Interdependence between Structural Engineering and Construction Management
Edited by Ozevin, D., Ataei, H., Modares, M., Gurgun, A., Yazdani, S., and Singh, A.

ISBN: 978-0-9960437-6-2

FRP-FLEXURAL STRENGTHENING OF STEEL BEAMS: A FINITE ELEMENT ANALYSIS STUDY

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Fiber reinforced polymer (FRP) strengthening has been widely used for concrete structures. However, limited studies have been conducted on its application to steel structures. The use of FRP materials to retrofit steel members is an effective replacement for welded or bolted steel plates and offer high strength-to-weight ratio, resilience to environmental degradation, and a robust fatigue performance. Past studies have shown that the application of FRP to steel is a promising technical solution to help against corrosion and also to increase the load carrying capacity of steel members. In the present study, finite element analysis (FEA) model of a steel beam strengthened with carbon fiber reinforced polymer (CFRP) laminates was developed using ANSYS Mechanical finite element software program. The model was validated by comparing the FEA and experimental results of an existing study in the literature and they were in good agreement. A parametric study was conducted on the validated steel beam model with the aim to investigate the effects of basalt fiber reinforced polymer (BFRP) and two types of adhesives on its performance under static loading. The FRP laminates provided an increase in flexural capacity and pseudo ductility of the beams. The optimum bond length was found to be 2/5 of the span length for the beam in this study.

Keywords: High-strength material, Bond length, Retrofit, Load capacity, Flexure, ANSYS.

1 INTRODUCTION

Large number of steel buildings and bridges in the US are deteriorating due to aging, harsh environmental exposure, creep, fatigue and lack of proper maintenance, (Al-Saidy *et al.* 2004). Most steel structures today are in need of repair and retrofit. Traditional retrofit techniques involve cutting out and replacing steel plates or attaching steel plates by welding or bolting externally which are problematic in terms of scale and workability (Zhaoa *et al.* 2007). Use of fiber reinforced polymers offers a great alternative retrofit scheme which is less labor intensive and has the ability to increase stiffness as well as being corrosion resistant (Linghoff *et al.* 2010). Colombi *et al.* (2006) conducted experimental and analytical study on steel beams reinforced with pultruded CFRP strips and observed 9% to 23% increase in load capacity and also considerable increase in stiffness. In addition to flexural strengthening, the fatigue life of the beams reinforced with CFRP plates was significantly longer than that of the beams repaired only with the welding method (Jiao *et al.* 2012). The strength of external FRP retrofit depends mainly on the bond between FRP and steel. Study performed by Linghoff *et al.* (2009) concluded that surface preperation plays an important role in the bond strength. Limited studies have been performed on FRP appication to steel structures as opposed to concrete structures. Furthermore, most FRP strengthening of steel structures involves carbon fiber reinforced polymer (CFRP). However, to the best of authors knowledge no study has been performed on basalt fiber reinforced polymer (BFRP) stregthened steel members. The focus of the present study is to numerically investigate the effect of CFRP and BFRP plates and various adhesives on the performance of steel beams.

2 FEA MODELING

Finite element analysis modeling of the steel beams was performed using the software program ANSYS Mechanical APDL. In order to reduce calculation time and due to symmetry only half of the beam adopted from experimental study by Lenwari *et al.* (2005) was modeled. The dimensions and material properties of the beams are listed in Table 1. SOLID185 and SOLID65 elements with eight nodes and three degrees of freedom at each node were employed to model steel beams and FRP plates, respectively. Steel pads were modeled using SOLID45 element, and placed at the locations of loading points and supports to distribute the load and to avoid stress concentration. For the validation purpose, beams retrofitted with three CFRP laminate lengths of 500, 650, and 1,200 mm were modeled. Figure 1 shows the steel and FRP materials stress versus strain relationships, where steel was assumed as multi-linear with elastic yield stress of 250 MPa and tangent modulus of 1,450 MPa; the FRP laminate and adhesive were assumed to depict elastic-linear behavior until failure.

