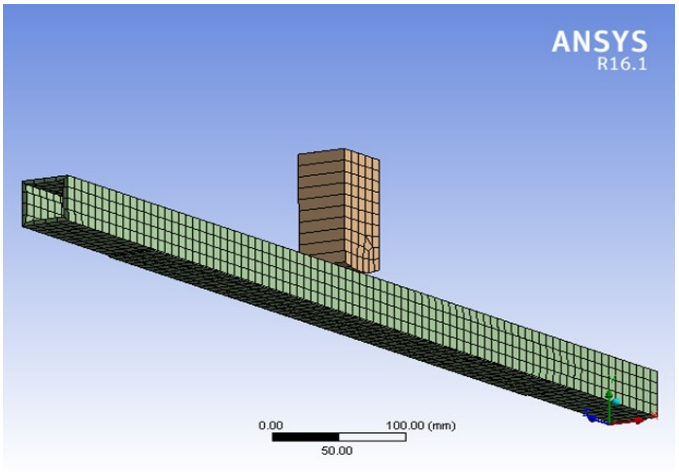

Fig. 1. Finite element model of the specimen- SHS beam, impactor and CFRP layer on the bottom surface of the beam

4.3.2 Material modelling

The density of steel was assigned as 7850 kg/m^3. The stress strain property of material is provided as tabular data. The Young's modulus of steel is provided as 185 GPa. Average yield stress of 538 MPa and ultimate strength of 611 MPa were provided. Poissons ratio was given as 0.3. Bulk modulus and shear modulus was given as 154.17 GPa and 71.154 GPa. All the above details were obtained from the experimental results of Khadim et al. 2019.

The CFRP sheet was modelled as orthotropic with elastic modulus in longitudinal and transverse directions as 105.3 GPa and 17 GPa. The density of CFRP was assigned as 1600 kg/m^3. In plane shear modulus was 17 GPa. The longitudinal and transverse tensile strengths were 1397.8 MPa and 50 MPa. The longitudinal and transverse compressive strengths were 1200 MPa and 250 MPa. The shear strength of CFRP in the longitudinal direction was 70 MPa.

4.3.3 Type of element and finite element mesh

The beam, and impactor are modelled using the SHELL181 element. SHELL181 is suitable for analyzing thin to moderately-thick shell structures. It is a four-node element with six degrees of freedom at each node: translations in the x, y, and z directions, and rotations about the x, y, and z-axes. (If the membrane option is used, the element has translational degrees of freedom only). The degenerate triangular option should only be used as filler elements in mesh generation.

SHELL181 is well-suited for linear, large rotation, and/or large strain nonlinear applications. Change in shell thickness is accounted for in nonlinear analyses. In the element domain, both full and reduced integration schemes are supported. SHELL181 accounts for follower (load stiffness) effects of distributed pressures. SHELL181 can be used for layered applications for modeling composite shells or sandwich construction. The accuracy in modeling composite shells is governed by the first-order shear-deformation theory (usually referred to as Mindlin-Reissner shell theory). The element formulation is based on logarithmic strain and true stress measures. The element kinematics allow for finite membrane strains (stretching). However, the curvature changes within a time increment are assumed to be small. Mesh size adopted is 10 mm for all elements. The meshed model is as shown in the Fig 2.

CFRP is modelled using SURF154 element. SURF154 is used for various load and surface effect applications in 3-D structural analysis. It can be overlaid onto an area face of any 3-D element. Various loads and surface effects may exist simultaneously.

4.3.4 Boundary conditions

Left end of the beam is modelled as fixed and other end is provided with sliding support to simulate the experimental conditions. The impactor is provided with a velocity of 4.43 m/s in the downward direction for simulation. Also, the translations except in the downward direction as well as the rotations in all directions are restrained for the impactor.

4.4 Validation

The time and maximum deformation obtained from the FE analysis was compared with that from experimental test conducted by Khadim et al. (2019). For the unstrengthened specimen, the time at which maximum deformation occurred in specimen after impact from FE analysis was obtained as 0.0140 seconds, whereas from the experiment was 0.0143 seconds and the maximum deformation obtained from FE analysis is 28.812 mm and that from experiment is 28.2914 mm. For the specimen with CFRP at the bottom face of the beam, the time at which maximum deformation occurred in specimen after impact from FE analysis was obtained as 0.0130 seconds, whereas from the experiment was 0.0134 seconds and the maximum deformation obtained from FE analysis is 25.976 mm and that from experiment is 25.8281 mm.

