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Experimental and finite element analysis of a double strap joint between steel plates and normal modulus CFRP

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Abstract

Strengthening of steel structures using externally-bonded carbon fibre reinforced polymers 'CFRP' is a rapidly developing technique. This paper describes the behaviour of axially loaded flat steel plates strengthened using carbon fibre reinforced polymer sheets. Two steel plates were joined together with adhesive and followed by the application of carbon fibre sheet double strap joint with different bond lengths. The behaviour of the specimens was further investigated by using nonlinear finite element analysis to predict the failure modes and load capacity. In this study, bond failure is the dominant failure mode for normal modulus (240 GPa) CFRP bonding which closely matched the results of finite elements. The predicted ultimate loads from the FE analysis are found to be in good agreement with experimental values.

Keywords: CFRP (carbon fibre reinforced polymer); Bond failure; Double strap joint; Steel plate; Finite element analysis

1. Introduction

There are many advantages in favour of the use of CFRP materials for repair and rehabilitation of bridges and structures. Cost savings may be realised through labour savings and reduced requirements for staging and lifting material. The dead weight added to a structure is minimal due to the high strength to weight ratio of CFRP materials. Application of bonded CFRP materials results in reduced stress-concentrations as compared to mechanical fastening. Despite the high material costs associated with CFRP materials, when overall costs for a strengthening project are determined, overall project costs are typically reduced.

The advantages of the use of carbon fibre to repair metallic structures have been shown in the strengthening of tunnel supports for the London underground railway system [1]. In the United States, several bridges have been strengthened with bonded CFRP strips, e.g. Bridge 1-704 over Christina Creek in Delaware [2] and a bridge in Iwoa [3]. More examples reported in the literatures [4–12] showed that there is a great potential for CFRP to be used in the retrofit of steel structures. However, many technical issues are yet to be resolved. One of them is bond between steel and CFRP.

There are several methods to conduct bond testing as reviewed in [13], such as double strap joint test [14,15–18], single strap test [19,20] and test to apply force directly on FRP [21]. This paper describes a series of double strap joint tests loaded in tension to investigate the bond between CFRP sheets and steel plates. The focus of the paper is on using nonlinear finite element (FE) method to predict the load–deflection behaviour and distribution of strain along the bonded length of the CFRP bonded steel plate.

2. Materials property

Three materials have been used to prepare the specimens. These are CFRP, adhesive and steel plates. Normal modulus CFRP CF130 has chosen with modulus of elasticity of 240 GPa and the nominal ultimate tensile strength is of 3800 MPa according to the manufacturer's specifications.

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Table 1
Material properties

	CFRP	Steel plate	Adhesive
Tensile modulus (GPa)	215	195	1.9
Tesile strength (MPa)	1710	484	32
Yield stress (MPa)	–	359	–
Tensile strain	0.008	0.015	0.04
Poisson's ratio	0.28	0.25	0.21

The adhesive Araldite 420 has chosen which has tensile strength of 32 MPa and tensile modulus 1900 MPa according to the manufacturer's specifications. Mild steel plates 210 mm long, 50 mm wide and 5 mm thick are used in the test program.

As part of a broader research work at Monash University, tensile coupon tests were conducted for CFRP [22] and steel plates [23] to verify the modulus, tensile strength and strain specified by the manufacturer. The tested values have been adopted in the FE analysis. Table 1 shows the properties of three materials used in FE analysis.

3. Experimental program

A total of four specimens were prepared with normal modulus CFRP. All steel plates have a dimension of 210 mm in length and 50 mm in width and 5 mm thickness. The steel plates were ground in the area to be bonded to ensure a better mechanical interlocking. The surfaces were cleaned with acetone to remove grease, oil and rust. Two steel plates were aligned in position in a jig before applying adhesives and CFRP. Three layers of CFRP sheets were applied on both sides of the plate. The specimens were cured for seven days and post-cured for one day at 70 °C. Each specimen was loaded in tension in a 500 kN capacity universal testing machine with a loading rate of 2 mm/min. The details of the tests and experimental results can be found in Fawzia et al. [15]. A schematic view of the specimen is shown in Fig. 1. The observed failure mode for the normal modulus CFRP was bond failure. Table 2 gives test results for different bond length.

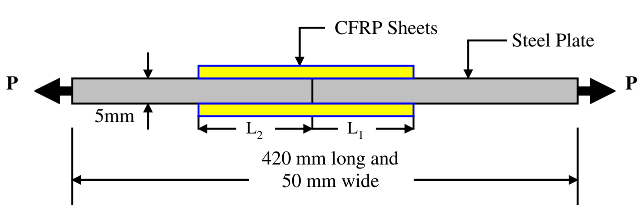

Fig. 1. A schematic view of specimen (not to scale).

Table 2
Results of specimen testing

Specimen label	Bond length L_1 (mm)	Ultimate load P_{ult} (kN)	Failure mode
SN40	40	49.9	Bond failure
SN50	50	69.8	Bond failure
SN70	70	80.8	Bond failure
SN80	80	81.3	Bond failure

4. Effective bond length

The ultimate load carrying capacity is plotted in Fig. 2 against the bond length L_1. It can be seen from Fig. 2 that the load carrying capacity reaches a plateau after the bond length exceeds a certain value. This length, beyond which no significant increase in load carrying capacity will occur, is called the effective bond length. The effective bond length of 75 mm for joints with normal modulus CFRP is adopted in the experiment which is same as that reported by Jiao and Zhao [20] for joints between steel tubes and normal modulus CFRP. It seems that the curved surface of steel tubes does not affect the effective bond length between steel and normal modulus CFRP.

5. FE model geometry, boundary conditions and loading

A three-dimensional finite element (FE) computing package, Strand 7 (version 2.2.5) [24] was used to simulate the CFRP bonded steel plate. The simulation was done by running nonlinear analysis solver to account for the nonlinear properties of the materials. Since the specimen is symmetric about all three axes, only one eighth of the specimen is modelled.

All constituent materials of the specimens were modelled with eight-noded brick elements as shown in Fig. 3. Three layers of CFRP are bonded to the steel on either side. Each layer has thickness 0.176 mm as given by the manufacturer. The adhesive layer thickness t_a is 0.224 mm [15]. Three layers combined with two epoxy resin layers produce a thickness of 0.976 mm.

Since one eighth of the specimen is modelled, a number of translation boundary conditions were applied in the model to account for symmetry as shown in Fig. 3.

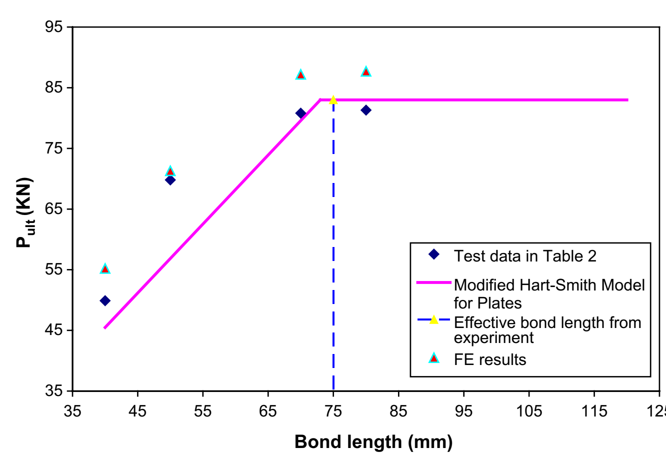

Fig. 2. Effective bond length for normal modulus CFRP joint.