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Flexural Strengthening of Steel I-Beam with Carbon Fiber Reinforced Polymer

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Abstract

Strengthening of steel structural member with carbon fiber reinforced polymer (CFRP) has gained much research attraction last couple of year. CFRP composites bonded to steel members offer many advantages over steel plate bonding including excellent corrosion resistance, high stiffness and high strength to weight ratios etc. In this paper flexural strength of steel I-beam is analyzed numerically. CFRP laminates and steel plates are added to the bottom of the steel I beam to strengthen the member. One bare beam along with strengthened beams using CFRP laminates and steel plates are investigated. Non-linear analysis with full three dimension is carried out using general purpose finite element software Ansys v18.1. Effect of CFRP and steel plate on flexural strengthening is shown by performing four-point bending analysis of I beam. The result shows, yielding of CFRP strengthened steel I beam occurred at much higher limit than bare beam and steel strengthened beam.

Keywords: CFRP, Non-linear, Flexure, Yielding.

1. Introduction

Construction of many bridges of railway, and highway, marine industries are the common example of usage of Steel I section. The use of CFRP laminates to strengthen and repair steel beams has been rapidly increased last couple of year. The benefits of using CFRP includes light weight, extra strong, high stiffness, excellent corrosion resistance etc. Though CFRP is expensive to produce, it has gained much acceptance due to its high strength to light weight ratio and high rigidity. Strength of CFRP is very high compared to conventional structural steel i.e. mild steel. Also, strength of CFRP can be 3.5 times the strength of GFRP and about 9-10 times the strength of mild steel; weight of CFRP is much less than mild for the same desired tensile strength. Numerous experiments have been carried out on the behavior of steel beams reinforced with flexure CFRP plates.

Conventionally steel plates are added to the bottom flange of I-beam. In similar fashion CFRP laminates are also added to the tension flange for flexural strengthening. Experimental studies on five different configurations of GFRP and CFRP were carried out by Edberg et al. The GFRP and CFRP were attached at the bottom flange of the I-beam to observe strengthening capacity. The results indicated that CFRP is more effective than other strengthening methods [1]. Deng et al performed a number of analysis regarding the strengthening of beam using CFRP. In a paper, calculation of stresses in reinforced beam by analytical method under mechanical as well as thermal loads are presented. Finally, numerical analysis was used to validate the analytical results and a parametric study was conducted to show how the maximum stresses were influenced by the adhesive and adhesive dimensions and material properties [2]. In other paper study on the static behavior of metallic beams bonded with CFRP plates was done. For different cases, a total of 10 specimens were tested. The results show that the strength of metallic beams is influenced by various factors [3]. Different steel structures, railway and bridges etc. strengthened 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 [4]. Linghoff et al. performed series of analysis regarding strengthening of beams with CFRP. At first, they reviewed the research works conducted at Chalmers University of technology during the last couple of years in this field. The results of different test types are summarized and discussed [5]. Then they perform analysis numerically and experimentally. Comparisons with the results of laboratory tests carried out on steel beams reinforced with bonded CFRP laminates indicate that the behavior of the reinforced beams can be captured using FE analyzes [6-7]. Narmashiri et al. investigated one bare control beam and some strengthened beams using different types and dimensions of CFRP strips experimentally investigated by Narmahiri et al. Failure modes of CFRP were also 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 [8]. 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 found that CFRP sheets were very successful in strengthening structural members and beam with CFRP showed much higher strength than unstrengthen one [9].

In this paper flexural behavior of the CFRP strengthened steel I-beams is observed with non-linear analysis. 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 study, Steel I section of ASTM(A36) is reinforced by CFRP laminates and steel plate. Only material non-linearity is considered for this analysis. Table 1 shows material properties of I section and steel plate. Figure 1 indicates the dimension of the specimens, and Fig. 2 depicts the dimensions of the steel I-section.

Table 1: material properties of steel I-beams.

Young's Modulus (N/mm^2)	Poisson's Ratio	Strength	
		Yield Strength (N/mm^2)	Tangent Modulus (N/mm^2)
210000	0.3	250	1450

In this study, two types of steel plate are used, where steel plate A is used for flexural reinforcement and steel plate B is used as stiffener. The stiffener is provided to prevent lateral torsional buckling, which is equipped at web with full depth. The dimensions of the steel plates are shown in table 2.

