BOND CHARACTERISTICS BETWEEN CFRP AND STEEL PLATES IN DOUBLE STRAP JOINTS

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Abstract: This paper describes a series of double strap shear tests loaded in tension to investigate the bond between CFRP sheets and steel plates. Both normal modulus (240 GPa) and high modulus (640 GPa) CFRPs were used in the test program. Strain gauges were mounted to capture the strain distribution along the CFRP length. Different failure modes were observed for joints with normal modulus CFRP and those with high modulus CFRP. The strain distribution along the CFRP length was found to be similar for the two cases. A shorter effective bond length was obtained for joints with high modulus CFRP whereas larger ultimate load carrying capacity can be achieved for joints with normal modulus CFRP when the bond length is long enough. The Hart-Smith Model was modified to predict the effective bond length and ultimate load carrying capacity of joints between the normal modulus CFRP and steel plates. The Multilayer Distribution Model developed by the authors was modified to predict the load carrying capacity of joints between the high modulus CFRP and steel plates. The predicted values agreed well with experimental ones.

Keywords: CFRP (Carbon Fibre Reinforced Polymer), Bond Failure, Double Strap Joints, Effective Bond Length, Steel Plate.

1. INTRODUCTION

Carbon fibre reinforced polymers (CFRP) are relatively new materials used in retrofitting, that is, to prolong the life of structural members and increase their load carrying capacity (Intelligent Sensing for Innovative Structures Canada (ISIS) [1], Moy [2], American Concrete Institute (ACI) Committee 440 [3], Teng *et al.* [4], Ohelers and Seracino [5]). The evolution of CFRP technologies and their versatility for applications in civil constructions require comprehensive and reliable codes of practice. Guidelines are available on the rehabilitation and retrofit of concrete structures with advanced composite materials. However, the practice for concrete can not be directly used for steel structures due to the fact that concrete and steel are very different materials [6]. There is a need to develop appropriate design guidelines for CFRP strengthened steel structures. It is important to understand the bond characteristics between CFRP and steel plates.

This paper describes a series of double strap shear tests loaded in tension to investigate the bond between CFRP sheets and steel plates. Both normal modulus (240 GPa) and high modulus (640 GPa) CFRPs were used in the test program. Strain gauges were mounted to capture the strain distribution along the CFRP length. Discussions are made on failure modes, strain distribution along the CFRP, ultimate load carrying capacity and effective bond length. Two theoretical models are proposed in this study for joints with normal and high modulus CFRPs, respectively. The Hart-Smith [7,8] model was originally developed for double strap adhesive joints. This model was modified to predict the ultimate load carrying capacity and effective bond length of steel plates bonded with multi-layer normal modulus CFRP. This proposed model is called "Modified Hart-Smith Model" in this paper. A Multilayer Distribution Model was developed by Fawzia *et al.* [9] for high modulus CFRP bonded to steel tubes. This model was modified to predict the load carrying capacity of joints between the high modulus CFRP with steel plates. The new model was called

"Modified Multilayer Distribution Model" in this paper. The predicted values agreed well with experimental ones.

2. MATERIALS

In the present research, MBrace fibre CF530 and CF130 were chosen. MBrace CF530 is called high modulus CFRP in this paper. It has a nominal modulus of elasticity of 640 GPa. CF130 is called normal modulus CFRP in this paper with a nominal modulus of elasticity of 240 GPa. The nominal ultimate tensile strength of CFRP is 2650 MPa for CF530 and 3800 MPa for CF130. Araldite 420 adhesive was chosen. Steel plates with a thickness of 5 mm are used in the test program. The yield stress of the steel plate is around 360 MPa.

3. SPECIMENS AND TEST SET UP

A total of eight specimens were prepared. All steel plates have a dimension of 210 mm in length and 50 mm in width. The steel plates were ground with linisha 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 alinged 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 7 days and postcured for one day at 70^{o}C. A schematic view of a specimen is shown in Figure 1 where the length L_1 is always less than L_2 to aim that the failure occurs on one end only. Several foil strain gauges were attached to the CFRP bonded length. One was located at the joint and others were located every 15 mm along the the bonded length. Each specimen was loaded in tension in a 500 kN capacity Baldwin universal testing machine with a loading rate of 2 mm/min in a similar way as reported in Fawzia *et al.* [9], Jiao and Zhao [10]. Figure 2 shows a typical test set up.