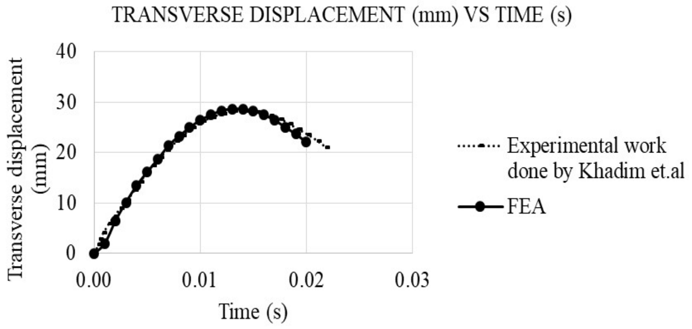

Fig. 2. Maximum Transverse displacement (mm) vs time (s) of unstrengthened specimen

The maximum transverse displacement (mm) vs time (s) graph of unstrengthened specimen of the SHS beam is shown in Fig 6. and the same of the specimen coated with CFRP at the bottom is illustrated in Fig 3.

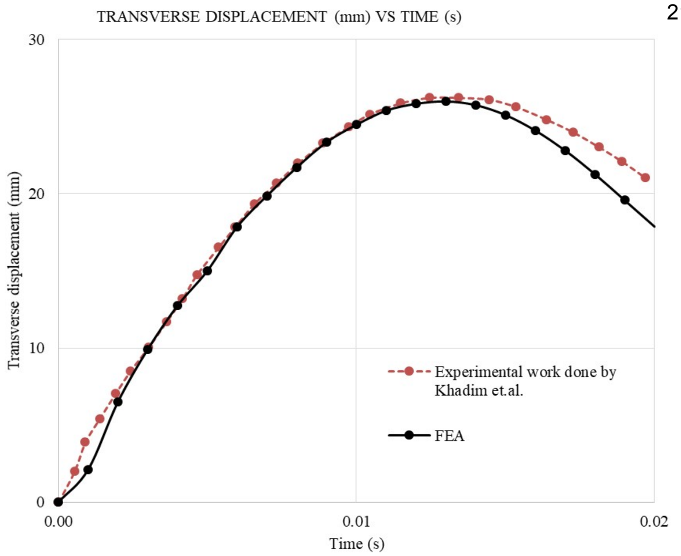

Fig. 3. Maximum Transverse displacement (mm) vs time (s) of the specimen with CFRP at the bottom face

For the unstrengthened specimen, maximum transverse deformation was found to be 28.2914 mm actually and 28.812 mm numerically and the error is calculated to be 1.84%. The time at which maximum deformation occurred was 0.0413 s and 0.0140 s experimentally and numerically respectively and the error involved was 2.097%. This error is because of the time lag which occurs between the actual experiment and numerical analysis.

Result	Unstrengthened specimen		Specimen with CFRP on bottom face	
	Maximum transverse deformation (mm)	Time (s)	Maximum transverse deformation (mm)	Time (s)
FEA	28.812	0.0140	25.976	0.0130
Experimental	28.2914	0.0143	25.8281	0.0134
Error percentage	1.84	2.097	0.573	2.98

For the strengthened specimen with 1.2 mm CFRP thickness throughout the bottom face, the maximum transverse deformation was found to be 25.8281 mm actually and 29.976 mm numerically and the error is calculated to be 0.573%. The time at which maximum deformation occurred was 0.0134 s and 0.0130 s experimentally and numerically respectively and the error involved was 2.98%. This error is also due to the time lag as discussed earlier.

5 PARAMETRIC STUDIES

5.1 Orientation of CFRP layer

Various studies were conducted using ANSYS 16.1 to determine the effect on flexural behavior of steel beam by changing the pattern in which CFRP layer is bonded to the beam. The cases examined were CFRP bonded to the base of the beam, CFRP bonded to base and to two lateral faces, CFRP layers placed only at the support ends at bottom face and then, at both bottom and sides, CFRP layers placed only at the loading point at bottom, and then, at both bottom and sides, CFRP layers placed inetmittent perpendicularly at bottom side, and then, at both bottom and sides, CFRP layers placed inetmittent diagonally at bottom side, and then, at both bottom and sides.