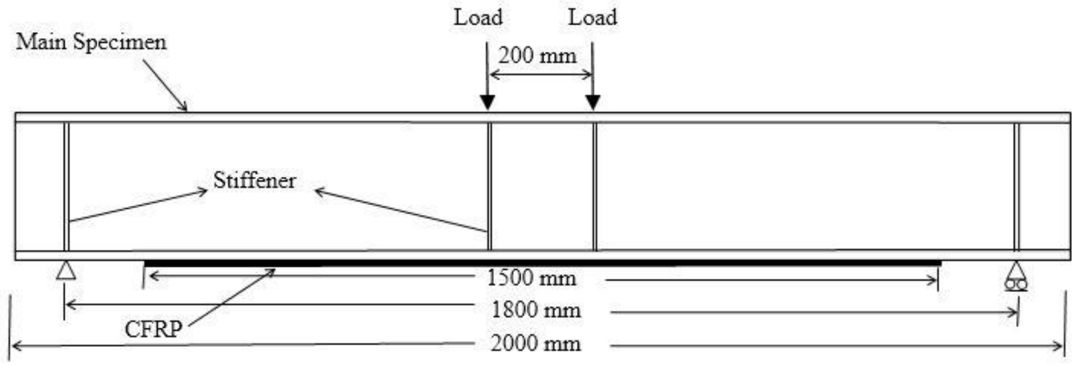


Fig. 1: Specifications of the strengthened steel I-beam.

CFRP is considered as linear orthotopic material. Also, flexural strength can be improved by strength of CFRP materials. Normally, CFRP is available in two general form, either a strip (plate) or a sheet (wrap). In this research, only CFRP laminates or sheets are used. CFRP strips are installed on the bottom flange 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[10].

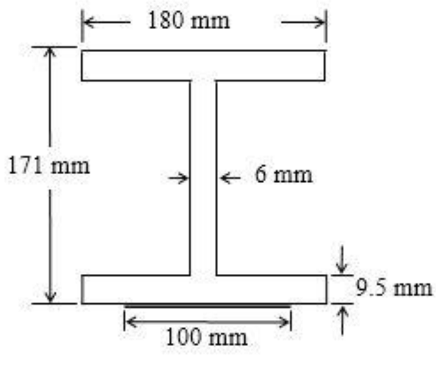


Fig. 2: Dimensions of steel I-Section.

Table 2. Dimensions of Steel plates, CFRP and Adhesive.

	Width (mm)	Length (mm)	Thick (mm)
Plate A	100	1500	6,8
CFRP	100	1500	1.2
Epoxy	100	1500	1

An adhesive named, Sikadur-30 is used for adding CFRP sheet or steel plate to the reference beam. The epoxy should be such that, it can take very high stress generated during loading. Table 2 and table 4 shows the dimensions and material properties of the Epoxy resin respectively [10].

Table 3: Material properties of CFRP (SikaCarboDur S512).

Parameter	Value
Young's modulus in *X* direction (N/mm^2)	310000
Young's modulus in *Y* direction (N/mm^2)	11200
Young's modulus in *Z* direction (N/mm^2)	11200
Poisson's Ratio *XY*	0.0058
Poisson's Ratio *YZ*	0.3
Poisson's Ratio *XZ*	0.0058
Shear Modulus *XY* (N/mm^2)	26500
Shear Modulus *YZ* (N/mm^2)	3700
Shear Modulus *XZ* (N/mm^2)	26500
Tensile strength (N/mm^2)	3100

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

Parameter	Value
E Modulus (N/mm^2)	11200
Tensile strength (N/mm^2)	29
Poisson's Ratio	0.3

2.2 Methods

This analysis is performed by the general-purpose finite element program, ANSYS v18.1. Flexural behavior of one non strengthened beam and other strengthened beams are analyzed numerically. Steel is considered as non-linear elastic material. Bi-linear isotropic hardening model is used to predict non-linearity of the material. The adhesive is considered as linear elastic material whereas CFRP is considered as linear orthotopic material. Higher order 3D 20-node solid elements SOLID186, were used to represent the problem main components (I-section, CFRP sheet, adhesive and steel plate). At supports and below the load points, vertical stiffeners are provided to withstand the premature yielding of the beam. The beam's free span is 1.8 m and the length of the CFRP sheets adhered to the tension flange is 1.5 m; the free length between the end of the CFRP and the supports is not strengthened.

