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Mechanically-fastened hybrid composites for flexural strengthening of steel beams

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ABSTRACT

Recent experimental studies by Sweedan et al. [17] and Alhadid et al. [2] on the behavior of mechanically fastened (MF) steel-FRP lap connections and steel beams strengthened with MF-FRP, respectively, revealed a promising efficiency of the fastening system in retrofitting deteriorated steel beams. The study demonstrated that the dominant failure mode, in the tested connections and beams, was due to excessive bearing in the FRP laminate at the locations of the fasteners as long as sufficient number of fasteners is used. The current study describes a three-dimensional nonlinear finite element (FE) model that accounts for the interfacial slip between the FRP laminates and the steel beam. The FE model is validated against the experimental results reported by Alhadid et al. [2], and excellent agreement is found. The FE model is then used to shed more light on the mechanical behavior of the tested composite steel-FRP beams including force distribution in steel fasteners especially during spread of yielding in the steel section, and the stress distribution in the FRP laminates. The study concludes that as the length of the FRP increases, the degree of composite action in the elastic range increases indicating higher efficiency of the FRP laminate. The FRP laminate contributes significantly in carrying the mid-span loads after yielding of the steel section.

1. Introduction and problem definition

Rehabilitation of steel structures has gained significant importance due to the highly increasing number of deteriorated steel structures in many places around the globe. In the USA alone, about 70,000 highway bridges with steel main structural system have been classified as structural deficient or functionally obsolete according to the National Bridge Inventory [12] compiled by the Federal Highway Administration (FHWA) as of December 2011. In general, the overall needs for US infrastructure rehabilitation are estimated to be over 1.6 trillion dollars in the next five years [6].

Conventional methods of retrofitting or strengthening of existing steel structures require replacing steel members or attaching external additional steel plates. These methods are usually time-consuming and require lifting heavy steel items that are corrodible and difficult to fix. Many of the drawbacks of the conventional strengthening systems can be overcome through the use of fiber reinforced polymers (FRP) due to their high strength-to-weight ratio. Furthermore, FRP materials are corrosion resistant which makes them more durable especially when environmental deterioration is a concern.

During the last two decades, many researchers have studied the behavior of steel beams strengthened with externally bonded FRP strips (EB-FRP). The outcomes of these studies revealed that steel beams strengthened with EB-FRP exhibit unfavorable brittle failure mechanism due to debonding of the FRP strips [5,11,13]. Recently, Alhadid et al. [2] studied experimentally the flexural behavior of steel beams strengthened with mechanically fastened FRP laminates (MF-FRP). The study revealed that MF-FRP leads to ductile response of the strengthened system provided that adequate number and strength of anchoring fasteners are used.

The promising results obtained by Alhadid et al. [2] provoke more investigations on the efficiency of MF-FRP strengthening technique. In the current paper, the general purpose finite element software ANSYS [3] is used to develop a detailed 3D nonlinear finite element model for simply supported I-shaped steel beams strengthened with MF-FRP laminates. The model takes into account material and geometrical nonlinearities and accounts for the relative slip at the steel-FRP interface. The load–deflection results of the simulated beams are validated with their experimental counterparts reported by Alhadid et al. [2]. Then, the calibrated finite element model is employed to investigate several aspects of the mechanical behavior of the composite steel-FRP beams that have not been considered experimentally.

2. Literature review

During the past few decades, externally bonded FRP laminates (EB-FRP) were used to strengthen reinforced concrete (RC) beams.

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In spite of the good efficiency of the EB-FRP system, the strengthened RC beams experienced brittle failure modes due to the debonding of the FRP laminate. This attracted researchers to consider mechanically fastened FRP systems (MF-FRP) to overcome such debonding problem, especially after the production of drillable, hybrid FRP laminates that can withstand considerable bearing stresses around each fastener's hole.

On the other side, researchers have always opposed the idea of using FRP laminates in strengthening steel beams due to the low elastic modulus of FRP as compared to that of steel. This has changed, recently, after the current advancement in the manufacturing of FRP laminates with high elastic modulus which is, in some cases, higher than that of steel. Availability of drillable FRP laminates with a reasonable value of elastic modulus has encouraged researchers to consider using the MF-FRP technique for strengthening steel beams.

