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NUMERICAL STUDY OF STRENGTH AND FAILURE ANALYSIS OF STEEL I-BEAM STRENGTHENED WITH CFRP AT BOTTOM FLANGE

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Abstract- *The use of carbon fiber reinforced polymer (CFRP) to strengthen and repair steel beams has been rapidly increased within the last decade. CFRP composites adhesively bonded to steel members offer many advantages over steel plate bonding including high stiffness and high strength to weight ratios, fatigue resistance and excellent corrosion. This study numerically investigates the failure and structural behavior of the CFRP flexural strengthened steel I-beams. One non-strengthened control beam and some strengthened beams using steel plates and CFRP strips were investigated. The beam was simulated in full three-dimension and linear analysis was carried out investigated by using general-purpose finite element program, ANSYS. Four-point bending tests were carried out numerically to show the effect of carbon fiber reinforced polymer on steel I beam. The results show, the flexural strength of CFRP strengthened I beam is much higher than that of bare steel. Results also indicate CFRP strengthened steel beam shows more strength than steel plate strengthened beam.*

Keywords: I-Beam, CFRP, Flexural-Strength, Mono-symmetric Ratio.

1. INTRODUCTION

Steel I-beams have been commonly used in the construction of many bridges of railway, and highway, marine industries, and others. These structures need retrofitting or repairing because of deterioration over time due to fatigue and corrosion. Some conventional methods like mechanical fastener such as welding, rivets, bolts, and bonding steel plates to the metallic structures are available at present. There are some drawbacks of these methods. The sensitivity of welded joint to fatigue and development of local stresses around the drilled holes are some of these. Carbon fiber reinforced polymer (CFRP) has been rapidly gained attention to strengthen and repair steel beams within the last decade. CFRP strengthened steel structures offer many conveniences over steel plate strengthened structures such as high stiffness to weight ratios or high strength, excellent resistance to fatigue and corrosion. The strength of CFRP can be up to 10 times the strength of general structural steel i.e. mild steel [1]. Generally, CFRPs are installed to the tension flange for flexural strengthening. Edberg *et al*. experimentally studied five different configurations of glass and carbon fiber reinforced polymers attached to the bottom of steel beams [2]. In addition, four-point bending was carried out on small scale steel beam by Tavakkolizadeh and Saadatmanesh [3]. Deng *et al*. had found significant amount of stress intensity on the adhesive at the tip of the CFRP plate. The reason behind this stress intensity is the discontinuity caused by the unexpected termination of the CFRP plate [4].

In comparison to conventionally available strengthening methods, like adding steel plate to the beam, use of CFRP is recommended for many reasons. The CFRP possesses much higher strength than structural steel, CFRP with high modulus of elasticity can be used to release significant amount of stresses from the existing structural member under service loads, high corrosion resistance of CFRP material will enhance the durability of structures suffering from corrosion and negligible weight of CFRP will not penalize the already suffering structure. Schnerch *et al.* investigated the Flexural strengthening of different steel structures, railway and bridges etc. by using FRP materials was examined by Schnerch *et al.* This study revealed that bond behavior of CFRP to steel beam is totally different from steel plate to steel beam in case of failure modes [5]. Al Emrani *et al.* investigated different types of fracture mode by testing composite elements with different combinations of CFRP-laminates and adhesives. The behavior and strength of CFRP bonded steel elements with different material parameters was examined [6]. Linghoff *et al.* performed experimental analysis and simplified analytical solutions were made for different parametric study. The experimental analysis and simplified analytical solutions indicate that bending moment capacity can be increased up to twenty percent [7]. Flexural behavior and failure mechanism of CFRP sheet strengthened steel beams under cyclic loading were studied by Fernando *et al.* This study was performed with one unstressed control beam with CRP sheet and four prestressed CFRP sheets. The results indicated that prestressed CFRP sheets experience less crack propagation rate than control beam [8]. Narmashiri *et al*. investigated one bare control beam and some strengthened beams using different types and dimensions of CFRP strips experimentally and failure modes of CFRP were investigated numerically. In this study experimental test was carried out under static loading with gradual increment. To study the specimens numerically, finite element-based software ANSYS was used and non-linear analysis was carried out [9]. Very recently Elkhabery *et al*. studied the reinforcing effect of CFRP, more than one hundred models were analyzed to cover common problem parameters. The parametric study revealed that CFRP sheets were very efficient in reinforcing structural member and beam with CFRP showed much higher strength than unstrengthen one [10].

