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Failure analysis and structural behaviour of CFRP strengthened steel I-beams

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ABSTRACT

This paper reports the experimental and numerical investigations on the Carbon Fibre Reinforced Polymer (CFRP) failure analysis and structural behaviour of the CFRP flexural strengthened steel I-beams. Understanding the CFRP failure modes is useful to find solutions for preventing or retarding the failures. One non-strengthened control beam and twelve strengthened beams using different types and dimensions of CFRP strips in both experimental test and simulation modelling studies were investigated. In the experimental test, four-point bending method with static gradual loading was applied. To simulate the specimens, the ANSYS software in full three dimensional (3D) modelling case and non-linear analysis method was utilized. The results show the CFRP failure modes used in flexural strengthening of steel I-beams include below point load splitting (BS), below point load debonding (BD), end delamination (EDL), and end debonding (ED). The occurrences and sequences of CFRP failure modes depended on the strengthening schedule. The structural performance of the CFRP strengthened steel beams also varied according to the strengthening specifications investigated in this research.

1. Introduction

The use of Fibre Reinforced Polymer (FRP) for strengthening of steel structures has gained significant interests recently. There are various methods used for the strengthening of steel structures. Amongst them are the application of additional steel parts, external pre-stressing of parts, and reducing or bridging the gap between the supports. These methods require considerable time and cost. In contrast, FRP is high in strength, light in weight, strong resistance to corrosion, and suitable for upgrading of steel structures.

Normally, the FRP for flexural strengthening are installed to the bottom (tensile) flange. Edberg et al. [1] presented an experimental study in which five different configurations of glass (GFRP) and carbon (CFRP) fibre reinforced polymers were attached to the tensile flange of small scale steel wide flange beams using adhesive bonding. Also, a similar study was carried out by Ammar [2]. In addition, Tavakkolizadeh and Saadatmanesh [3] tested small scale steel beams in four-point bending. All these aforementioned researches showed that it is feasible to flexural strengthen steel beams using CFRP plates.

Identification of CFRP failure modes in flexural strengthening of steel I-beams is useful in order to overcome or retard these failures. Deng et al. [4] had highlighted an important feature of the reinforced steel beam which is the significant stress intensity on the adhesive at the tip of the CFRP plate due to discontinuity by the abrupt termination of the CFRP plate.

Buyukozturk et al. [5] reviewed their achievements in the strengthening of both reinforced concrete and steel members. They concluded that failures of FRP flexural strengthened reinforced concrete (RC) and steel members occur due to different mechanisms, and it is dependent on the parameters of strengthening. They found that shear failure takes place when the shear capacity of the beam is not able to accommodate the increment of the flexural capacity due to flexural strengthening. They indicated that the following are the failure modes of an FRP strengthened steel member: (a) buckling of top flange in compression, (b) buckling of web in shear, (c) FRP rupture, and (d) FRP debonding.

Schnerch et al. [6,7] investigated the flexural strengthening of steel structures and bridges by using FRP materials. They indicated that the bonding behaviour of FRP to steel structures completely different from concrete structures in terms of failure modes. The test results also indicated that for steel structures and bridges, very high bonding stresses had occurred.

Al-Emrani and Kliger [8] examined different types of fracture mode by testing composite elements with different combinations of CFRP-laminates and adhesives. The effect of various material parameters on the behaviour and strength of bonded steel–CFRP elements was examined.

The delamination failure of steel beams flexurally strengthened by externally bonded FRP was presented by Colombi [9]. He used

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Table 1
Dimensions and material properties of steel I-section.

Steel I-section – mild steel A36-ASTM								
Steel I-section dimensions (mm)				E-modulus (N/mm^2)	Stress (N/mm^2)		Strain	
Width	High	Flange thick.	Web thick.	Mean value	Yielding (F_y)	Ultimate (F_u)	Yielding (ε_y) %	Ultimate (ε_u) %
100	150	10	6.6	200,000	250	370	0.12	13.5

the simplified fracture mechanics based approach to investigate the edge delamination of the reinforcement strips.

Benachour et al. [10] developed a closed-form rigorous solution for interfacial stress in simply supported beams strengthened with bonded prestressed FRP plates. The results show that high concentration of both shear and normal stresses occurred at the ends of the laminate which can result in premature failure of the strengthened specimens at these locations.

Czaderski and Rabinovitch [11] investigated the displacements between the steel beam and the FRP plate. These displacements resulted from the interaction between the steel surfaces and FRP plates. One of the findings was that the slip values calculated with the shear stress–slip approach are notably different from the ones measured experimentally and determined by the FE model.

The objective of this research is to investigate the CFRP failure modes used in strengthening of steel I-beams. Also, the effects of the strengthening schedule on some structural behaviour of steel beams such as load bearing capacity, deformations, and strain in different regions will be investigated. Different types and dimensions of CFRP strips are chosen, and both numerical simulation and experimental test studies are employed.

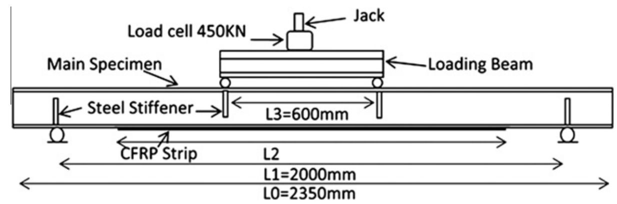

Fig. 1. Test setup and dimensions of steel beams.

