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On the Numerical Modelling of Steel Beams Strengthened by Purely Fastened FRP Sheets

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Abstract **-** Strengthening of steel beams using fasteners was recently introduced by a few researchers to overcome the undesirable de-bonding failure of the adhesively bonded FRP-steel beams. This paper investigates numerically the performance of steel beams strengthened by FRP sheets anchored using steel fasteners without a bonding agent. Detailed numerical models of fastened FRP-steel beams were developed using ANSYS software and verified against published experimental results. The calculated error between the experimental and numerical ultimate loads ranged from 2.6 to 10.2% proving the accuracy of the developed model. The verified model was used to evaluate the effectiveness of applying the fastening technique in enhancing the load capacity of FRP-steel beams subjected to one-point and two-point loads while adopting various FRP thicknesses of 3.175, 6.35 and 12.7 mm. Ultimate load improvements of 7.8, 20.2 and 25.8% were obtained for beams subjected to one-point load and fastened by the 3.175, 6.35 and 12.7 mm thick FRP sheets, respectively. Meanwhile, beams subjected to two-point loads showed 18.7, 21.5 and 25.2% enhancements in the ultimate load for the three thicknesses, respectively. Increasing the thickness of the FRP sheet boosted the ultimate load of the fastened FRP-steel beam; however, the ductility of the system was reduced.

Keywords**:** Steel beams, FRP sheets, steel fasteners, finite element, one-point load, two-point loads, FRP thickness.

1. Introduction

The rehabilitation of steel girders has gained significant attention globally due to the increased number of deteriorated steel bridges. In 2016, a total of 56007 bridges were classified as structurally deficient according to the National Bridge Inventory of the Federal Highway Administration (FHWA), with 52% of them having steel as their main structural material [1]. Fiber-reinforced polymers (FRP) have been widely used in rehabilitating structural steel elements due to their corrosion resistivity, lightweight and high strength-to-weight ratio. The common practice of strengthening steel structures involves bonding FRP composites to targeted steel members using adhesive [2–4]. Numerous research was conducted on bonded FRP-steel joints to assess the effects of the bond length, adhesive thickness and chemical composition on the bond behavior of the bonded system [5, 6]. Several end-anchorage techniques were used companioned with the bonding process in attempts to delay the de-bonding failure [7–10]. Despite the effectiveness of the bonding technique in improving the load capacity of the rehabilitated steel beams, de-bonding of the adhesive generally controls the failure of the bonded system and risks its ductility [2, 3].

The undesirable de-bonding failure of the adhesive evoked researchers to investigate the adequacy of purely fastening the FRP to the targeted steel elements without a bonding agent. The performance of purely fastened FRP-steel joints considering various fastening parameters was examined by several researchers proving the ability of the fastening technique to overcome the undesirable brittle failure of the bonded FRP-steel system [11–14]. In 2016, Sweedan et al. implemented the fastening technique on full-scale steel beams to investigate their experimental behavior adopting different FRP lengths and thicknesses [15]. Additionally, few experimental and analytical studies examined the effectiveness of the pure fastening technique on the performance of FRP-steel beams considering a limited number of fastening conditions [16–18].

The former studies proved the effectiveness of the purely fastening technique in replacing the common bonding technique; however, the reliability of the fastened system needs further investigation. The available database is still insufficient to assess the performance of the fastened FRP-steel beams under various fastening parameters and loading scenarios. This study investigates the numerical performance of purely fastened FRP-steel beams subjected to one-point load and two-point loads. The effect of the FRP thickness on the fastened FRP-steel beams in both loading scenarios was examined. The ultimate loads of the strengthened beams along with the resulting load-deflection curves were reported. A discussion of the generated stresses in each loading scenario was presented.