Unlike research work on RC beams with MF-FRP, a very limited number of studies on steel beams strengthened with MF-FRP is available in the literature. A study on the mechanical behavior of fastened steel-FRP connections was conducted by Sweedan et al. [17]. The study started by investigating the performance of 24 mechanically fastened double-shear lap connection between one steel plate (10-mm thick) and two FRP laminates (each is 3.175 mm thick) experimentally. The experimental findings were used to establish a non-linear load–slip relationship at the interface (i.e., between steel plate and one 3.175-mm FRP laminate) at each fastener. The proposed interfacial load–slip model was incorporated in 3D FE analyses to examine the influence of various geometrical parameters on the behavior of double-shear lap connections. A more recent study by Alhadid et al. [2] reported testing of a group of steel beams strengthened with FRP laminates of different lengths and thicknesses. The investigators showed that the strengthened beams exhibit ductile failure mode accompanied by significant bearing deformations in the FRP when a sufficient number of fasteners is used. On the contrary, strengthened beams with insufficient fasteners failed in a brittle manner by sudden shear failure in the fasteners. The experimental results also revealed that increasing the thickness and length of FRP results in a slight improvement in the yield moment (i.e., moment at first yield in the steel section). Meanwhile, a significant enhancement in the ultimate flexural capacity of the strengthened beams is evident by the experimental outcomes. This is attributed to the fact that the contribution of the FRP laminates becomes more perceptible upon onset of yielding in the steel beam. At this stage, the elastic modulus of the FRP is significantly higher than the post-yield modulus of steel. The associated increasing slip between steel and FRP results in more forces to be transferred from the yielded steel to the FRP laminates. The following section sheds more light on the experimental work of Alhadid et al. [2] that is used for the validation of the FE model developed in the current study.

Table 1
Mechanical properties of SAFSTRIP hybrid FRP laminates.

Property	Average value (MPa)
Tensile strength	852
Tensile modulus	62,190
Clamped bearing strength	351
Unclamped bearing strength	214

3. Testing of full-scale steel beams with MF-FRP laminates

The experimental investigation involves testing of eleven full-scale UB203 × 102 × 23 universal steel beams with average yield stress of 335 MPa, modulus of elasticity of 190 GPa, and ultimate strength of 429 MPa [2]. While three of these beams are used as control specimens, the remaining eight are subjected to various strengthening configurations using SAFSTRIP hybrid carbon-glass fiber pultruded laminates. The FRP laminate may be drilled without splitting and has considerable bearing between any steel fasteners in typical connections. The mechanical properties of a typical laminate are summarized in Table 1 [16]. Hexagonal galvanized zinc coated M6 Hilti fasteners, made of high tensile steel of grade 8.8 with 375 MPa shear strength and 1.0 GPa bearing strength, are used to fasten the FRP laminate into the tension flange of the steel beam.

3.1. Test specimens geometry

Fig. 1 shows the geometry and dimensions of the typical steel specimen UB203 × 102 × 23 which is defined by its span between supports L, flange width b_f, flange thickness t_f, web height h_w, and web thickness t_w. Stiffeners and end plates are used to prevent local flange instability and/or web crippling as depicted by Fig. 1.

Table 2 reports the eleven specimens used in the experimental study; three are tested as control specimens (CB) without strengthening, six specimens (S1200, S1800, and S2200; with two specimens each) are strengthened with one layer of FRP laminate, and two specimens (D1200 and D2200) are strengthened with two layers of FRP laminates. The FRP laminates geometry is characterized by the length L_{frp}, thickness t_{frp} and width b_{frp} = 101.6 mm. Fig. 2 presents the sample geometry of the S1200 specimen used by Alhadid et al. [2] while Fig. 3 shows a sample bottom view of the S1200 specimen with typical gauge line spacing and edge distance of the fasteners.

Table 2
Specimen designation and geometrical details.

Designation of specimen	Number of specimens	No. of FRP layers	L_{frp} (mm)	Total t_{frp} (mm)	Spacing between fasteners p (mm)
CB	3	N/A	N/A	N/A	N/A
S2200	2	1	2200	3.175	100
S1800	2	1	1800	3.175	100
S1200	2	1	1200	3.175	100
D2200	1	2	2200	6.35	50
D1200	1	2	1200	6.35	50

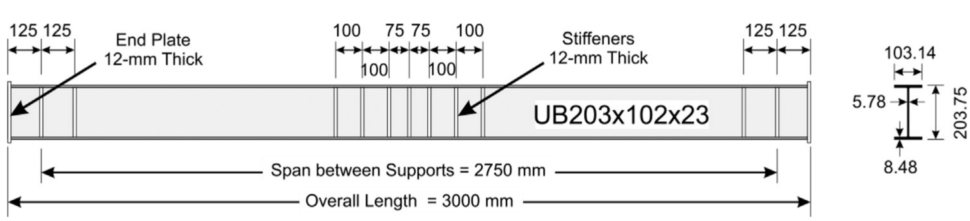

Fig. 1. Schematic front view of a typical steel beam specimen [2] (dimensions are in mm).