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Factors effect on the effective length in a double strap joint between steel plates and CFRP

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ABSTRACT

This paper presents the behavior of axially loaded flat steel plates strengthened using carbon fiber reinforced polymer sheets. Two steel plates were joined together with adhesive and followed by the application of carbon fiber sheet double strap joint with different bond lengths. The effective length of CFRP sheet has been study by using commercially available finite element analysis software ANSYS V12.1. A parametric study has been performed by numerical modeling with the variables of CFRP sheet thickness, adhesive layer thickness, steel plate thickness and number of CFRP sheet layer.

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1. INTRODUCTION

There are many advantages in favor of the use of CFRP materials for repair and rehabilitation of bridges and structures. Cost savings may be realized through labor 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.[1]

Bond strength can be defined as the ratio of maximum load and interfacial area. However, a local bond–slip relationship is independent of geometric conditions, and therefore a local bond–slip model may be appropriate to measure bond performance. While a great deal of research has been carried out on bond–slip relationships of CFRP sheet/plate bonded to concrete joints [2–9], research on CFRP plate/sheet to steel bonded joints is limited [10–15].

Previous research [10] showed a significant strength increase by using CFRP–epoxy strengthening technique. In this research a theoretical model was developed to estimate the load carrying capacity of butt-welded very high strength steel tubes strengthened using CFRP. In previous papers [11–14], the authors showed significant strength enhancement of CFRP strengthened steel plate and steel tube by experimental, theoretical and finite element analysis. None of the above research developed bond–slip relationship.

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 behavior and distribution of strain along the bonded length of the CFRP bonded steel plate.

2. NUMERICAL WORK
2.1. Finite Element Model
In this study, finite element method (FEM) is used to perform tensile testing simulations by nonlinear static analysis on double strap joints bonded by adhesive and CFRP sheet material. Special attention needs to be paid when joining two different materials, in this particular case adhesive bonding between steel and CFRP. The simulation was implemented using commercially available finite element analysis software ANSYS V12.1, the elements used to build this model listed as below:

2.1.1. Brick Element (SOLID45 as denoted in ANSYS [16])
The element is defined by eight nodes having three degrees of freedom at each node: translations in the nodal x, y, and z directions. The element has plasticity, creep, swelling, stress stiffening, large deflection, and large strain capabilities. The geometry, node locations, and the coordinate system for this element are shown in Figure 1. This element used to model steel plate.

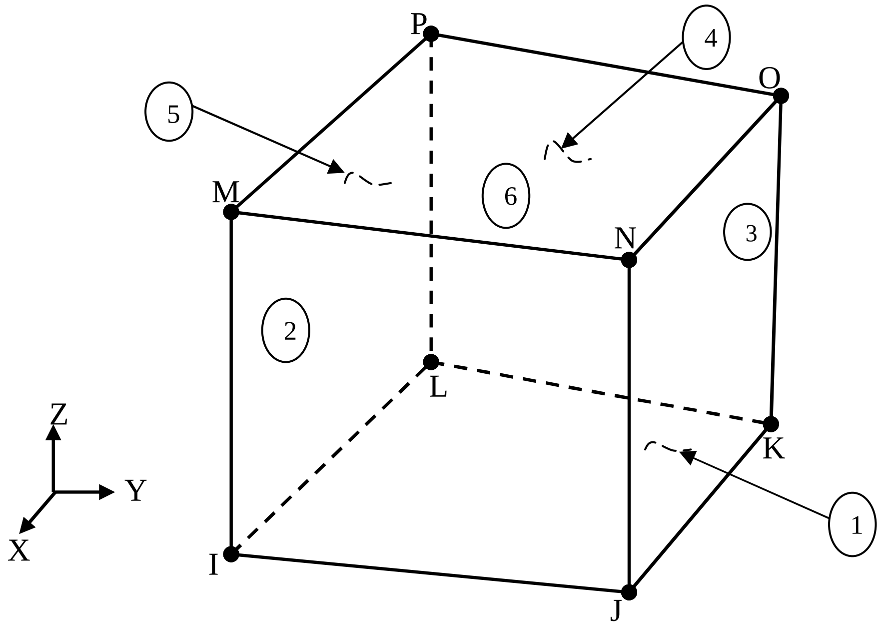

Figure 1. (SOLID45) Element Geometry [16]