2. Description of the Finite Element Model

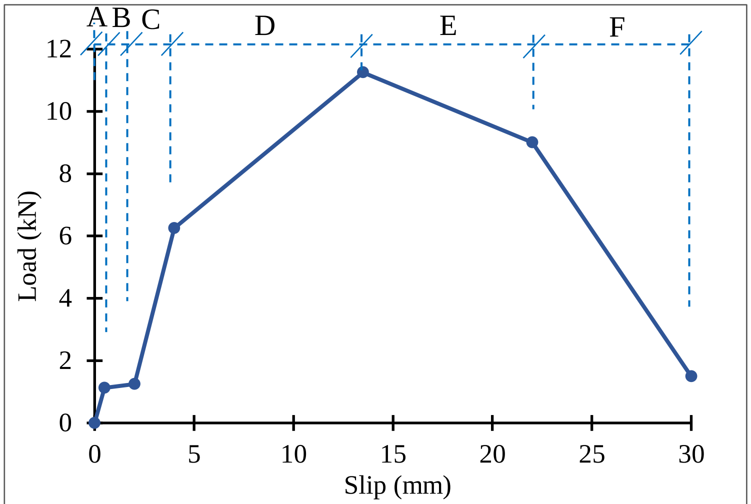
A detailed numerical model was developed using the multipurpose finite element (FE) software ANSYS (2020 R1) to simulate the behavior of experimentally tested UB203x102x23 steel beams subjected to two-point loads displaced 600 mm from the supports. Detailed descriptions of the experimental setup and tested configurations are reported in [16]. The modeled steel beams were strengthened by hybrid carbon-glass FRP sheets at their bottom flange using M6x40 steel fasteners. The geometrical dimensions and mechanical properties of the steel beams, FRP sheets and steel fasteners are displayed in Table 1.

Table 1: Mechanical properties and geometrical dimensions of the fastened materials.

Steel Beam (UB203x102x23)		FRP Sheet	
Property	*Value*	*Property*	*Value*
Yield strength (MPa)	465	Ultimate Strength (MPa)	852
Ultimate Strength (MPa)	620	Elastic Modulus (GPa)	62.19
Elastic Modulus (GPa)	180	FRP width (mm)	101.6
Beam depth "d"(mm)	203.75	FRP length (mm)	1620
Flange thickness "t_f" (mm)	8.48	FRP thickness (mm)	3.175, 6.35 and 12.7
Web thickness "t_w" (mm)	5.78	**M6x40 Steel Fasteners**	
Beam length (mm)	2000	*Property*	*Value*
Beam clear span (mm)	1800	Shear Strength (MPa)	375
		Bearing Strength (MPa)	1000
		Diameter (mm)	6
		Shank length (mm)	40

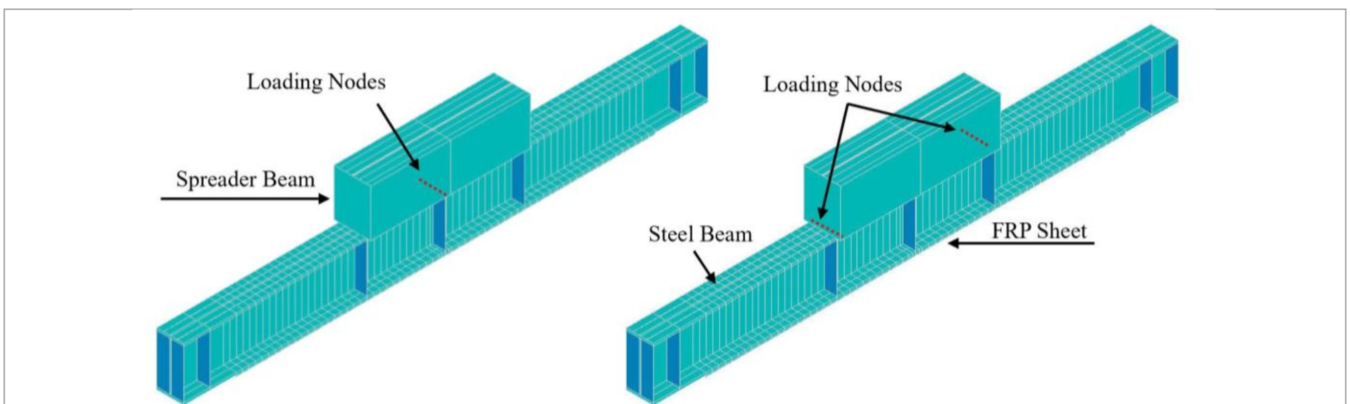
The mechanical ANSYS Parametric Design Language (APDL) was used in developing the FE model to accurately define the geometrical and material properties of the modeled elements. The steel beam, FRP sheet and spreader beam were modeled using the 8-node structural solid element SOLID185. Meanwhile, the connectivity between the bottom steel flange and the FRP sheet was incorporated into the model using a spring element characterized by the load-slip model shown in Fig. 1 [11]. Boundary conditions were imposed on the model to reflect the restrictions of the braces and the supports as reported in [16].

