Flexural Strengthening of Steel Beams using CFRP Sheets

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Abstract - *While traditional retrofitting methods for steel structures could be time consuming and uneconomical, an alternative repair method is suggested using Carbon Fiber Reinforced Polymers (CFRP) sheets, providing engineers with a competitive solution that will increase the life-cycle of steel structures. This study investigated feasibility of CFRP as an option to strengthen and rehabilitate steel structures. The main advantages of using CFRP sheets are their light weight and durability, which results in ease of handling and maintenance. The research conducted experimental to evaluate the effectiveness of strengthening steel beams by the use of novel CFRP laminate sheets configurations. The research involved the testing of five experimental composite beams to analyse the variation in yield load, ultimate load and deformation characteristics. When the steel beam wrapped with CFRP sheets in the lower and upper portion of bottom flange as well as in the bottom portion of web i.e, SB 4, there was an increase of 10% and 8.54% in the yield load and ultimate load respectively.*

Key Words: **CFRP, Debonding, Steel Beam, Adhesive, Retrofitting, Flexural Behaviour**

1. INTRODUCTION

Traditional strengthening techniques of steel beams involve an expensive process of welding/bolting steel plates to the tension flange of the section. These plates are heavy, impractical and face many difficulties in site-installation. Thus, Fibre Reinforced Polymer (FRP) laminates/strips which are characterized by their high strength to weight ratio offer an attractive strengthening alternative. Lately, FRP laminates/strips were widely used to retrofit reinforced and prestressed concrete structures.

Regarding strengthening of steel structures using FRP laminates/strips, investigations to-date have been limited to applying the laminates/strips to the tension flanges of the steel beams in order to increase the beam's flexural strength. However, for thin walled I-section steel beams the risk of buckling failure is also a major concern. For flexural strengthening I-beams, the CFRP strip is installed on the tensile flange due to its significant tensile strength. One of the most important criteria for the CFRP strengthened steel structures is the bonding between CFRP, adhesive, and steel surfaces.

As an alternative to strengthening or repairing steel structures with welded or bolted plates, bonded CFRP laminates can be used. The improvements that can be expected are increased stiffness and strength and an extension to the fatigue life of the strengthened member. One advantage of using CFRP is its high tensile strength and stiffness compared with its low self-weight. The strengthening scheme is less labour intensive compared with other existing techniques, which makes it even more interesting as a system for repairing and/or strengthening existing structures. Laminate bonding relies on the strength of the adhesive layer. Both theoretical work and laboratory tests have shown that this strength is governed by stresses along the bond line, which occur due to differences in strain, caused by external loads or the difference in coefficients of thermal expansion between the steel beam and the laminate. Concentrations of interfacial stresses occur in the vicinity of the geometric discontinuities; in particular, at the end of a bond line but also at the location of a crack in the substrate or a bond defect in the adhesive layer.

1.1. Literature Survey

Omar H. Elkhabeery, Sherif S. Safar, Sherif A. Mourad (2018) conducted study on reinforcing effect of CFRP, one hundred and seventy-eight models were analysed to cover six variables representing the common problem parameters; the variables were the slenderness ratio of web (hw/tw), the mono-symmetric ratio of I beam (ψ), the area of CFRP (Acfrp), the modulus of elasticity of CFRP (Ecfrp), the tensile strength of CFRP (Fucfrp), and the length of CFRP sheet (Lcfrp). The adhesive properties used in parametric analysis were determined from experimental tests conducted for double-strap steel-to-CFRP joints with various bond lengths (50 to 200mm). The parametric study revealed that CFRP sheets were very efficient in reinforcing compact mono-symmetric sections, whereas the enhancement in beams with non-compact sections was very small. CFRP sheets were able to reach its ultimate strength provided that enough bond length was ensured [11]

Linghoff, Al-Emrani, Kliger (2010) investigated the behaviour of steel beams reinforced with different configuration of CFRP laminates in service and ultimate states. Laboratory tests and simplified analytical solution were adopted for the parametric study. The laboratory tests and analytical solutions showed that the increase in bending moment capacity reached 20%. Debonding problems have been noticed for only one of the tested beams which was attributed to poor adhesion between CFRP and steel; for other beams, rupture in CFRP laminates controlled the cross section strength. The strengthening system that produced the most desirable strength and serviceability behaviours was the CFRP laminates with high tensile strength and Young's modulus equivalent to that of steel. The analytical models showed that further increase in moment capacity was not possible since the yielding of top compression flange controlled the section strength. [4]