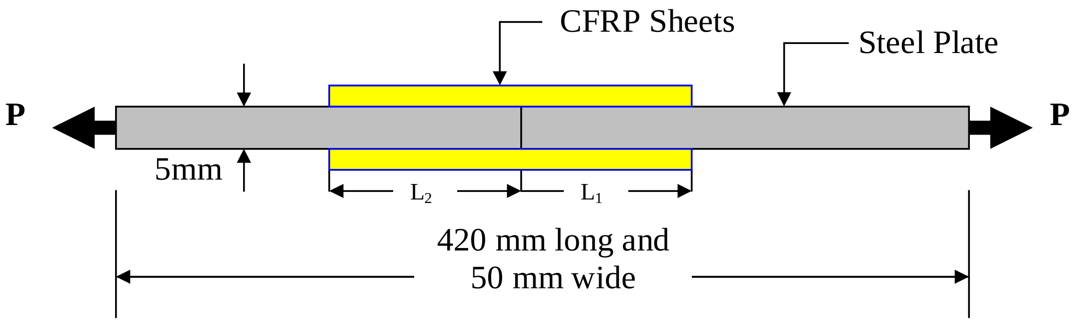


Figure 1. A schematic view of specimen (not to scale)

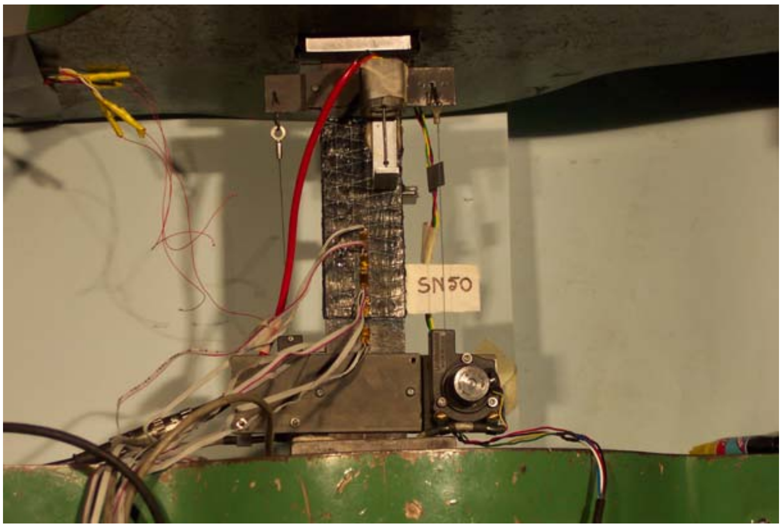


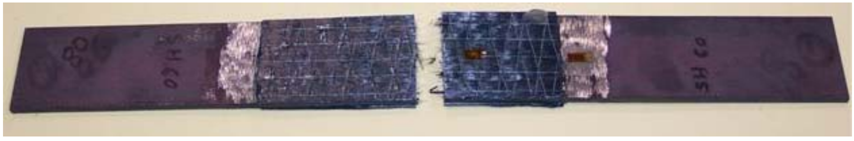
Figure 2. A typical test set up

4. TEST RESULTS

4.1 Failure Modes

The failure mode for joints with normal modulus CFRP was found to be bond failure whereas fibre break failure was observed for joints with high modulus CFRP. This is similar to those observed previously from similar tests on CFRP and steel tubes [9,10]. Typical failure modes are presented in Figure 3.