Of all these cases, the best result was obtained when the CFRP layers placed inetmittent diagonally at bottom side, and the best result when it is placed at both bottom and sides. The best result was obtained when CFRP layer is placed 45^0 to the edge of the beam, by bonding it onto the beam diagonally in an intermittent manner. Two specimens are modelled, one, named CIDBS, in which CFRP placed intermittent diagonally at both bottom and side faces of beam, and the other named CIDB in which 1.2 mm thick CFRP is bonded intermittent diagonally only at the bottom face of the beam. The meshed finite element model of CIDBS specimen is shown in Fig. 4.

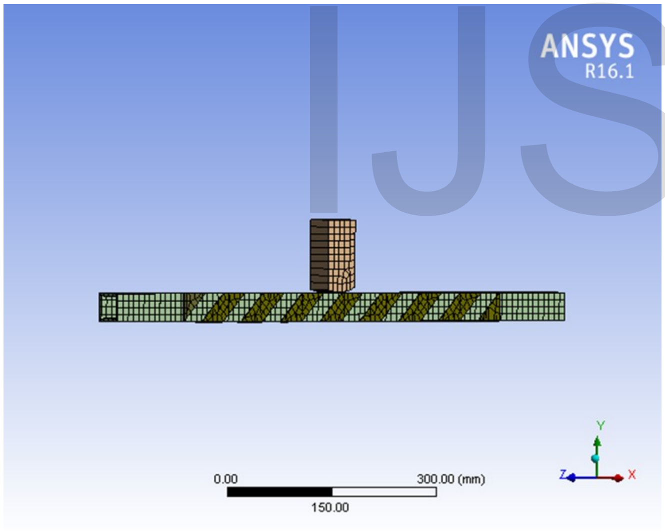

Fig. 4. Finite element meshed model of CIDBS specimen

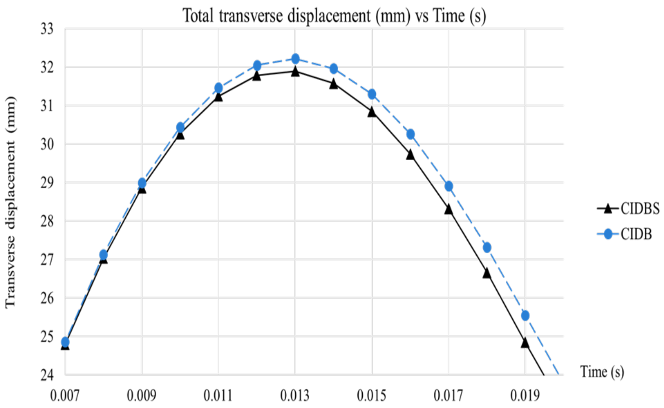

Fig. 5. Maximum total transverse displacement (mm) vs time (s) of the CIDBS and CIDB specimens

When unstrengthened beam is subjected to impact loads, maximum deformation obtained is 28.812 mm as per the experiment conducted by Khadim et.al. When the beam is strengthened with 1.2 mm thick CFRP at bottom face only i.e., in the case of CIDB specimen, the maximum deformation is 26.036 mm. CFRP decreased the maximum deformation of the beam by 9.63%. In the case of CIDBS specimen, maximum transverse deformation is 25.984 mm, therefore a reduction of 9.84% has occurred.

5.2 Thickness of CFRP layer

Another parametric study is conducted by varying the number of layers of CFRP, or by increasing the thickness of the CFRP layer. Fig 10 shows the results obtained after analysis of each specimen bonded at the bottom of the beam with two to eight layers of CFRP as depicted by thicknesses of 2.4 mm to 9.6 mm.

The results indicate that the maximum transverse deformation of specimens decreases as the number of layers increases. The percentage of reduction of maximum transverse deformation in each of the cases are depicted in Table 2.

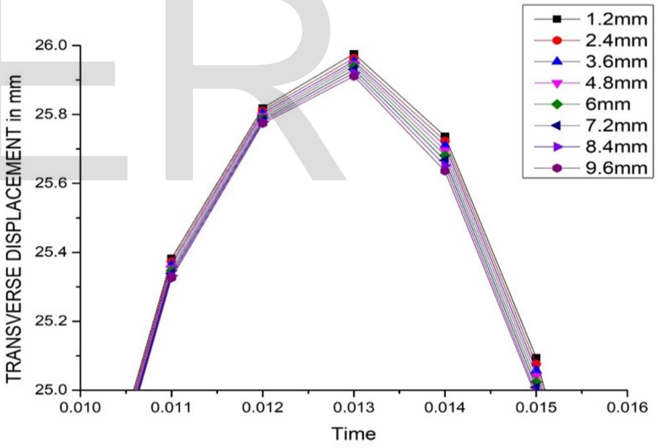

Fig. 6. Maximum total transverse displacement (mm) vs time (s) of the specimens with different numbers of CFRP bonded together

The comparison of the values of percentage decrease of maximum deformation of the beams bonded with different layers of CFRP or in other words, with varying thickness of CFRP layers are depicted in the Fig. 7.