Kambiz Narmashiri1, Ramli Sulong and Mohd Zamin (2011) investigated that flexural behaviours of steel I-beams are improved using CFRP strips. The application of different thicknesses and types of CFRP plates used in strengthening steel I-beams caused change in the CFRP failure modes, load bearing capacity, and strain on CFRP plates. One of the most efficient approaches to increase the strength of beam against the below load splitting was by increasing the CFRP thickness. Applying a thicker CFRP plate caused significant increment in the load bearing capacity, but the CFRP showed brittle behaviour, and premature end debonding occurred. Application of the IM-CFRP plates caused considerable increment in the load bearing capacity, due to the larger elasticity modulus. [6]

1.2. Objectives

- To investigate the effectiveness of CFRP sheets in flexural strengthening of steel beams.
- To investigate the effect of strengthening scheme of CFRP in the yield load, ultimate load and deformation characteristics of steel beams.

1.3. Scope Of Study

The number of civil infrastructures which have deteriorated and no longer fulfil the requirements of safety standards is continuously increasing day by day. Over the past few decades, there has been increasing interest in applying adhesively bonded composites to repair existing and/or strengthen new civil engineering structures. Extensive research has been conducted on FRP strengthening of concrete structures, whereas relatively less work has been done on FRP strengthening of steel structures. Among the FRP materials available, Carbon Fibre Reinforced Polymers (CFRP) where found to be the most suitable for strengthening steel structures because of their well known high mechanical properties and high strength to weight ratio. Therefore it is important to investigate the effect of CFRP strengthening in the load capacity, and deformation characteristics of steel beams. The scope of this study is limited to the strengthening of steel beams using CFRP sheets in flexure only.

2. MATERIAL PROPERTIES

2.1. Steel beam

The steel beam used in the study is ISMB 100 (Fig-2.1). The steel beam was of grade Fe 250 and corresponding tensile strength is 410 MPa as per IS 2063:2011. The nominal dimensions mass and sectional properties of ISMB 100 as shown in table-2.1

Table-2.1: Nominal dimensions of ISMB 100

Mass,M	8.90 kg/m
Sectional area,a	11.40 cm^2
Depth,D	100.00mm
Width of flange, B	50.00mm
Thickness of web, t	4.70 mm
Thickness of flange, l	7.00 mm
Maximum Flange slope, α	98.000
Radius at foot R_1	9.00 mm
Radius at foot R_2	4.50 mm
Moment of inertia about X-X axis, I_x	183.00 cm^4
Moment of inertia about Y-Y axis, I_y	12.90 cm^4
Radius of gyration about X-X axis, r_x	4.00 cm
Radius of gyration about Y-Y axis, r_y	1.05 cm
Modulus of section about X-X axis, Z_x	36.60 cm^3
Modulus of section about Y-Y axis, Z_y	5.16 cm^3

Fig-2.1 ISMB 100

2.2. CFRP

Fig-2.2 CFRP Sheet

It is an extremely strong and light fiber reinforced plastic which contains carbon fiber. CFRP sheets of 0.42 mm thickness is used in the experimental study (Fig-2.3). For strengthening CFRP sheets in 3 layers are used. The properties of CFRP sheets are provided by manufacturer is shown in Table-2.2.

Table-2.2 Properties of CFRP

Tensile Strength (GPa)	3.45
Modulus of elasticity (GPa)	230.00
Percentage Elongation (%)	1.60
Density (g/cm^3)	1.80

2.3. Adhesive

Fig-2.3 Epoxy adhesive

The adhesive used is Araldite AW 106 epoxy resin with hardener HV 953 IN in order to bond CFRP sheet to steel beam and also to bond layers of CFRP sheets together. Equal quantity by volume of epoxy resin and hardener is mixed thoroughly to get adequate bonding property. The properties of epoxy adhesive a provided by the manufacturer is shown in Table-2.3.