In this paper structural behavior of the CFRP flexural strengthened steel I-beams is observed. Effect of Carbon fiber reinforced polymer in strengthening I-beam rather than bare beam and steel strengthened beam is investigated.

2. MATERIALS AND METHODS

2.1 Materials

In this analysis, steel I-beam of grade ASTM(A36) is strengthened by CFRP strip and steel plate as well. Table 1 shows material properties of the I-beams. Figure 1 indicates the dimension of the specimens, and Fig. 2 shows the dimensions of the steel I-section.

Table 1: material properties of steel I-beams

E	Stress (N/mm^2)		Strain	
Modulus (N/mm^2)	Yielding (F_y)	Ultimate (F_u)	Yielding (ε_y) %	Ultimate (ε_u) %
200000	250	370	0.12	13.5

The steel plates used for flexural reinforcement and stiffener are of the same grade as the steel I-beams. Steel plate A is installed on the bottom flange by using adhesive and plate B is welded on the web as a stiffener. The dimensions of the steel plates are shown in table 2.

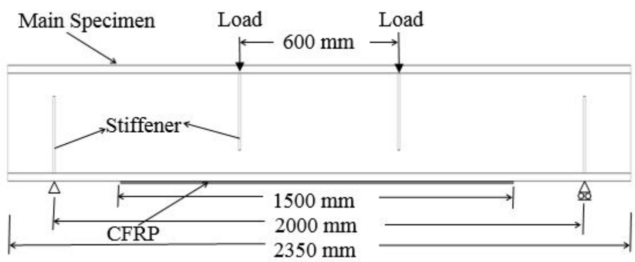

Fig. 1: Specifications of the strengthened steel I-beam

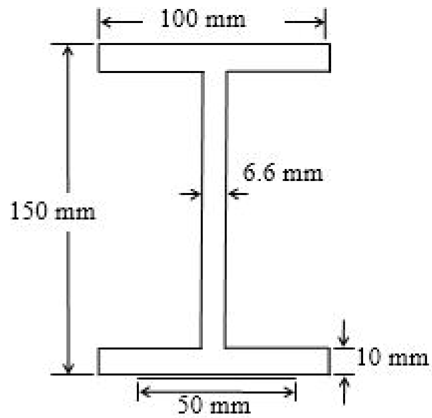

Fig. 2: Dimensions of steel I-Section

Table 2. Dimensions of Steel plates, CFRP and Adhesive

	Width (mm)	Length (mm)	Thick (mm)
Plate A	50	1500	2.4
Plate B	45	100 (Height)	8
CFRP	50	1500	1.2×2
Epoxy	50	1500	1

CFRP materials have high tensile strength which can improve the structural behavior of structures. Normally, CFRP is produced in the form of a strip (plate) or a sheet (wrap). In this research, only CFRP strips are used. In this study CFRP strips are installed on the tensile region to improve the load bearing capacity of structures. Table 2 shows the dimensions and material properties of the CFRP strips are shown in table 3[11].

Table 3: Material properties of CFRP (SikaCarboDur S512)

Parameter	Value
E Modulus (N/mm^2)	212000
Tensile strength (N/mm^2)	3100
Strain at break, in %	1.8

CFRP and steel plates used for strengthening reference beam are added by using epoxy resin. The epoxy should be such that, it can take very high stress generated during loading. A structural adhesive, named Sikadur-30 is chosen as adhesive to be applied as it is widely used. Table 2 shows the dimensions and material properties of the Epoxy resin are shown in table 4[11].

Table 4: Material properties of Epoxy Resin (Sikadur-30)

Parameter	Value
E Modulus (N/mm^2)	11200
Tensile strength after 7 days (N/mm^2)	26-31
Shear strength after 7 days (N/mm^2)	16-19

2.2 Methods

This analysis was performed numerically by the general-purpose finite element program, ANSYS v16.2. The flexural behavior of steel I-shape beams strengthened with CFRP sheets as well as steel plate at bottom flange was simulated. Higher order 3D 20-node solid elements SOLID186, were used to represent the problem main components (I-section, CFRP sheet, adhesive and steel plate). The beams were equipped with vertical stiffeners at supports and below points of load application to prevent local yielding of web and flange. The free span of the beam is 2.0 m and the length of the CFRP sheets adhered to tension flange was 1.5 m; the free length between CFRP end and supports were left unreinforced.