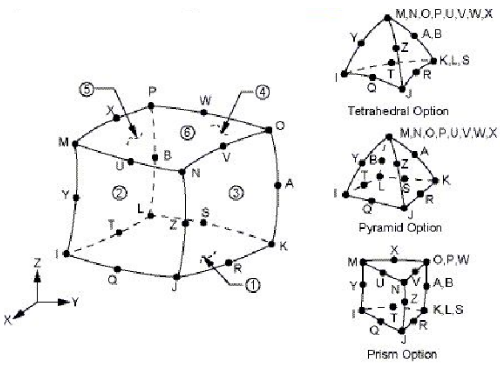


Fig. 3: SOLID186 element in ANSYS.

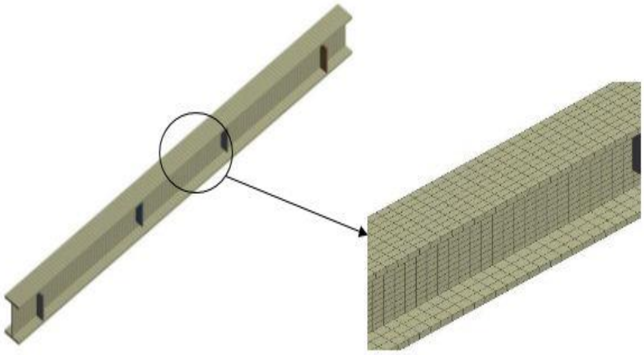


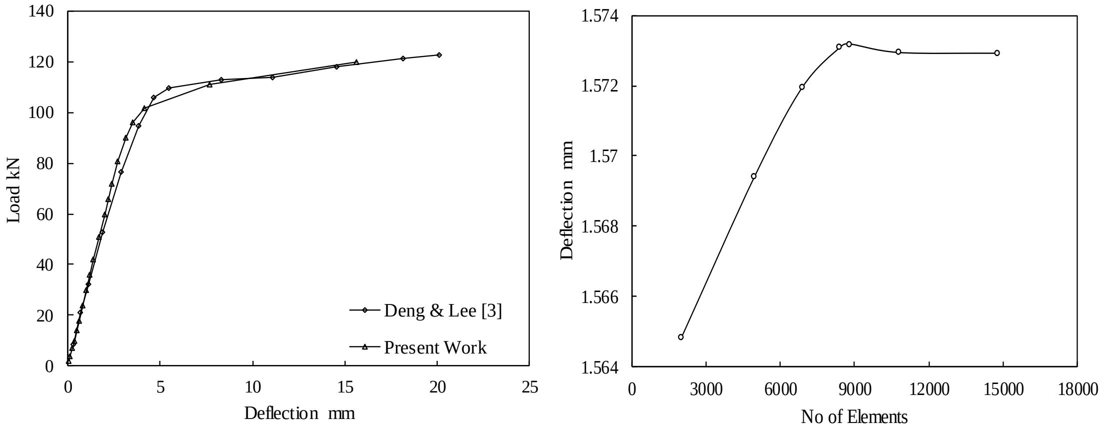
Fig. 4: Three-dimensional model of specimen with structured mesh.

A beam, equipped with four-point bending test, is shown in Fig. 1. Linear and non-linear properties of materials were defined. For meshing, complete structured meshes were used. A schematic arrangement of the 3D modelled specimen with structured mesh is shown in Fig. 4.

3. Results and Discussion

3.1 Model Validation

The model is investigated by using general-purpose finite element program. It has been validated against result obtained in the literature as shown in fig. 5 (a). To validate the present model, the specimen was equipped and material properties were taken as of reference specimen from literature. Figure 5 (a) depicts 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.



(a) (b)