(a) Steel plates with normal modulus CFRP (this paper)



(b) Steel plates with high modulus CFRP (this paper)

(c) Steel tubes with normal modulus CFRP (Jiao and Zhao (2004))

(d) Steel tubes with high modulus CFRP (Fawzia et al (2004b))

Figure 3. Typical failure modes

4.2 Strain Distribution along the Bonded Length

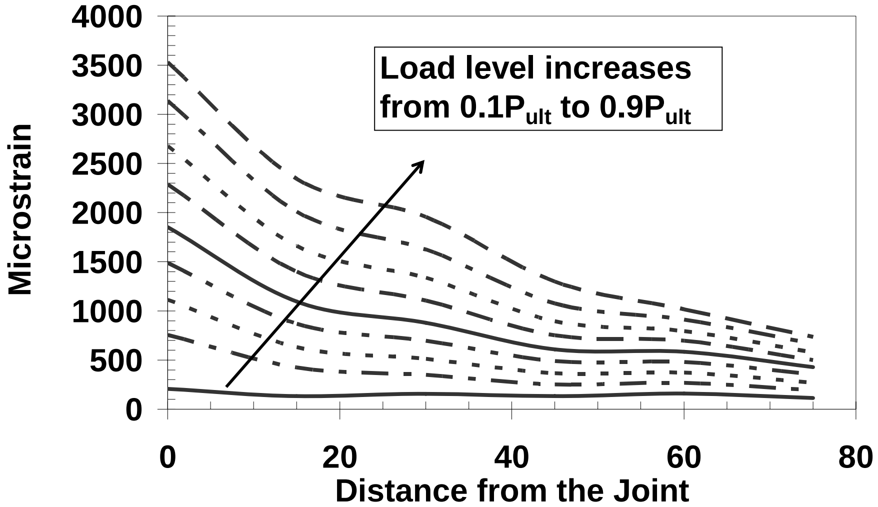
The distribution of strain along the bonded length can be found from the gauge readings at the top layer. These readings are plotted in Figure 4 under different load level. The load level is defined as a ratio of applied load to the maximum load (P_{ult}) achieved in the test. Only the average readings from all specimens are shown in Figure 4. It is clear from the figure that strain generally decreases with the distance away from the joint between the two plates. The distribution for normal modulus CFRP joints seems to be nonlinear whereas that for high modulus CFRP joints seems to be linear. As expected, smaller strain values were obtained for joints with high modulus CFRP.

4.3 Ultimate Load

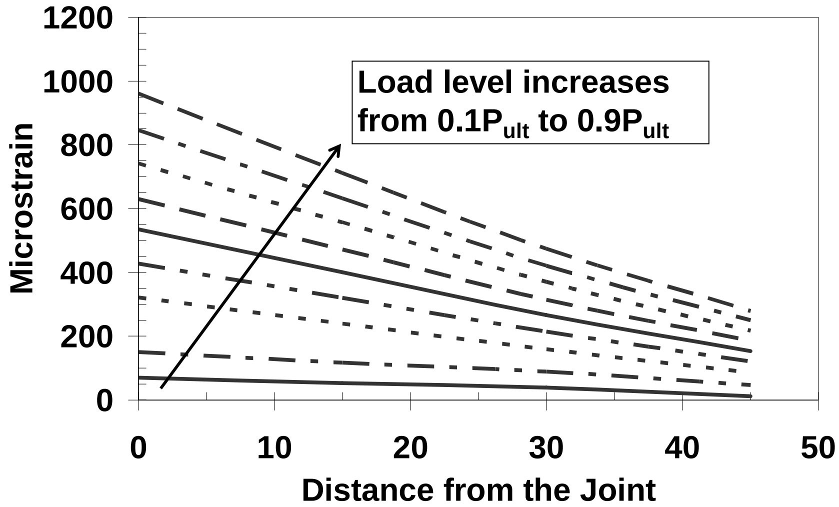
The ultimate load carrying capacity (P_{ult}) obtained in the tests are summaried in Table 1. The first letter (S) in a specimen label means specimen. The second letter (N) indicates normal modulus CFRP or (H) means high modulus CFRP. The numbers (20, 40, 50, 60, 70 or 80) indicates the bonding length (L_1) defined in Figure 1.

