Thin-Walled Structures 51 (2012) 147–157

Contents lists available at SciVerse ScienceDirect

Thin-Walled Structures

journal homepage: www.elsevier.com/locate/tws

Bond characteristics between ultra high modulus CFRP laminates and steel

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ARTICLE INFO

Article history:
Received 24 June 2011
Received in revised form
13 October 2011
Accepted 13 October 2011
Available online 17 November 2011

Keywords:
Bond
Carbon Fibre Reinforced Polymer (CFRP)
Ultra high modulus CFRP
Steel

ABSTRACT

The use of high modulus CFRP laminates in strengthening steel members has the advantage of increasing the strength and stiffness of such members. In this paper, the bond characteristics between ultra high modulus (UHM) CFRP laminates with a modulus of 460 GPa and steel were studied. A series of experiments with double strap steel joints bonded with UHM CFRP laminates were conducted. Experimental results presented in this paper include failure modes, bond strength, effective bond length, CFRP strain distribution, adhesive layer shear stress distribution and bond slip relationship. Comparison was made with previous research on CFRP sheet–steel and normal modulus CFRP laminate–steel systems and different aspects of bond characteristics were discussed. Theoretical models were employed for the prediction of the specimen bond strength and effective bond length, and their applicability for UHM CFRP–steel joints was verified by comparisons with experimental results. Nonlinear finite element analysis was carried out to simulate the experimental specimens. The FEA results agreed well with those from experiments.

1. Introduction

Fibre reinforced composites (FRP) have attracted increasing research interest in civil infrastructure applications due to their high strength to weight ratio and resistance to harsh environmental effects [1,2]. Recent studies [3–9] showed that the use of Carbon Fibre Reinforced Polymer (CFRP) offers an excellent alternative method for retrofitting deteriorated structures. Traditional methods like welding, bolting, attaching steel plates and introducing post-tensioning suffer from some inherent drawbacks like further corrosion threat, residual stresses from welding, increase of localised stresses, adding extra weights and most importantly, such methods are labour intensive thus increasing maintenance cost [10–12].

Limited research has been conducted on CFRP strengthening of metallic structures [2,13]. In contrast, extensive studies have been conducted on concrete structures [2,3,14,15].

The elastic modulus (E_{CFRP}) of commonly used CFRP sheets can reach 640 GPa, whereas the modulus of CFRP laminates are mostly lower than 210 GPa [2,16–18]. In this paper, a CFRP laminate with modulus of 460 GPa was adopted. The term "ultra high modulus" (UHM) is used to describe this laminate product. Other CFRP laminate products with modulus less than 210 GPa are named "normal modulus laminate" in this paper. Since the UHM CFRP laminates have greater modulus than common steel products, it is possible to increase the elastic behaviour of their retrofitted steel structures. To ensure confident and wide application, the bond characteristics between UHM CFRP and steel need to be fully studied.

To the knowledge of the authors, there are few researches on the bond characteristics of UHM CFRP laminate and steel [7,10], although studies have been done with CFRP sheets (with E_{CFRP} up to 640 GPa) [19–22] and CFRP laminates (with E_{CFRP} less than 210 GPa) [3,22,23]. Double strap joints with CFRP sheets (240 GPa and 640 GPa) were tensioned to failure in [20]. Results showed that the failure modes and effective bond length were dependent on CFRP modulus. The failure mode was a combination of cohesive failure (adhesive layer failure) and CFRP delamination (separation of some carbon fibres from the resin matrix) for 240 GPa CFRP sheet, whereas it changed to CFRP rupture when 640 GPa CFRP was used. Moreover, the effective bond length was 75 mm for 240 GPa CFRP and 40 mm for the other. Similar experiments were also carried out by Lam et al. [22] in which both CFRP sheet of 128 GPa and CFRP laminate of 176 GPa were adopted to study the influence of stiffness ratio between CFRP and steel on bond behaviour. Normal modulus CFRP laminates of 165 GPa were attached to rigid steel blocks in a single pull-off experiment conducted by Xia and Teng [23] to investigate the effects of adhesive properties and adhesive thickness on bond behaviour. It indicated that the failure modes were determined by the adhesive thickness. Cohesive failure would happen if adhesive thickness was less than 2 mm, nevertheless the failure modes

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doi:10.1016/j.tws.2011.10.010