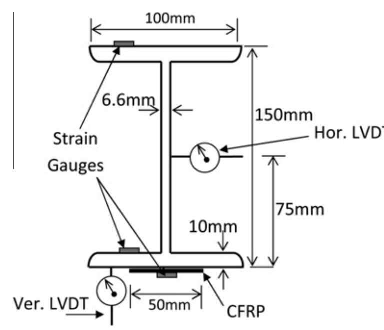

Fig. 2. Dimensions of steel I-section and locations of strain gauges and LVDT.

2. Materials and methods

In order to investigate the CFRP failure modes and structural behaviours of steel I-beams, one non-strengthened control beam and twelve strengthened beams with different types and dimensions of CFRP strips are chosen.

2.1. Materials

The steel I-sections with the mild-steel property are chosen. Table 1 shows the dimensions and material properties of the selected steel I-sections. The dimension of the selected steel I-section and the test setup are also indicated in Figs. 1 and 2.

CFRP materials have high tensile strength which can improve the structural behaviour of structures. Normally, CFRP is produced in the form of a strip (plate) or a sheet (wrap). In this research, only CFRP strips are used. According to the one directional behaviour of CFRP strips, they are grouped in the orthotropic materials [12]. CFRP strips are made in different widths and thicknesses and classified based on the strength and modulus of elasticity. In this research, two following types of CFRP strips are used: (a) low modulus–high tensile strength (HT) and (b) normal tensile strength–intermediate modulus (IM). The material properties of these two types of CFRP strips are shown in Table 2. The widths of both CFRP types are the same i.e. 50 mm. The chosen thicknesses of CFRP strips are 1.2 mm, 1.4 mm, 2 mm, and 4 mm. For the beams strengthened using HT-CFRP, different bonded lengths are selected i.e. 600 mm, 1000 mm, 1500 mm, 1700 mm, and 1800 mm. The dimensions of the CFRP strips are shown in Table 2.

The engineering epoxy (structural adhesive) for installing the CFRP strips on the steel structures must be strong enough to transfer the interfacial stress between the common surfaces [6,7]. A structural adhesive is chosen to be applied as it is widely used [13–16]. This adhesive is a two-part epoxy resin (resin and hardener, in 3:1 proportions) that must be mixed with 1% in weight of ballotini (1 mm diameter) to ensure a uniform thickness of the bond line. Table 3 shows the dimensions and material properties of the selected adhesive.

2.2. Specifications of the beams

Specifications, load capacities, and the sequences of CFRP failure modes are shown in Table 4. Different CFRP dimensions and types are selected to investigate the effects of the CFRP dimensions on the occurrences and sequences of CFRP failure modes.

The dimensions of steel I-beams are the same for all specimens, but CFRP types and dimensions are varied for each beam. The specimens F_1 is not strengthened and used as the control beam. The beams F_2, F_3, F_4, F_5, and F_6 are strengthened with the CFRP strip type HT with 1.2 mm in thickness and varied lengths (600 mm, 1000 mm, 1500 mm, 1700 mm, and 1800 mm). The beams F_7, F_8, and F_9 are strengthened using the CFRP strip type HT with 1500 mm in length and varied thicknesses (1.4 mm, 2 mm, and 4 mm). The beams F_{10}, F_{11}, F_{12}, and F_{13} are upgraded with the CFRP type IM with 1500 mm in length and varied thicknesses (1.2 mm, 1.4 mm, 2 mm, and 4 mm).

All beams were numerically simulated and only beams F_1, F_4, F_5, F_6, F_7 and F_{11} were experimentally tested.

2.3. Test setup

The experimental setup is based on the four-points bending test. The test setup of the specimens is shown in Fig. 3. In order to measure strain and deflection, strain gauges and Linear Variable Deformation Transducers (LVDTs) were installed in different regions of the specimens as shown in Fig. 2. The load was applied by using a hydraulic jack via a load cell of 450 kN capacity. The load was transferred from the jack to the main specimen by using a loading beam. The middle of the loading beam was subjected to jack pressure, and two symmetrically point loads were applied to transfer the load's pressure to the main specimen. Two roller supports, carried the reactions, so the loading state was four incremental bending point loads.

2.4. Numerical simulation

To model the specimens, the full 3D simulation using ANSYS software was performed. The steel I-sections, steel stiffeners, CFRP plates, and adhesive were simulated by using the 3D solid triangle elements (ten-nodes 187.) The interface of common surfaces was defined between the steel I-beam, adhesive, and CFRP plates. Debonding, delamination, and splitting occurred when the plastic strains exceeds the ultimate strain. Non-linear static analysis was carried out to achieve the failures. In this case, the load was applied incrementally until the plastic strain in an element reached to its ultimate strain (element is killed). Linear and non-linear properties of materials were defined. The CFRP plate material properties were defined as linear and orthotropic because CFRP materials have linear properties and they were unidirectional [12]. The steel beams and adhesive were defined as the materials having non-linear properties. For meshing, combination of the auto meshing and map meshing were used. In the critical region, the elements were meshed smaller than the other regions. A schematic of the 3D modelled specimen is shown in Fig. 4. The comparison between the results of modelling and experiments was carried out through several models simulated in either two-dimensional (2D) or