Table 1. Test results

Specimen Label	Bond Length L_1 (mm)	Ultimate Load P_{ult} (kN)	Failure Mode
SN20	20	33.7	Bond Failure
SN40	40	49.9	Bond Failure
SN50	50	69.8	Bond Failure
SN70	70	80.8	Bond Failure
SN80	80	81.3	Bond Failure
SH20	20	42.8	Fibre Break
SH40	40	53.1	Fibre Break
SH60	60	52.2	Fibre Break



(a) normal modulus CFRP



(b) high modulus CFRP

Figure 4. Distribution of strain along the bonded length

4.4 Effective Bond Length

The ultimate load carrying capacity is plotted in Figure 5 against the bond length (L_1). It can be seen from Figure 5 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 capcaity will occur, is called the effective bond length. A similar concept was used by Teng *et al.* [4] and Jiao and Zhao [10]. It seems that the effective bond length for joints with high modulus CFRP (about 40 mm) is smaller than that for joints with normal modulus CFRP (about 75 mm). This matches the failure mode shown in Figure 3, i.e. a longer bond length is required for normal modulus to build up the full strength of the joint through bond capacity. This may be due to the fact that the use of high modulus CFRP results in lower shear strain deformations in the epoxy layer. The effective bond length of 75 mm for joints with normal modulus CFRP is almost the same as that reported in Jiao and Zhao [10] 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.

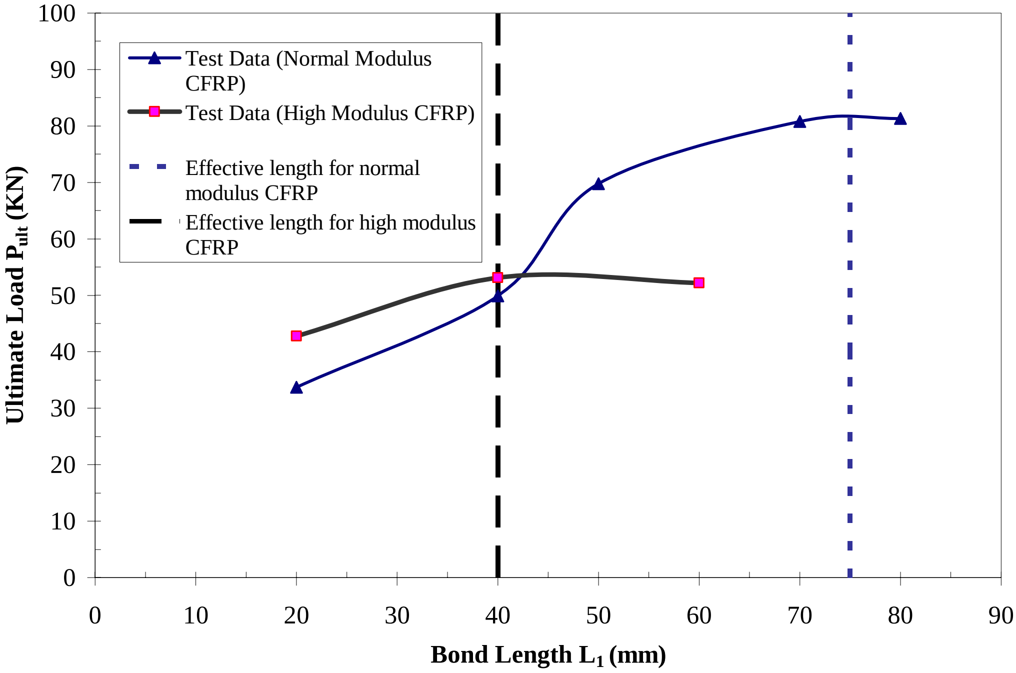


Figure 5. Effective bond length for joints with normal and high modulus CFRP

Another interesting phenomenon shown in Figure 5 is that the load carrying capacity of joints with normal modulus CFRP is lower than that of joints with high modulus CFRP when the bond length is short, around 40 mm in this case. This is most likely because the normal modulus CFRP has not become fully effective yet. When the bond length increases further the load carrying capacity of joints with normal modulus CFRP becomes larger. This is due to the fact that the normal modulus CFRP has a higher tensile strength than the high modulus CFRP. Designers may utilize this phenomenon to select different CFRP and bond length to acheive certain load carrying capacity.