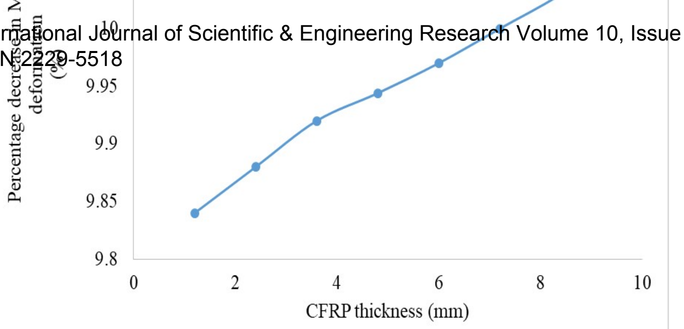

Fig. 7. Comparison of the values of percentage decrease of maximum deformation of the beams bonded with different layers of CFRP

TABLE 1
Percentage decrease in Maximum transverse deformation of beams bonded with 1.2 mm thick CFRP layer at

Thickness of CFRP (mm)	Maximum Deformation (mm)	Percentage decrease in Maximum deformation (%)
1.2	25.976	9.84
2.4	25.964	9.88
3.6	25.954	9.92
4.8	25.947	9.944
6.0	25.94	9.97
7.2	25.931	10.00
8.4	25.921	10.03
9.6	25.911	10.07

5.3 CONCLUSION

The intention of this paper is to investigate the behavior of CFRP strengthened steel beams subjected to impact load numerically. A numerical model was validated against and experimental model of Khadim et.al, and the following conclusions can be drawn from this investigation.

1. For the beam series examined, CFRP-strengthening technique showed a good performance in enhancing the steel beam against impact loads. It was found that when using a 1.2 mm CFRP thickness, when the number of layers are increased, the maximum transverse displacement reduces.
2. When 1.2 mm thick CFRP is used, there is a decrease of 9.84% in the maximum transverse displacement as compared to the unstrengthened beam.
3. The pattern of CFRP bonding also influences the strengthening process effectively. When using a diagonal intermittent manner of binding CFRP onto the steel beam, it showed an excellent improvement in strengthening process when compared to the case when CFRP is bonded onto the steel beam completely on any face.
4. When a thicker CFRP layer is used, the impact force plateau is found to be higher than a less thick CFRP layer. When a shorter CFRP layer is used, it results in a reduction in the plateau value for the same CFRP thickness. A similar observation can be found in terms of the transverse displacement–time history and the residual transverse displacement.
5. When the mass falling on the beam is increased, we can vary the impact energy applied onto the beam. When a higher impact energy is imparted onto the beam, the visible indendation on the surface of the beam increases accordingly.
6. At the bottom surface of the beam, the deformation occurring is lesser than that at the top surface. This is due to the massive indendation caused by the falling mass or impactor
7. The effectiveness of CFRP shows an increasing trend when the bottom surface of beam is considered. The effectiveness of CFRP in reducing flexural behavior is less when the top surface is considered. These are due to the indendation caused at the top surface of the beam.
8. Plastic deformation of the beam occurs and the strength of beam in resisting deformation reduces. Due to this, the strength of steel reduces and at this moment, CFRP becomes more effective. Thus, the effectiveness of CFRP in resisting the transverse deformation can be explained.
9. The reduction in maximum transverse deformation is found to be directly dependent on the number of layers of CFRP or the CFRP layer thickness.
10. The pattern in which CFRP is bonded to the beam also influences the effectiveness of CFRP in reducing maximum transverse deformation. Maximum improvement is observed when the CFRP is bonded to the surface of the beam in such a way that the angle between the edge of CFRP and that of the SHS steel beam is 45^0.

ACKNOWLEDGMENT

I am very happy to take this opportunity to acknowledge my debts of gratitude associated with the preparation and presentation of this report. I express my heartfelt thanks to Dr. K. N. Rajesh, Professor, Department of Civil Engineering, Government College of Engineering, Kannur, for his moral support and for the valuable guidance and constant encouragement that he has rendered as my project guide. I also wish to thank all faculty members of our department for their support and encouragement during this work.

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