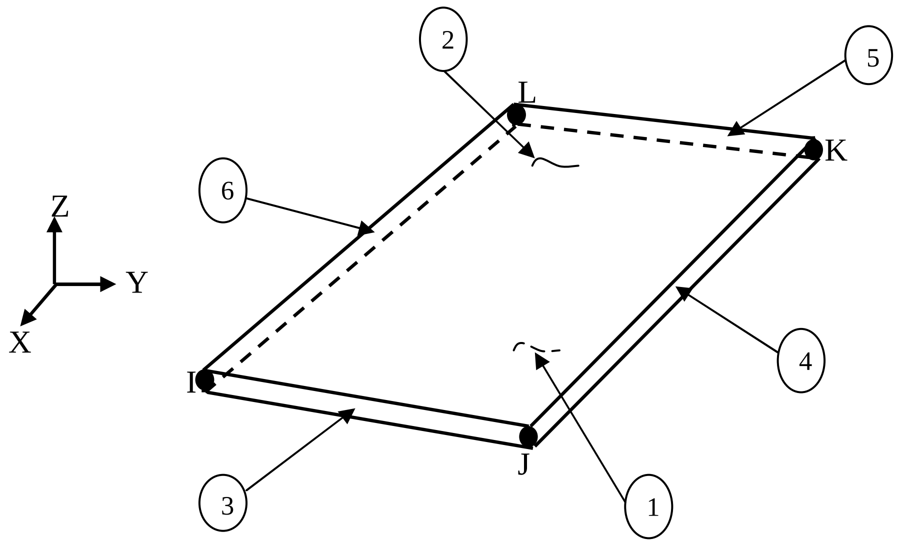

Figure 2. (SELL41) Element Geometry [16]

2.1.2. Shell Element (SHELL41 as denoted in ANSYS [16])

The element is defined by four nodes, four thicknesses, a material direction angle and the orthotropic material properties. Orthotropic material directions correspond to the element coordinate directions. The element have membrane stiffness (no bending stiffness) so the element is used to model the CFRP laminate. The element may have variable thickness. The thickness is assumed to vary smoothly over the area of the element, with the thickness input at the four nodes. If the element has a constant thickness, only one thickness (in any node) need be input. If the thickness is not constant, all four thicknesses must be input (for four nodes). The geometry, nodes location, and coordinate of the element are shown in Figure 2.

2.1.3 Target element (TARGE170 as denoted in ANSYS [16])

In studying the contact between two bodies, the surface of one body is conventionally taken as a contact surface and the surface of the other body as a target surface. The “contact-target” pair concept has been widely used in finite element simulations. For rigid-flexible contact, the contact surface is associated with the deformable body; and the target surface must be the rigid surface. For flexible-flexible contact, both contact and target surfaces are associated with deformable bodies. The contact and target surfaces constitute a “Contact Pair”. TARGE170 is used to represent various 3-D "target" surfaces for the associated contact element (CONTA174). Hence, a “target” is simply a geometric entity in space that senses and responds when one or more contact elements move into a target segment element. The target surface is modeled through a set of target segments; typically several target segments comprise one target surface. Each target segment is a single element with a specific shape or segment type, 4 node quadrilateral element is used in this study.

2.1.4. Contact element (CONTA174 as denoted in ANSYS [16])

CONTA174 is used to represent contact and sliding between 3-D “target” surfaces (TARGE170) and a deformable surface, defined by this element. The element is applicable to 3-D structural and coupled field contact analyses. This element is located on the surfaces of 3-D solid or shell elements without mid-side nodes. It has the same geometric characteristics as the solid or shell element face with which it is connected. Contact occurs when the element surface penetrates one of the target segment elements (TARGE170) on a specified target surface. The element is defined by four nodes; the node ordering is consistent with the node ordering for the underlying solid or shell element.

2.2. Materials properties

2.2.1. Steel Plate

A typical uniaxial stress-strain curve for a steel specimen loaded monotonically in tension is shown in Figure 3.

The stress-strain diagram may for simplicity consist of two branches as shown in Figure 3: the first branch starts from the origin with a slope equal to *Es* (modulus of elasticity), up to *fy* (yield stress). A second branch is horizontal or, for practical use of computers, is assumed to have a very small slope such as (*0.01*Es*) and this last case is limited to the strain 0.01 according to EC4 [17].