The verified model was used to investigate the effectiveness of adopting the pure fastening technique in improving the load capacity of steel beams subjected to a one-point load and two-point loads as shown in Fig. 2. The loading nodes were located at the mid-span of the beam in the case of one-point loading scenario. Meanwhile, in the case of two-point loads, the loading nodes were placed at one-third and two-thirds of the clear span (i.e., 600 and 1200 mm from the support). In each loading scenario, four models were developed including a reference un-strengthened control beam and three strengthened beams fastened by 3.175, 6.35 and 12.7 mm thick FRP sheets. The designation of each model is presented in the form of "#PL-$"; where "#" reflects the number of loading points; "1" for one-point load and "2" for two-point loads. Meanwhile, "$" in the designation shows the thickness of the FRP sheet as an integer number. The FRP thickness and the loading scenario of each model are shown in Table 2. A constant FRP length of 1620 mm was maintained in all models along with 35 mm spacing between the fasteners.



A: Relative friction between steel and FRP
B: Relative slippage between steel and FRP
C: Bearing between steel fasteners and FRP
D: Bearing, bending of fastener, and folding of washers
E: Initial tear-out of FRP
F: Block shear rupture of FRP

Fig. 1: Load-slip model of fastened FRP-steel joints using M6 steel fasteners [11].



(a) One-point load Scenario | (b) Two-point loads Scenario

Fig. 2: Schematic showing the locations of the loading nodes in the two modeled loading scenarios.

Table 2: Designation and peak loads of the FE models

Model Designation	Loading Scenario	FRP Thickness (mm)	Peak Load (kN)	Increase in Peak Load (%)
1PL-0	One-point	N.A.	272.84	-
1PL-3	One-point	3.175	294.18	7.8
1PL-6	One-point	6.35	328.05	20.2
1PL-12	One-point	12.7	343.19	25.8
2PL-0	Two-point	N.A.	345.98	-
2PL-3	Two-point	3.175	410.56	18.7
2PL-6	Two-point	6.35	420.52	21.5
2PL-12	Two-point	12.7	433.23	25.2

3. Results and Discussions

The verification of the developed model and the obtained numerical results are outlined and discussed in the following subsections.

3.1. Model Verification

The developed model was used to predict the behavior of all the fastened FRP-steel beams reported in [16]. An excellent match between the numerically predicted and the experimental load-deflection curves was obtained verifying the accuracy of the developed FE model. The calculated error between the experimental and numerical yield loads ranged from 0.05 to 2.95%, while that for the ultimate loads ranged between 2.6 and 10.2%. Figure 3 shows the numerically predicted and the experimental load-deflection curves for a sample configuration reported in [16].