5. MODEL FOR JOINTS BETWEEN STEEL PLATES AND NORMAL MODULUS CFRP

5.1 Hart-Smith Model for Double Strap Joints

Various theoretical analyses of adhesively bonded joints were carried out by many researchers. Double-Strap joint was treated as a symmetrical configuration consisting of two Double-Lap joints [8]. Detailed explanation on the stress and strain distribution can be found in Hart-Smith [8]. The non-uniform distribution of the strains and stresses in the Double-Strap joints is illustrated in Figure 6 [11]. For the short overlap joints, the minimum adhesive stress and strain are as high as maximum values. While for the long overlap joints, the load transfer is confined to two end zones with a lightly-loaded elastic trough in between. This section summarizes the formulae for the effective bond length and the ultimate load carrying capacity per unit width for Double-Strap Joints. Detailed derivations can be found in Hart-Smith [7,8]. The effective bond length (L_e) is expressed as:

$$L_e = \frac{\sigma_{ult} \cdot t_i}{\tau_p} + \frac{2}{\lambda} \qquad \text{where} \quad \lambda = \sqrt{\frac{G_a}{t_a}\left(\frac{1}{E_o t_o} + \frac{2}{E_i t_i}\right)} \qquad (1)$$

in which, σ_{ult} is the ultimate tensile strength of the inside adherent, τ_p is the adhesive shear strength in the idealized elastic-plastic stress-strain curve, G_a is the adhesive shear modulus, t_a is the adhesive thickness, E is the Young's modulus of adherent and t is thickness of the adherent while the subscripts o and i represent outside and inside adherents, respectively.

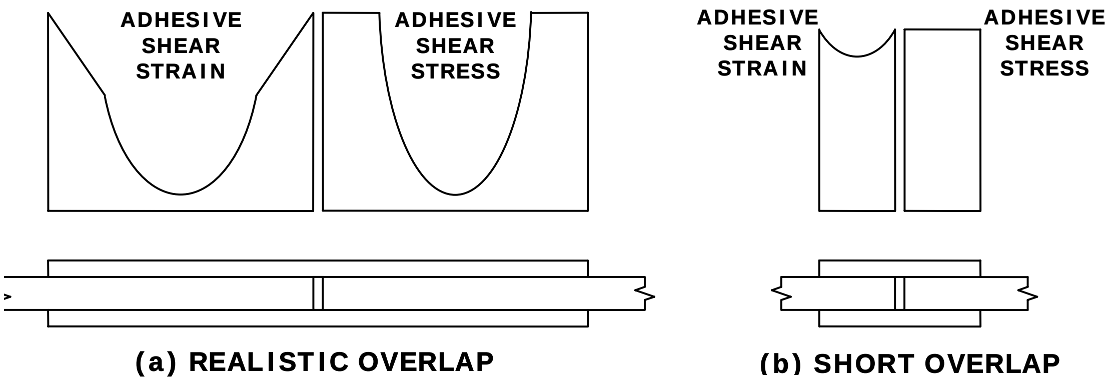


Figure 6. Non-uniform strains and stresses in double strap joints (Hart-Smith 2001)

The ultimate load carrying capacity per unit width is taken as the lesser of P_i and P_o:

$$P_i = \sqrt{\left[2 \cdot \tau_p \cdot t_a \cdot (\frac{1}{2} \cdot \gamma_e + \gamma_p) \cdot 2 \cdot E_i \cdot t_i \cdot \left(1 + \frac{E_i \cdot t_i}{2 \cdot E_o \cdot t_o}\right)\right]} \qquad (2a)$$

$$P_o = \sqrt{\left[2 \cdot \tau_p \cdot t_a \cdot \left(\frac{1}{2} \cdot \gamma_e + \gamma_p\right) \cdot 4 \cdot E_o \cdot t_o \cdot \left(1 + \frac{2 \cdot E_o \cdot t_o}{E_i \cdot t_i}\right)\right]} \qquad (2b)$$

where γ_e and γ_p represent elastic and plastic adhesive shear strains, respectively.