Table 1. Material properties.

Description	Dimensions	Elastic modulus (GPa)	Poisson's ratio	Ultimate strain (%)	Density (g/cm^3)
Steel Beam	W100 x 17.2	200	0.26		7.8
SikaCarboDur H514 (C)	50 mm x 1.4 mm	300	0.3	>0.45%	1.6
SikaCarbodur S512 (C')	50 mm x 1.2 mm	165	0.3	>1.7%	1.6
Sikadur30	1 mm thick	12.2	0.3	>0.29%	
Sikadur300	1 mm thick	3.5	0.3	>1.5%	
BFRP	50 mm x 1.4 mm	89	0.3	>3.15%	2.7

Bilinear bond slip model was employed for the interface between the steel beam (substrate) and the FRP laminate (reinforcement) based on the study by (Xia and Teng 2005) (Figure 2). To model the interface the elements TARGET170 and CONTA174 were used. The bond-slip model requires the maximum shear, slip at maximum shear, and slip at debonding. The model proposed by Xia and Teng (2005) helps calculate the maximum elastic slip given by Eq. (1):

$$\delta_1 = \tau_f\, t_a / G_a \tag{1}$$

δ_1 is the slip at local-bond strength τ_f which is calculated from Eq. (2):

$$\tau_f = 0.8\, \sigma_{max} \tag{2}$$

where σ_{max} is the tensile strength of adhesive; t_a is the thickness of the adhesive layer, G_a is the shear modulus of the adhesive. The value of slip at complete debonding is given by Eq. (3):

$$\delta_f = 62\, (\sigma_{max}/G_a)^{0.56}\, (t_a^{0.27}/\, \tau_f) \tag{3}$$

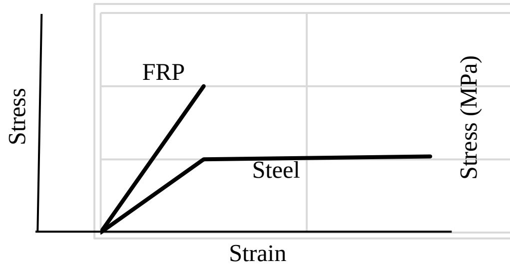

Figure 1. Stress-strain curves.

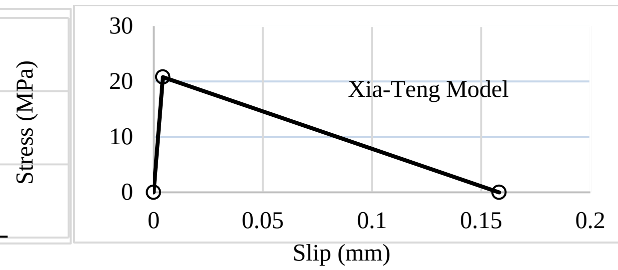

Figure 2. Bond-slip model.

3 VALIDATION OF FEA BEAM MODELS

The experimental study by Lenwari *et al.* (2005) was selected for validation of FEA models in order to perform further parametric study. The beams in the experiment had two types of failures; debonding and rupture of FRP plates. To avoid localized buckling of compression flange and yielding in compression, a steel plate was attached to the compression flange of the beams in the experiment which was also modeled in FEA. The beam models with three different lengths of CFRP plates were validated through comparing the experimental data with FEA results discussed in later section. Figure 3 shows the schematic diagram of the four-point bending test for the simply-supported steel beam.