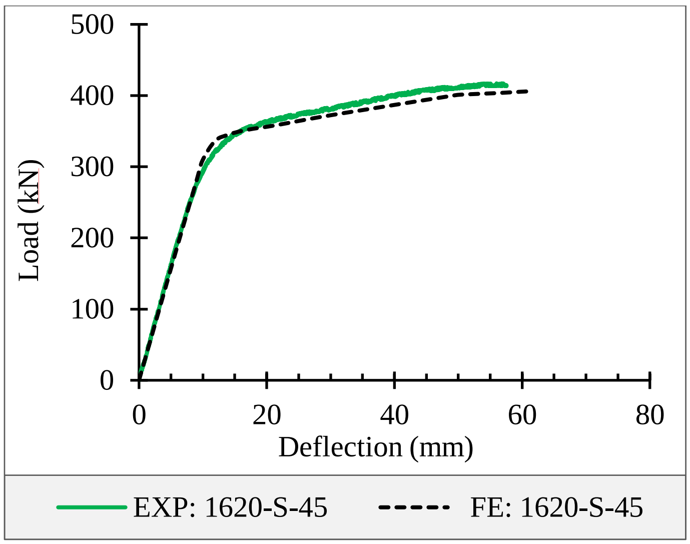


Fig. 3: Numerical and experimental load-deflection curves for beam 1620-S-45 in [16].

3.2. Effect of FRP Thickness

The numerical load-deflection curves of beams subjected to one-point load and two-point loads are depicted in Fig. 4a and Fig. 4b, respectively. The plots show significant improvement in the performance of the strengthened beams compared to the un-strengthened beams (1PL-0 and 2PL-0). Beams 1PL-3, 1PL-6 and 1PL-12 showed 7.8, 20.2 and 25.8% improvement in the ultimate load, respectively, compared to the un-strengthened 1PL-0 beam. Meanwhile, ultimate load enhancements of 18.7, 21.5 and 25.2% were calculated for 2PL-3, 2PL-6 and 2PL-12, respectively, compared to 2PL-0. Increasing the FRP thickness risked the ductility of the system in 1PL-6, 1PL-12 and 2PL-12 due to the shear failure of the fasteners as reflected by the sudden drop in their load-deflection curves. Increasing the thickness of the FRP sheets led to higher bearing between the FRP and the fasteners, and hence higher shear stresses were induced in the fasteners causing their failure. The reported shear failure of the fasteners could be avoided by increasing their number, which can be attained by reducing the spacing between the fasteners.

3.2. Effect of Loading Scenario

Figure 5 displays the lateral deformations of sample models at the end of the simulation. Beams subjected to a one-point load showed noticeable web local buckling (WLB) due to the high shear stresses near the loading point (see Fig. 5a). Meanwhile, beams subjected to two-point loads experienced major lateral torsional buckling (LTB) and flange local buckling (FLB) as shown on Fig. 5b.

The numerical models showed higher yield and ultimate loads for beams subjected to two-point loads compared to those subjected to one-point load (refer to Fig. 4). The numerically generated shear and bending stresses and their distribution along the beam span were analyzed in each loading scenario. The high bending stresses generated in the one-point load scenario ($M = \frac{PL}{4}$) reduced the effectiveness of the web in resisting the shear stresses as the bending stresses penetrated from the flanges into the web gradually causing early WLB [19]. Meanwhile, beams subjected to two-point loads preserved the web capacity due to the lower bending stresses generated at the same load ($M = \frac{PL}{6}$).