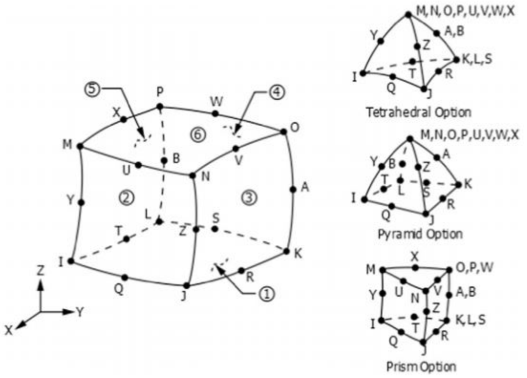

Fig. 3: SOLID186 element in ANSYS

Figure 1 shows a strengthened beam equipped with four-point bending test. Linear static analysis was carried out to observe different driving parameters. Linear and non-linear properties of materials were defined. The CFRP plate material properties were defined as linear and orthotropic because CFRP materials have linear properties and they were unidirectional [7]. But analysis was solely limited to linear analysis in both cases. For meshing, complete structured meshes were used. A schematic arrangement of the 3D modelled specimen with structured mesh is shown in Fig. 4.

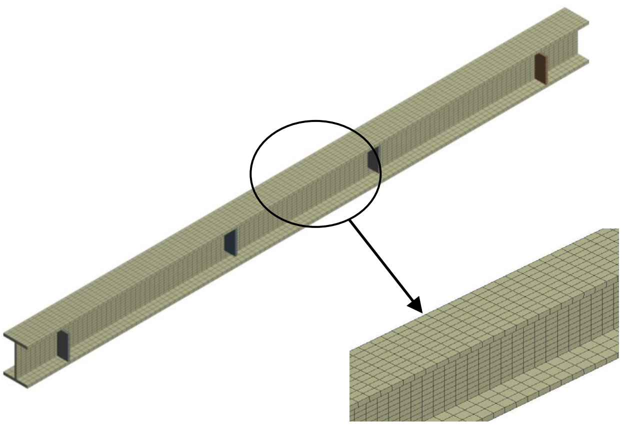

Fig. 4: Three-dimensional model of specimen with structured mesh.

3. RESULT AND DISCUSSION

3.1 Model Validation

The model is investigated by using general-purpose finite element program, ANSYS v16.2. It has been validated against result obtained in the literature as shown in fig. 5. To validate the present model, the specimen was equipped and material properties were taken as of reference specimen from literature. Fig. shows Load-deflection curve at midspan of the both beam (reference and present) with no strengthening. It is observed that the present study maintains very good agreement with the reference beam from literature.

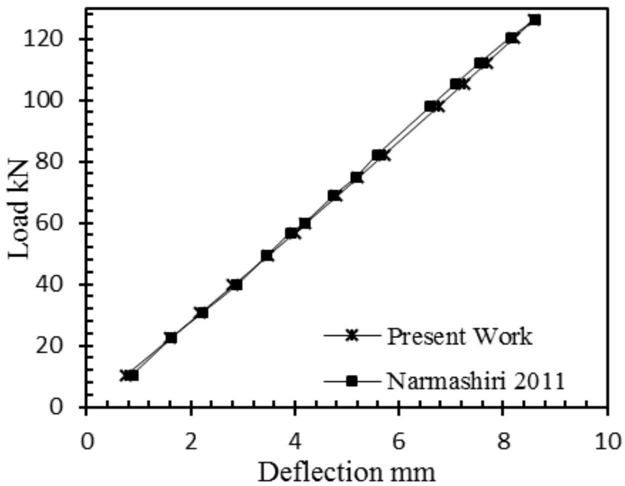

Fig. 5: Validation of present work with previous work from literature.

3.2 Mesh Independence Test

To obtain independent mesh for the further analysis a result is compared for different meshing combination. In this case deflections along the length of the beam for a specific loading condition(100kN) for different elements are shown in fig. 6. It is found that for different elements and nodes the change in deflection is very few or negligible. That indicates independence of the model. Finally, a model with elements of 7200 and nodes of 40957 was selected for further analysis.