5.2 Modified Hart-Smith Model (MHSM)

The Hart-Smith model presented above was derived for double-strap joints with one layer of outside adherent. For the joint between steel plates and CFRP defined in Figure 1, more than one layer of CFRP was applied with adhesives between each layer. Some modification is necessary before using the Hart-Smith model.

Obviously the steel plate is the inside adherent. It is assumed in this paper that the adhesive to be used for the model is the adhesive between the steel plate and the first layer of CFRP. The rest of the material above this layer of adhesive is considered as the outside adherent. The modulus of elasticity E_o is approximately taken as that of CFRP (E_{CFRP}). Therefore the thicknesses t_i, t_o, t_a and modulus E_o can be determined as follows based on equal thickness epoxy between the CFRP and steel and between each of the CFRP layers:

$$t_i = t_{steel} \quad (3a)$$

$$t_a = \frac{\frac{1}{2} \cdot (T - t_{steel})}{n} - t_{CFRP} \quad (3b)$$

$$t_o = n \cdot t_{CFRP} + (n-1) \cdot t_a \quad (3c)$$

$$E_o = E_{CFRP} \quad (3d)$$

in which, t_{steel} is the thickness of the steel plate, t_{CFRP} is the thickness of the CFRP sheet, T is the average total thickness of the specimen at the joint and n is the number of CFRP layers on one side of the joint.

The modulus of elasticity E_i is that of steel. The adhesive shear modulus G_a is taken as 1000 MPa as adopted by Matta [12]. The adhesive shear strength τ_p is that for Araldite 420 given by the manufacturer.

The parameters used in calculating the effective bond length are summarized in Table 2. The value of $L_{e,MHSM}$ (stands for effective bond length based on modified Hart-Smith model) so calculated is 73 mm.

Table 2. Parameters used in the calculations for the modified Hart-Smith model

T (mm)	t_{steel} (mm)	t_{CFRP} (mm)	t_i (mm)	t_a (mm)	t_o (mm)	σ_{ult} (MPa)	τ_p (MPa)	G_a (MPa)	E_o (GPa)	E_i (GPa)	n
7.5	5.1	0.176	5.1	0.224	0.976	430	36	1000	240	200	3

The ultimate load carrying capacity predicted by the modified Hart-Smith model ($P_{ult,MHSM}$) for the joint shown in Figure 1 (a) becomes:

$$P_{ult,MHSM} = b \cdot \min\{P_i, P_o\} \quad (4)$$

where b is the width of the joint which is 50 mm in this case, P_i and P_o are defined in Eq (2).

The elastic adhesive shear strain γ_e is equal to τ_p/G_a. The value of the plastic adhesive shear strain γ_p is taken as 3 times γ_e in this paper to allow certain amount of shear deformation for the joint shown in Figure 1. The ultimate load obtained using Eq (4) is about 83 kN.

The load carrying capacity for any bond length (L_1) can be expressed as follows if one assumes that the load is linearly proportional to the bond length:

$$P_{CFRP,MHSM} = L_1 \cdot \frac{P_{ult,MHSM}}{L_{e,MHSM}} \qquad \text{if } L_1 \leq L_e \quad (5a)$$

$$P_{CFRP,MHSM} = P_{ult,MHSM} \qquad \text{if } L_1 > L_e \quad (5b)$$

where $P_{ult,MHSM}$ is given by Eq (4) and $L_{e,MHSM}$ is given by Eq (1) with modifications defined in Eq (3). The modified Hart-Smith model is compared with the test results in Figure 7 where good agreement is evident. More details about the modified Hart-Smith model and other empirical models can be found in Liu *et al.* [13].