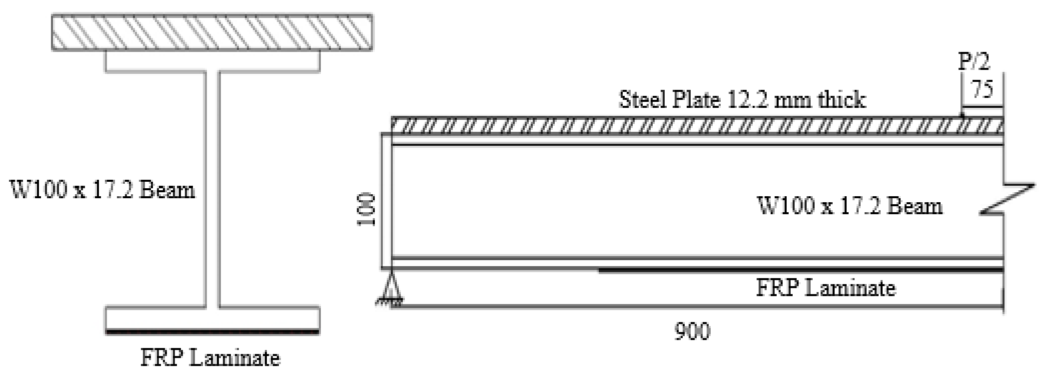

Figure 3. Schematic diagram of beam setup.

4 RESULTS AND DISCUSSIONS

The comparison of experiment and FEA and parametric study results are shown in Table 2. The FEA models were identified as follows: the first letter indicates the member being a beam, first number refers to bond length, second letter indicates the FRP types (CFRP: C for high, and C' for low modulus, and B for BFRP) and the last number indicates adhesive types (Sikadur 30 and Sikadur 300). For example, B750-C'-30 represents the beam with 750 mm bond length, SikaCarbodur S512 FRP plate and SikaDur30 adhesive. The validated FEA beam models, B500-C-30, B650-C-30 and B1200-C-30 correspond to B50-1, B65-1 and B120-1 specimens of the experimental study, respectively. Whereas, B750-C-30, B750-C'-30, B750-B-30 and B750-B-300 represent the beams modeled to investigate the effect of parameters such as bond length, FRP and adhesive types. The failure load results of validated FEA beam models and tested specimens from the literature (Lenwari *et al.* 2005) were in good agreement with less than 4% discrepancy. The modes of failure in FEA steel beam models were also identical to the ones in the experiment.

Table 2. Load and mode of failure.

Beam Identification	Mode of Failure	Failure Load (KN)		Difference between Experimental and FEA Results (%)
		Experiment	FEA	
B500-C-30	Debonding	90.2	94.16	4
B650-C-30	Debonding	105.9	109.24	3
B750-C-30	Plate rupture	-	137.67	-
B750-C'-30	Plate rupture	-	148.1	-
B750-B-30	Plate rupture	-	154.88	-
B750-B-300	Debonding	-	83.6	-
B1200-C-30	Plate rupture	143	144.2	1

As shown in Figure 4 (a), after certain increase in the FRP laminate length, the load deflection curves were almost similar. The FRP laminate length ranged from 500 to 1200 mm and when it changed from 750 mm to 1200 mm the failure load did not change significantly. When BFRP laminate was employed, the strengthened beam observed lower failure load, but had higher displacement capacity making it more ductile as illustrated in Figure 4 (b). For the BFRP strengthened beam, the laminate length was 750 mm and two different types of adhesives were tested, BFRP-SikaDur30 combination failed by rupture whereas BFRP-SikaDur300 combination failed at a much lower load by debonding as shown in Figure 4(c).