Table-2.3 Properties of epoxy adhesive

Viscosity	45000.0
Minimum cure time	12 hours
Shear strength (for 5 days curing)	17.6 MPa
Ultimate Tensile Strength	33.0 MPa
Elongation	9.0 %

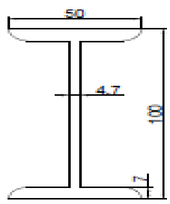
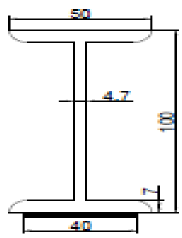
An adhesive for a particular rehabilitation scheme must perform three functions. First, the adhesive must have adequate bond strength so that the composite material can be optimally utilized. Consequently, this requires the failure mode of the system to be governed by the ultimate strength capacity of the composite and not by a bond failure. Second, the system must be sufficient durable in the design environment to match the life expectancy of the structure. Finally the adhesive must also be easy to utilize under field conditions.

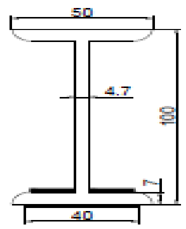
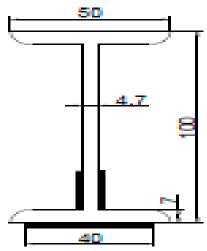
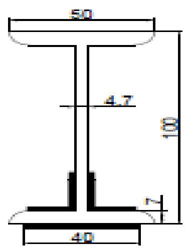
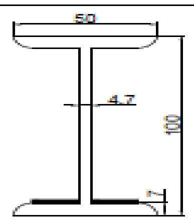
3. EXPERIMENTAL STUDY

3.1. Specimen Details

The strengthening effectiveness of CFRP sheets on steel beam were studied by testing 6 steel beams. One of them is unstrenghtened and served as control beam. The details of the specimens are shown in Table-3.1. The length of the specimen is 800 mm. And other beams were strengthened using 0.42 mm thick CFRP sheets in 3 layers so as to get an overall thickness 0f 1.2 mm.

Table-3.1 Specimen details

Sl. no	Beam Design-ation	Description	Schematic diagram
1	UB	Unstrengthened beam	
2	SB 1	Strengthening beam using scheme 1 [CFRP attached to lower portion of bottom flange]	

3	SB 2	Strengthening beam using scheme 2 [CFRP attached to lower and upper portion of bottom flange]	
4	SB 3	Strengthening beam using scheme 3 [CFRP attached to lower portion of bottom flange as well as in the bottom portion of web]	
5	SB 4	Strengthening beam using scheme 4 [CFRP attached to lower and upper portion of bottom flange as well as Bottom of web]	
6	SB 5	Strengthening beam using scheme 5 [CFRP attached to upper portion of bottom flange]	

3.2. Specimen Preparation And Procedure

The steel beam were 0.80 m length. The dimensions were properly checked using a vernier caliper and a meter scale. The procedure for adopted for specimen preparation and strengthening is briefly described here.

- Step 1: Surface preparation

Surface preparation is the key to a strong and durable adhesive bond. The steel surface is treated using a sand paper to remove the irregularities on the surface and the rust present. It is necessary for obtaining a rough surface for the better bonding of CFRP on the steel beam by epoxy adhesive. The dust on the surface is removed using a brush. The materials used for surface preparation of steel beams.

- Step 2: Marking of specimen

The steel surface is marked for bonding CFRP sheet and for testing (Fig-3.1).The length of CFRP sheet adopted for strengthening was 600 mm and is marked in the beam. The position for placing the spreader beam and the roller supports were also marked. It is taken as 100 mm center to center. The overall length of beam is 800 mm with a clear span of 720 mm (40 mm overhanging to each support).The distance between the two point loads of the spreader beam was 100 mm.

Fig-3.1 Steel beam marked for testing

- Step 3: Cutting the CFRP sheets to proper dimensions

The CFRP sheet is cut down to proper dimensions. The CFRP sheets were cut to a length of 600 mm and width according to the placement position.

- Step 4: Preparation of epoxy adhesive.

The adhesive used is a two component viscous epoxy. Equal quantity b volume of epoxy resin and hardener is mixed thoroughly to get a consistent mixture of adequate bonding property

- Step 5: Application of epoxy on steel beam surface and on CFRP

The preparation mixture of epoxy adhesive is applied evenly on the prepared surface of the steel beam and on the CFRP.

- Step 6: Placement of CFRP on steel beam.