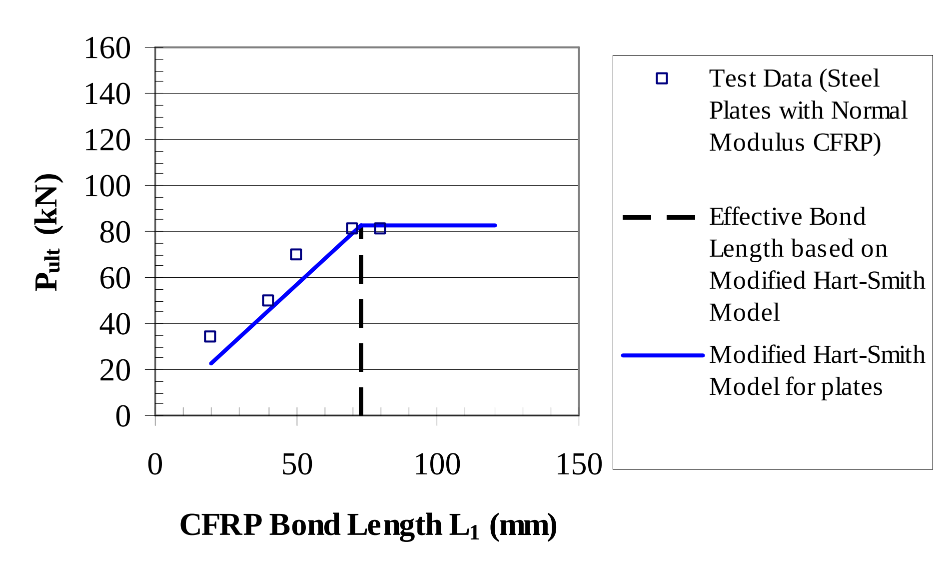


Figure 7. Results of modified Hart-Smith model for steel plates and normal modulus CFRP

6. MODELS FOR JOINTS USING HIGH MODULUS CFRP

6.1 Multilayer Distribution Model (MDM) for Steel Tubes by Fawzia et al (2004b)

A theoretical model was developed by the authors [9] to estimate the maximum load for multilayer high modulus CFRP bonded to circular hollow sections. The model was based on the measured strain distribution across the CFRP layers. The formula can be summarized as:

$$P_{p,MDM} = \sum_{i=1}^{n} A_i \cdot E_{CFRP} \cdot \frac{\varepsilon_{u,CFRP}}{\sqrt{i}} \tag{6}$$

where i is the layer number, A_i is the area of CFRP at layer i, E_{CFRP} is the modulus of CFRP, $\varepsilon_{u,CFRP}$ is the measured ultimate tensile strain of CFRP and n is the number of CFRP layers. The predicted ultimate load was found [9] to be very close (within 0.5% on average) to that experimentally obtained.

6.2 Modified Multilayer Distribution Model (MMDM) for Steel Plates and High Modulus CFRP

The model developed for steel tubes and CFRP can be modified for the case with steel plates and CFRP. The total area of CFRP at layer i on both sides of the plate can be expressed as $A_i = 2 \times t_{CFRP} \times b$. Therefore the ultimate load using the modified multilayer distribution model (MMDM) can be written as:

$$P_{ult,MMDM} = 2 \cdot \sum_{i=1}^{n} t_{CFRP} \cdot b \cdot E_{CFRP} \cdot \frac{\varepsilon_{u,CFRP}}{\sqrt{i}} \tag{7}$$

where t_{CFRP} = 0.19 mm, b = 50 mm, $\varepsilon_{u,CFRP}$ = 2113 x 10^{-6} (measured value from Ref. [9]) and E_{CFRP} = 508,386 MPa (measured value from Ref. [9]) and n = 3.

The predicted ultimate load is compared in Figure 8 with the experimental data. It can be seen that the predicted value is about 10% lower than the experimental ones when the bond length exceeds the effective bond length.