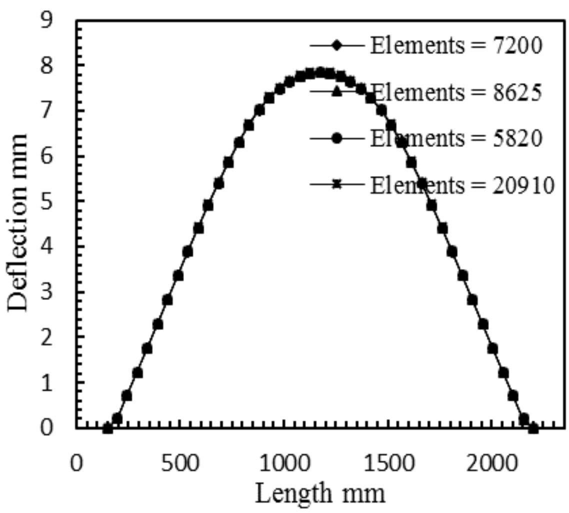

Fig. 6: Variation of vertical deflection along the length of the beam for different elements.

3.3 Vertical deflection

Vertical deflection is one of the most important parameters that must be studied in flexural strengthening of structural members. Maximum deflections, which occur at the mid span of the beam, are investigated. Fig.7 shows the mid span deflection for different applied load. Load-deflection curves for three different cases- bare beam, which is reference beam, steel strengthened beam and CFRP strengthened beam. Comparing three curves it is prominent that CFRP strengthened beam experiences lower amount of deflection for all loads. It is also clear that steel strengthened beam experiences lower deflection than bare beam, but that amount very much less than CFRP strengthened beam.

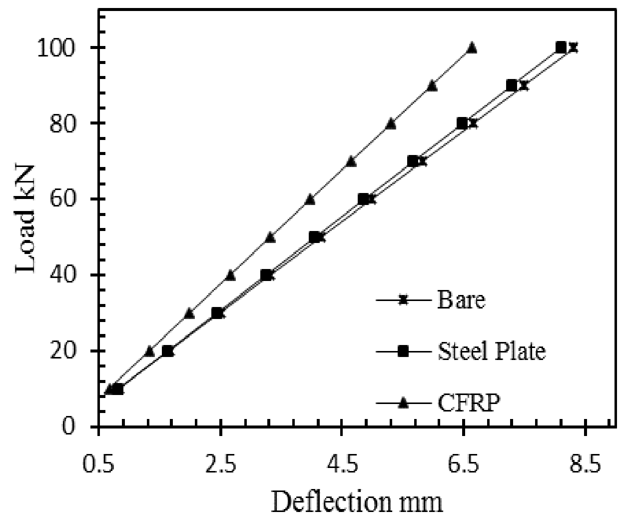

Fig. 7: Vertical Deflection at the midspan of the beam

Figure 8 shows deflection at the bottom flange of the beam for a specific loading condition. Observing deflection along length of the I-beam, same conclusion can be drawn as previous, i.e. deflection for CFRP strengthened beam is much less than other two cases.

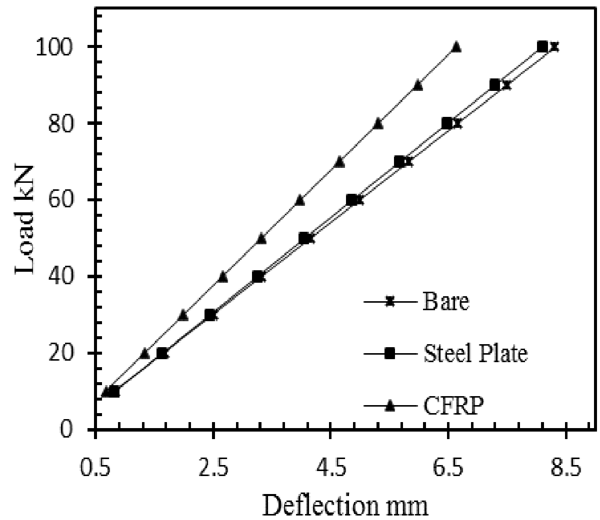

Fig. 8: Variation of vertical deflection along the length of the beam.

3.4 Strain on the tensile flange

The maximum tensile strain occurred at the mid-span of the beam, according to the loading condition. Normal elastic strain at the midspan as well as along the length of the beam shown in fig 9-10. Fig.9 shows micro strain for different loading conditions for three cases. Bare beam and steel strengthened beam possess larger strain than CFRP strengthened I-beam, as per graphical representation. Same phenomena for strain along the length of the beam for a specific loading condition.