After applying the epoxy adhesive on the steel beam and on CFRP layer, the first layer of CFRP is placed over the steel surface. Similarly 3 layers of CFRP were placed

- Step 7: Removal of air pockets.

The trapped air was removed by rolling with a roller after placing each layer of CFRP.

- Step 8: Curing and testing

The strengthened specimen is cured for 1 week even though the curing period of adhesive at room temperature is 12 hours. The specimen is tested after 1 week of curing.

3.3. Test Setup

The experimental setup is based on four point bending test and is performed in the Universal Testing Machine of 1000 kN capacity. The experimental setup is shown in Fig-4.2. The effective length adopted was 70 mm. The load was applied uniform rate till failure. The load was transferred to the main specimen by using a loading beam with two point loads with center to center distance 100 mm. Deflection at the mid span of the beam is measured using a dial gauge of least count 0.01 mm. The mid span deflection is noted for the specimen at a load increment of 5 kN till the failure. The range adopted for testing was 0-200 kN.

Fig-3.2 Experimental setup

4. RESULTS AND DISCUSSIONS

4.1. Test Results

The beam is tested upto failure. The ultimate load of specimen is noted and yield loads are obtained from load deflection curves of each tested specimen. The yield load, ultimate load and mid span deflection are given in Table-4.1

Table-4.1: Test results

Sl .No	Beam Desig-nation	Yield Load (kN)	Mid span deflection correspo-nding to yield load (mm)	Ultimate load (kN)	Mid span Deflection correspo-nding to ultimate load (mm)
1	UB	80.0	4.50	99.5	35
2	SB 1	83.0	4.00	103.0	29
3	SB 2	82.5	3.90	103.5	30
4	SB 3	82.0	3.65	104.0	38
5	SB 4	88.0	3.80	108.0	50
6	SB5	81.0	4.00	101.0	36

4.2. Effectiveness Of Strengthening Of Steel Beam Using CFRP

4.2.1. Load Deflection Curves

The load deflection curves of tested specimens are shown in Chart-4.1

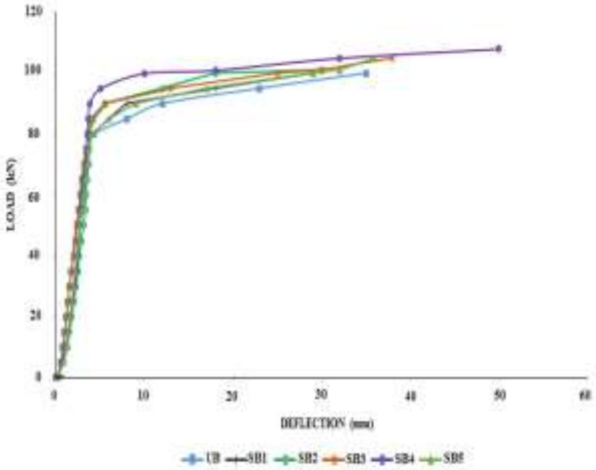


Chart-4.1 Load deflection graph

It can be seen that all the strengthened scheme have more yield load and ultimate load carrying capacity than unstrengthened beam.

4.2.2. Load Carrying Capacity

The most important parameter required in the strengthening of structures is the increment on the load carrying capacity of the strengthened beam compared to the unstrengthened beam. Effectiveness of strengthening scheme with respect to both yield load and ultimate load is studied.

Table 4.2 shows the percentage increase in yield load and ultimate load with respect to the unstrengthened beam.

Table-4.2 Percentage increase in yield load and ultimate load

Beam designation	Yield load (kN)	Percentage increase in yield load (%)	Ultimate load (kN)	Percentage increase in ultimate load (%)
UB	80.00	-	99.50	-
SB1	83.00	3.75	103.00	3.52
SB2	82.50	3.13	103.50	4.02
SB3	82.00	2.50	104.00	4.52
SB4	88.00	10.00	108.00	8.54
SB5	81.00	1.25	101.00	1.50

(i) Yield load

It is the load corresponding to the beginning of yielding in steel and will be obtained from the load deflection curve. Fig-4.1 shows the percentage increase in yield load of strengthened specimen with respect to the unstrengthened beam. In all schemes it shows increase in the yield load compared to unstrengthened beam.