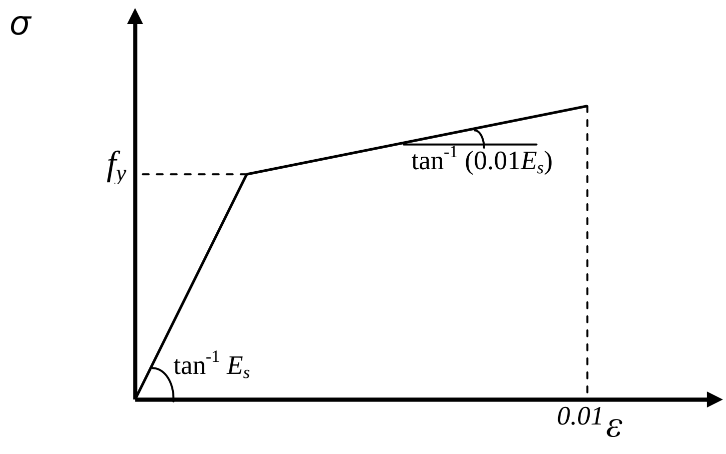

Figure 3. Idealization for computer calculations [17]

2.2.2. FRP material

The FRP composites being modeled here were adhesively bonded to the steel. The CFRP strips used in tests were 50 mm wide and 0.176 mm thick. The CFRP material properties, summarized in Table 1, were previously determined from tests and reported by Fawzia et al. [1].

2.2.3. Bond–slip models

The FRP-to-steel interface behaves like an isotropic material and can be modeled by a thin layer of elements. The strength criterion of the thin layer interface material is dominated by shear debonding failure. The properties of this layer depend on bonded material properties as listed in table 1 were reported by Fawzia et al. [1].

Table 1 Bonded material properties

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

3. SIMULATION OF A DOUBLE STRAP JOINT BETWEEN STEEL PLATES AND CFRP

The homogenized material model for steel together with an elastic material model for the CFRP and the bi-linear interface element material model were coded into the finite element program ANSYS 12.1 to simulate the behavior of a CFRP strips bonded to a steel plate. In the experiments reported by Fawzia et al. [1] 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. Three layers of CFRP sheets were applied on both sides of the plate. 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. [14]. A schematic view of the specimen is shown in Figure 4. The observed failure mode for the normal modulus CFRP was bond failure. Table 2 gives test results for different bond length.

Table 2 Results of specimen testing

Specimen label	Bond length *L1* (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

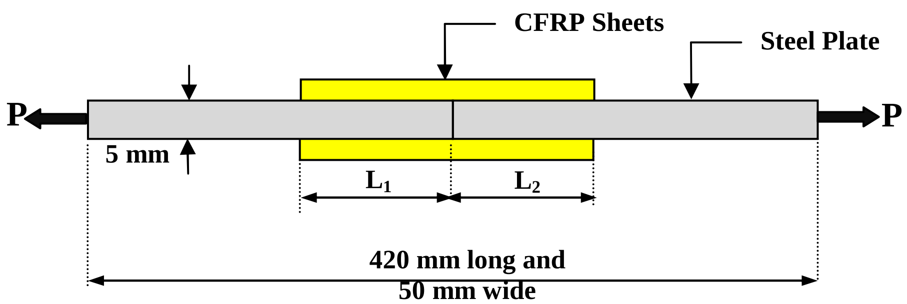

Figure 4. A schematic view of specimen (not to scale) [1]

Figures 5, 6, 7, and 8 show the load–displacement curves for the experimental and the numerical simulation where it can be seen that the homogenized model gave very good predictions. The value of maximum strains at specimen (SN80) also compared well with the test data as shown in Table 3.