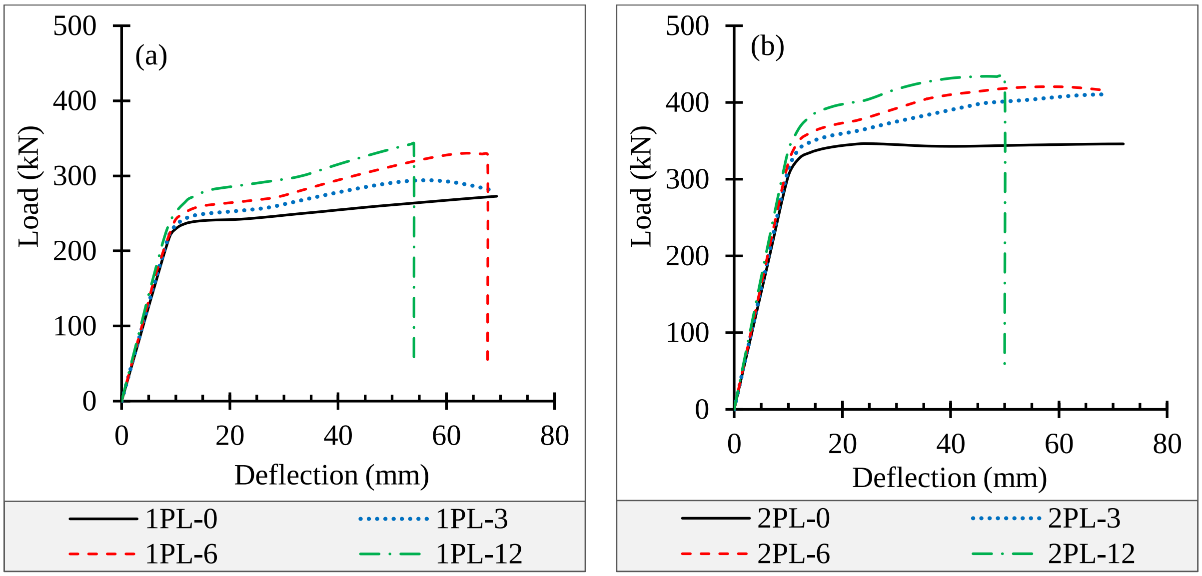


Fig. 4: Load-deflection curves of the modeled FRP-steel beams: (a) one-point load and (b) two-point loads.

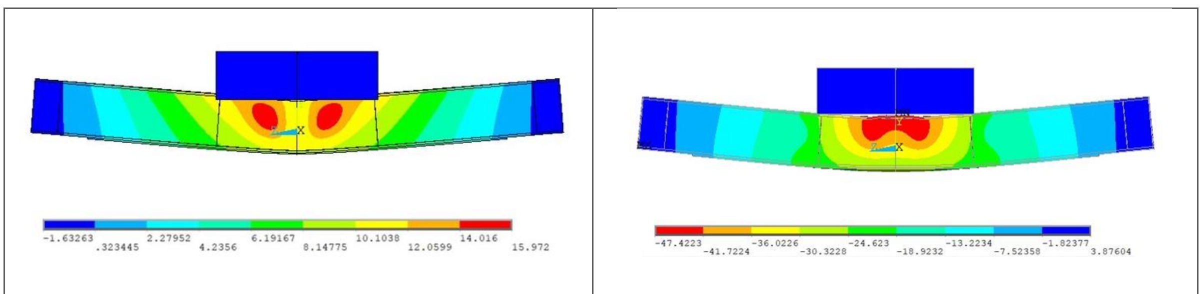

(a) 1PL-6 (b) 2PL-6

Fig. 5: Lateral deformation of models: (a) 1PL-6 and (b) 2PL-6.

4. Conclusion

A detailed numerical study was conducted using ANSYS software to assess the performance and load capacity of steel beams purely fastened by FRP sheets using steel fasteners. The developed model was verified against previous experimental results and showed an error range from 2.6 to 10.2% in the ultimate load. The verified model was used to assess the performance of steel beams fastened by FRP sheets and subjected to one-point load and two-point loads. Beams subjected to two-point loads showed higher yield and ultimate loads than beams subjected to one-point load due to the lower shear stresses at the web in the case of a two-point load scenario. Increasing the thickness of the fastened FRP sheets enhanced the load capacity of the beams; however, the ductility of the system was reduced due to the shear failure of the steel fasteners. The study highlighted the effectiveness of adopting the pure fastening technique to enhance the performance of steel beams strengthened by FRP sheets without using adhesive highlighting an ultimate load enhancement of 25.8% compared to the un-strengthened beam.

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