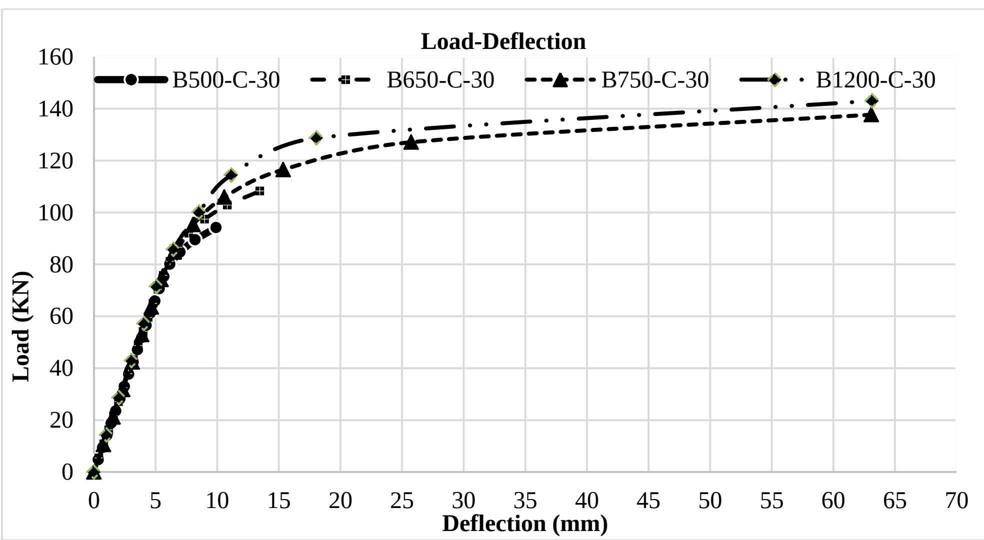

Figure 4 (a). CFRP-strengthened steel beam.

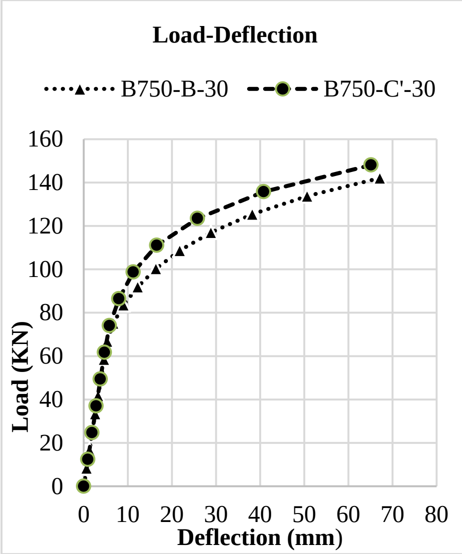

Figure 4 (b). Beam with CFRP and BFRP plates bonded with Sikadur30.

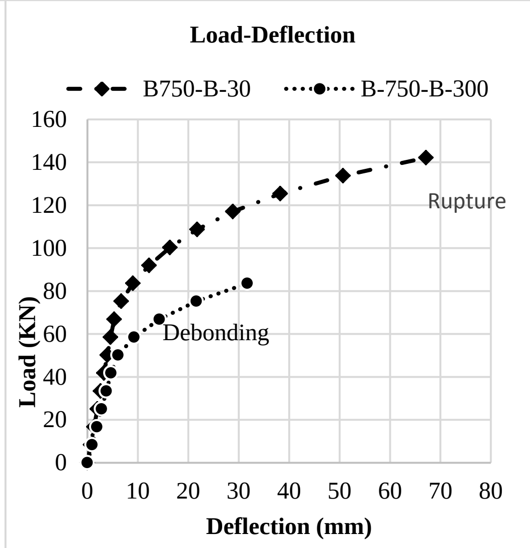

Figure 4 (c). Beams with BFRP plates bonded with different types of adhesives.

5 CONCLUSIONS

In the present study, FEA beam models were developed and validated with the experimental data available in the literature. The effect of bond length, various FRP, and adhesive types were explored. The following conclusions were drawn.

i. Application of CFRP laminates to the tension flange of steel beam increased the flexural capacity and pseudo ductility of the beam.
ii. For partial length lay-ups, after certain increase in the laminate length load capacity did not change significantly (the optimum length was 750 mm equivalent to 2/5 of the beam span) which is useful to know for the design of an equivalent steel beam.
iii. Combination of BFRP laminate with SikaDur30 provided higher load capacity for the beam as compared to bonding the BFRP to the steel substrate using SikaDur300.
iv. In summary, the BFRP laminate application to steel beams, currently in need of maintenance, repair or retrofit, offers an innovative strengthening technique as an alternative to applying steel plates by welding or bolting.

Acknowledgments

Graduate student, Mr. Aman Dhakal, contributed in modeling the interface between the FRP plate and steel beam.

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