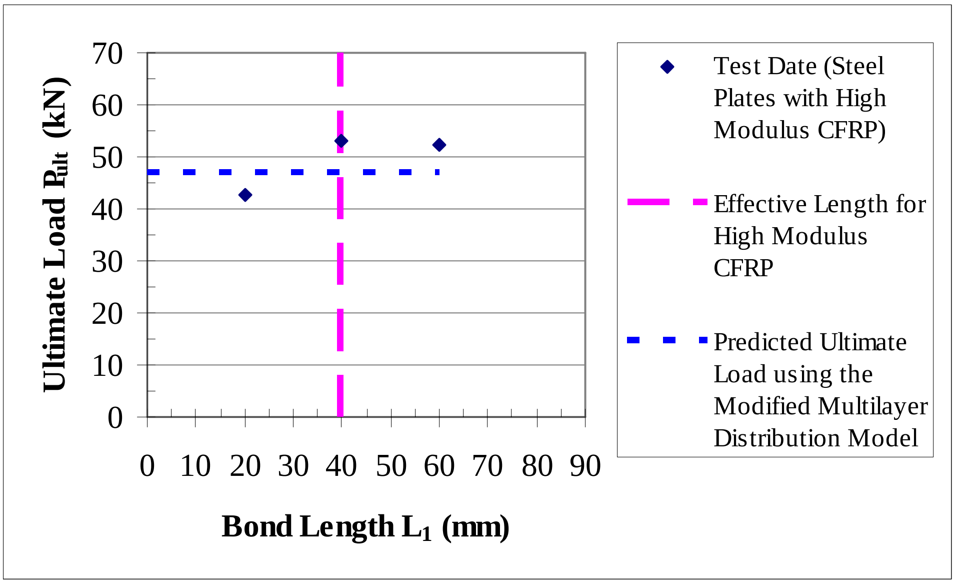


Figure 8. Results of modified multilayer distribution model for steel plates and high modulus CFRP

7. CONCLUSIONS

A series of tests on double strap joints were carried out to investigate the bond between CFRP sheets and steel plates. Both normal modulus (240 GPa) and high modulus (640 GPa) CFRPs were used in the test program. The following conclusions and observations are made based on the limited test results.

1. Different failure modes were observed for joints with normal modulus CFRP (bond failure) and those with high modulus CFRP (fibre break).
2. The strain distribution along the CFRP length was found to be similar irrespective of the CFRP modulus although much smaller strains were generated in joints with high modulus CFRP.
3. The load carrying capacity of joints with normal modulus CFRP is lower than that of joints with high modulus CFRP when the bond length is short. Larger ultimate load carrying capacity can be achieved for joints with normal modulus CFRP when the bond length is long enough.
4. A shorter effective bond length was obtained for joints with high modulus CFRP.
5. The load carrying capacity estimated by the Modified Hart-Smith Model for steel plate bonded with normal modulus CFRP was found to be in close agreement with that obtained experimentally.
6. The load carrying capacity predicted by the Modified Multilayer Distribution Model for steel plates bonded with high modulus CFRP agreed reasonably with the experimental results.

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NOTATION

A_i = Area of CFRP at layer i
E = Modulus of elasticity
E_{CFRP} = Modulus of CFRP sheet
E_i = Modulus of inside adherent
E_o = Modulus of outside adherent
G_a = Adhesive shear modulus
L_1 = Short bond length
L_2 = Long bond length
L_e = Effective bond length
P = Tensile load
P_i = Ultimate load of inside adherent
P_o = Ultimate load of outside adherent
P_p = Predicted load
P_{ult} = Ultimate load
T = Total thickness of specimen
b = Width of steel plate
i = 1, 2 and 3
n = Number of CFRP layers
t_a = Thickness of adhesive
t_{CFRP} = Thickness of CFRP sheet
t_i = Inside adherent thickness
t_o = Outside adherent thickness
t_{steel} = Thickness of steel plate
τ_p = Adhesive shear strength
λ = Effective parameter to calculate effective bond length
γ_e = Elastic adhesive shear strain
γ_p = Plastic adhesive shear strain
$\varepsilon_{u,CFRP}$ = Ultimate strain of CFRP
σ_{ult} = Ultimate tensile strength

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