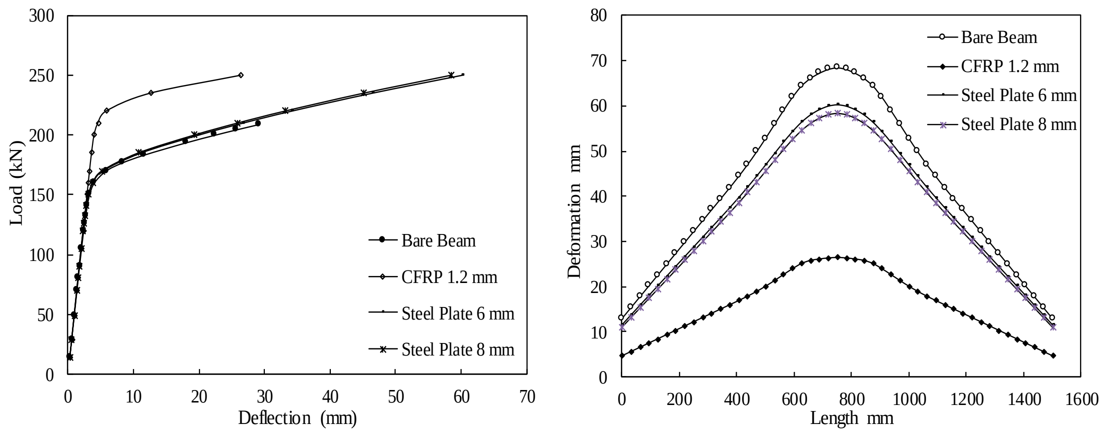
Fig. 5: (a)Validation of present work with previous work from literature (b) Variation midspan deflection of the beam for different elements.

3.2 Mesh Independence Test

To obtain independent mesh for the further analysis a result is compared for different meshing combination. In this case midspan deflections for a specific loading condition (80 kN) for different meshing elements are shown in fig. 5 (b). It is found that for different elements the change in deflection is very few or negligible. Finally, a model with number of elements 10800 is selected for further analysis.

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.6 (a) 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 are analyzed. It is prominent that CFRP strengthened beam experiences lower amount of deflection for all loads. There is one important point to make, that is, yielding of strengthened beam occurred at much higher limit than the bare beam and beam with steel plate.



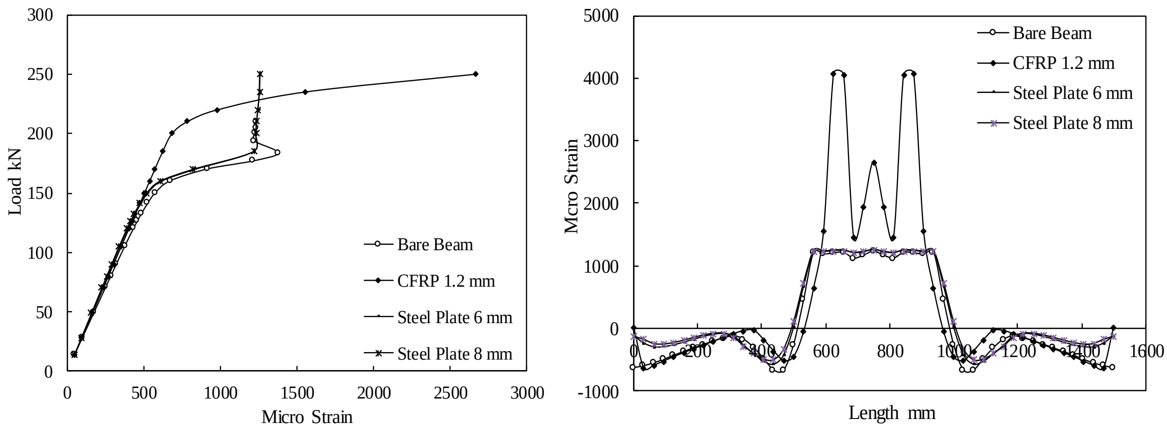
(a) (b)

Fig. 6: (a) Vertical Deflection at the midspan of the beam (b) Variation of vertical deflection along the length of the beam.

Figure 6 (b) 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 lower than the bare beam. Steel plate strengthened beam experienced much higher deflection than CFRP strengthened beam, but slightly lower than the bare 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 are shown in fig 7. Figure 7 (a) shows micro strain for different loading conditions for four cases. It is found that, bare beam and steel strengthened beam possess lower yielding than CFRP strengthened beam. Bare beam and steel strengthened beam possess larger strain than CFRP strengthened I-beam, as per graphical representation. Same phenomena is observed for strain along the length of the beam for a specific loading condition.



(a) (b)

Fig. 7: (a) Normal elastic strain at the midspan of the beam (b) Variation of normal elastic strain along the length of the beam.

4. Conclusion

Flexural strengthening of I-beam is investigated numerically in the current study. The specific outcomes of this investigation are as follows-

- The flexural strength is much improved by using CFRP to strengthen I-beam.
- Yielding is much improved in CFRP strengthened beam than other beams.
- Vertical deflection at the midspan of the beam is much less in CFRP strengthened Beam as compared with bare and steel strengthened beam.
- Normal elastic strain on the bottom flange also improved in the CFRP strengthened I-beam.

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