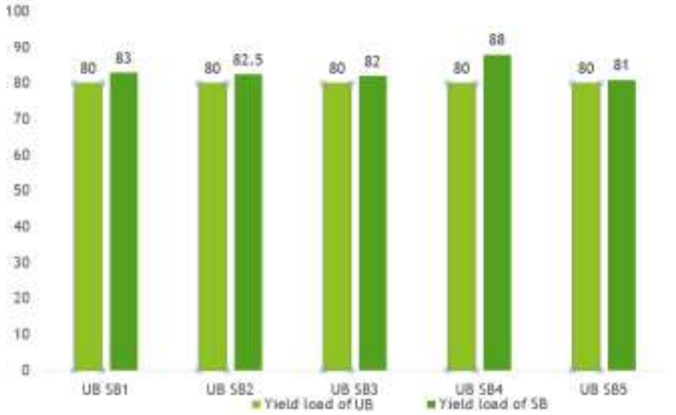


Fig-4.1 Percentage increase in yield load

The yield load of unstrengthened beam, UB is 80 kN. When scheme 4 is adopted 10% increment in yield load is obtained i.e, SB4 using CFRP sheet in the lower and upper portion of bottom flange as well as in bottom portion of web, the yield load obtained as 88 kN.

(ii) Ultimate load

It is the load corresponding to the failure of the beam. Fig-4.3 shows the percentage increase of ultimate load of strengthened beams with respect to the unstrengthened beam. In all schemes it shows increase in the ultimate load compared to unstrengthened beam.

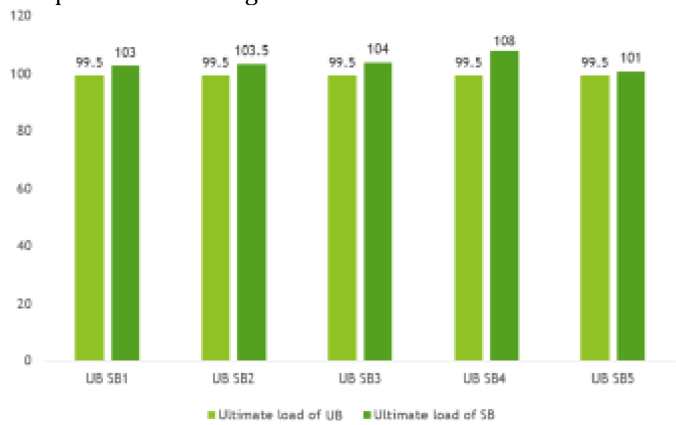


Fig-4.2 Percentage increase in ultimate load

The ultimate load of unstrengthened beam, UB is 99.5 kN. When the beam was strengthened using scheme 4 it shows the maximum increment in the ultimate load. When scheme 4 is adopted 8.54% increment in ultimate load is obtained, i.e, SB4 using CFRP sheet in the lower and upper portion of bottom flange as well as in lower portion of bottom web, the ultimate load obtained as 108 kN.

5. CONCLUSIONS

Based on experimental investigation carried on the unstrengthened beam and CFRP strengthened beam specimens, the following conclusions are drawn:

- CFRP strengthening was found effective in enhancing the flexural strength of the beam.
- An increment of 1.25 %, 2.5%, 3.13%, 3.75%, 10% and 1.5%, 3.52%, 4.02%, 4.52% 8.54% were observed in the yield load and ultimate load for the various strengthening schemes adopted.
- The percentage increase in yield load was found higher as 3.75% and 10% for the SB1 and SB4 i.e, the beam strengthened with CFRP in the lower portion of bottom flange and the beam strengthened with CFRP at the lower and upper portion of the bottom flange as well as in the bottom of the web than the increase in the ultimate load i.e, 3.52% and 8.54%. this is because of the early debonding of CFRP sheets from the beam
- Of the strengthening schemes investigated scheme 4, SB 4 in which beam is strengthened with CFRP at the bottom and upper portion of the bottom flange and in the lower portion of web was found to be more effective in enhancing the load carrying capacity of the steel beams.
- When scheme 4 was adopted, there was an increase of 10% in the yield load and 8.54% in the ultimate load with respect to unstrengthened beam, UB. This is due to the confining effect given by the CFRP in the strengthening scheme 4.
- All the tested beams failed in flexure after yielding of steel. The failure mode of CFRP in the strengthened specimens was partial debonding from the ends.

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