Notation

b_p	width of the CFRP laminate
E_a	modulus of adhesive
E_{CFRP}	modulus of CFRP laminate
E_{steel}	modulus of steel
$f_{t,a}$	adhesive tensile strength
$f_{t,CFRP}$	CFRP tensile strength
G_a	adhesive shear modulus
G_f	interfacial fracture energy
L_1	bond length
L_e	effective bond length
P_i, P_o	bond strength per unit width of double strap joint
P_{ult}	bond strength of double strap joint
t_a	adhesive thickness
t_{CFRP}	thickness of CFRP laminate
t_n	normal stress in adhesive layer
t_n^o	normal strength of adhesive layer
t_s	shear stress in adhesive layer
t_s^o	shear strength of adhesive layer
t_{steel}	thickness of steel plate
t_t	shear stress in adhesive layer
t_t^o	shear strength of adhesive layer
t_{total}	total thickness of specimen
δ_1	initial slip in bond slip curve
$(\delta_{avg})_i$	relative slip between CFRP and steel
δ_f	maximum slip in bond slip curve
γ_e	elastic shear strain of adhesive
γ_p	plastic shear strain of adhesive
λ	coefficient for the determination of effective bond length in Hart-Smith model
$(\tau_{avg})_i$	average shear stress between strain gauges $(i+1)$ and (i)
τ_f	adhesive shear strength
υ_a	Poisson's ratio of adhesive
ξ	reading of strain gauges
Δ	spacing between strain gauges $(i+1)$ and (i)
QUADSCRT	quadratic traction damage initiation criterion for cohesive surfaces

changed to CFRP delamination for thicker adhesive layer. Other studies with CFRP laminates [24,25] were also conducted with different set-ups on bond issues between the adherents.

In this paper, the bond characteristics between an UHM CFRP laminate (with E_{CFRP} of 460 GPa) and steel will be thoroughly studied by experiments with double strap joints. Different adhesives were used in order to compare their effectiveness when used for bonding UHM CFRP laminate with steel. Experimental results including bond strength, effective bond length, CFRP strain distribution, shear stress distribution in adhesive layer and bond slip relationship were introduced and compared with previous research on CFRP sheets and normal modulus CFRP laminate. Theoretical models were employed for prediction of bond strength and effective bond length. Nonlinear finite element models were adopted to simulate the experimental specimens. Existing bond slip models for CFRP sheets and normal modulus CFRP laminates were compared with those for UHM CFRP laminate. Comments are made on the differences.

2. Experimental programme

In the present study, thirteen double strap joints with UHM CFRP laminates bonded to steel plates were prepared and tested in tension. Fig. 1 shows the schematic view of a typical specimen. Specimens with various bond lengths (L_1 is named as bond length in the following parts of this paper) were prepared to study the effects of bond length on the bond strength. Two types of adhesive (Araldite and Sikadur) were adopted to bond the CFRP to steel surface so that the influence of adhesive on bond behaviour can be studied. Table 1 lists the specimens along with the test results. Specimen designations, which start with "A" indicate Araldite and those with "S" indicate Sikadur. The number that follows the letter is the bond length L_1.

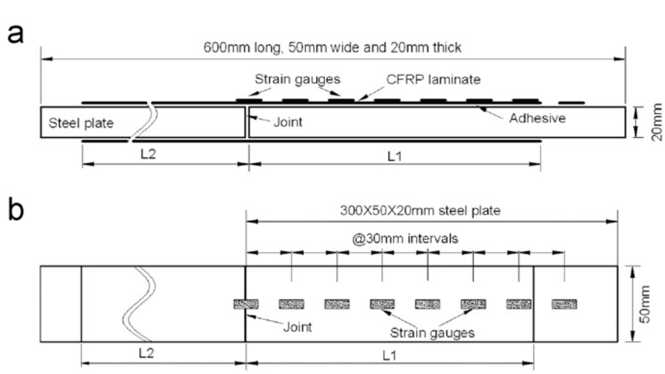

Fig. 1. A schematic view of the specimen and the location of strain gauges (not to scale). (a) Side view of the specimen, (b) Application of strain gauges.

2.1. Material properties

CFRP laminates "MBRACE® LAMINATE 460/1500" supplied by BASF were adopted. It is an ultra high modulus laminate with a nominal elastic modulus of 460 GPa and a nominal tensile strength of 1500 MPa. The modulus and the tensile strength are around 2.3 and 4 times higher than those of common steel products. The laminate thickness is 1.45 mm.

Araldite 420 and Sikadur 30 were used as adhesives for bonding CFRP to steel plates. They are two-part epoxies with material properties that are quite different. This enables the determination of the influence of adhesive properties on bond behaviour.

The steel plates are hot rolled structural steel HA300. They have a nominal yield stress of 300 MPa. The steel plates are all 20 mm thick and with the same width of 50 mm as the CFRP laminates. The material properties and dimensions of steel plates were selected in such a way so as to avoid steel yielding during the tension loading process.

The material properties of CFRP and steel plates were obtained through coupon tests, which were carried out according to ASTM E8 and ASTM D3039, respectively [26,27]. The coupon specimens are shown in Fig. 2 with detailed dimensions. The measured material properties of CFRP and steel are listed in Table 2 along with those of adhesives reported in [20].

2.2. Specimen preparation and test setup

Double strap joints were prepared with UHM CFRP laminates connecting two steel plates with a dimension of 300 × 50 × 20 mm (length × width × thickness). The steel surface was sand-blasted to ensure a better interlocking between CFRP and steel. The surfaces were then cleaned with acetone immediately before the adhesive application. Two steel plates were aligned in position after which a