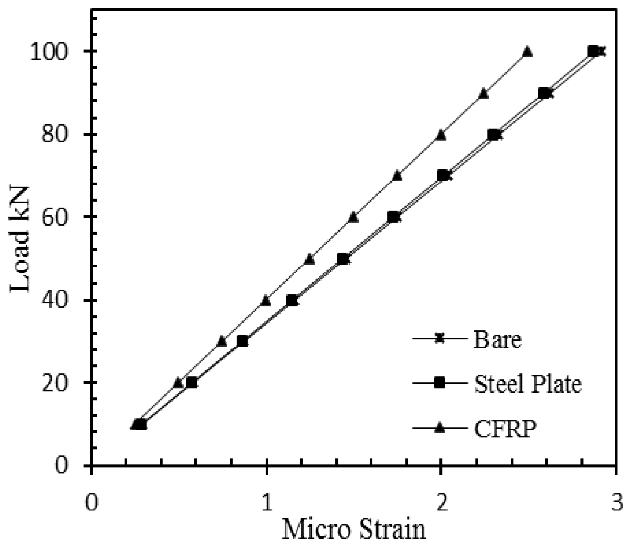

Fig. 9: Normal elastic strain at the midspan of the beam.

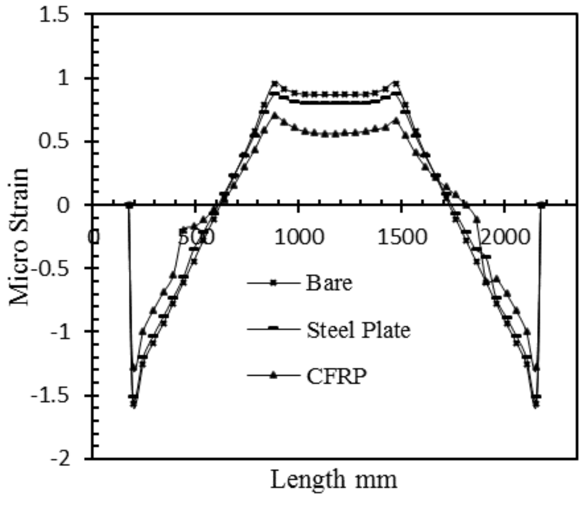

Fig. 10: Variation of normal elastic strain along the length of the beam.

3.5 Stress along beam length

Figure 11 shows stress distribution along the length of the beam between two supports. It shows stresses at the supports are maximum and the stress for the CFRP strengthened beam is lowest among the three beams. But it is to be noted that stresses for steel plate and CFRP strengthened beam are comparable in magnitude.

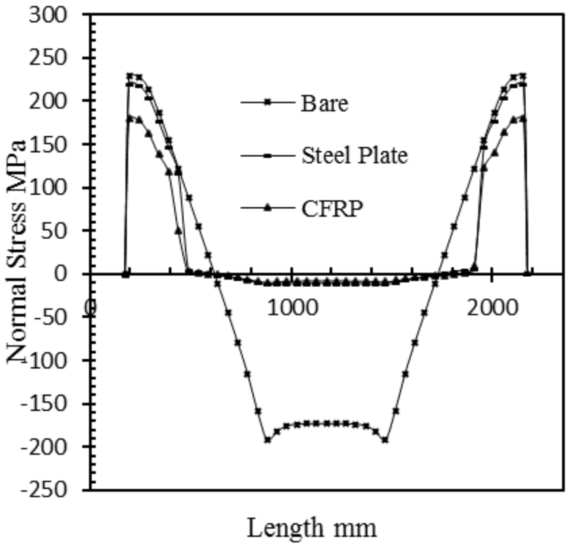

Fig. 11: Variation of normal elastic stress along the length of the beam.

4. CONCLUSION

A comprehensive investigation on strengthened I-beam is presented. The investigation is done to show the enhancement in flexural strength due to to use of carbon fiber reinforced polymer instead of using steel plates. The parameters investigated are, vertical deflection, strain in the bottom flange and stress on the tensile flange. The result clearly shows that-

- The flexural strength is much improved by using CFRP to strengthen I-beam.
- Vertical deflection at the midspan of the beam is much less in CFP strengthened Beam than bare and Steel strengthened beam.
- Normal elastic strain on the bottom flange also lower in the CFRP strengthened I-beam.
- Stress for CFRP strengthened beam is lowest among all three beams.

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