Table 3 Comparison of maximum strain of (SN80) at different load value

Load	SN80	
	Numerical	Experiment
100 % of UL	0.0067	0.0063
75 % of UL	0.0051	0.0041
50 % of UL	0.0029	0.0025
25 % of UL	0.0011	0.0011

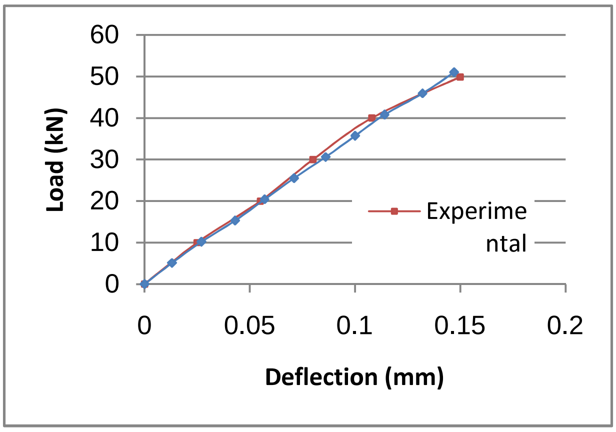

Figure 5. Load vs deflection for bond length 40 mm.

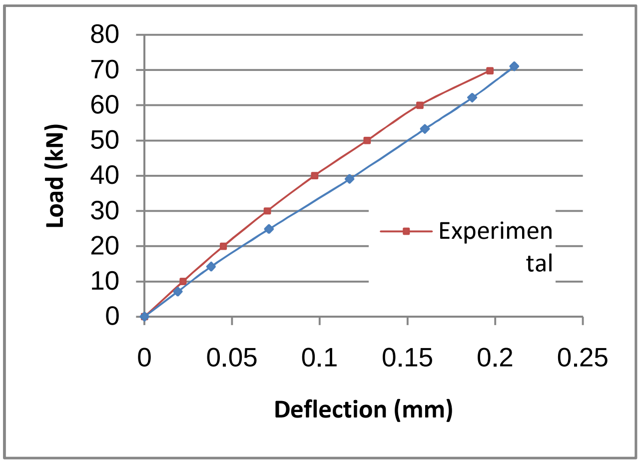

Figure 6. Load vs deflection for bond length 50 mm.

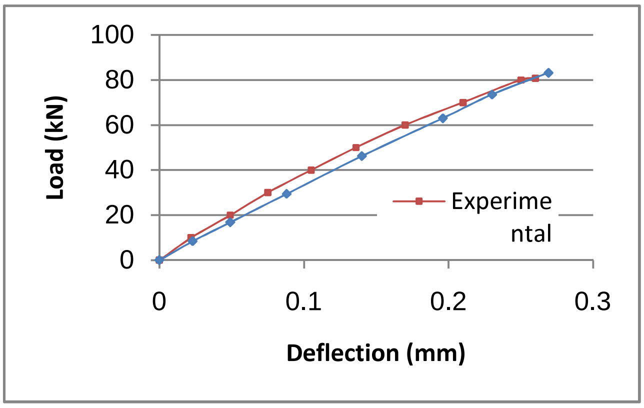

Figure 7. Load vs deflection for bond length 70 mm.

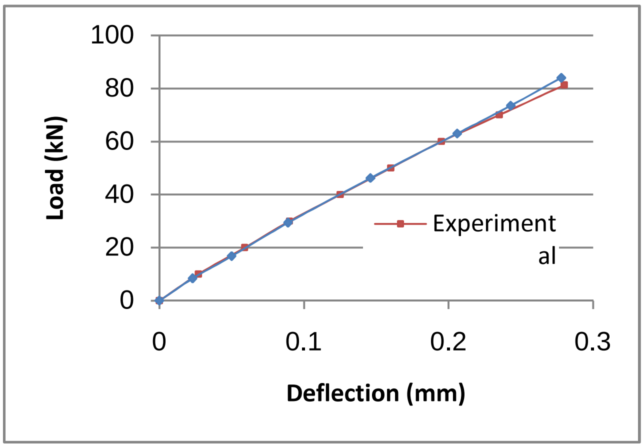

Figure 8. Load vs deflection for bond length 80 mm.

4. EFFECTIVE BOND LENGTH

The ultimate load carrying capacity is plotted in Figure 9 against the bond length L1. It can be seen from Figure 9 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 [18] 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. In this study many parameters will be taken to examine the changes of effective length under same conditions.

4.1. Effect of CFRP sheet thickness

Finite element analysis has been carried out for bond lengths of 40, 50, 60, 70 and 80 mm for two values of CFRP sheet thickness. Two values of CFRP sheet thickness specimens exhibited similar behavior. Figure 9 gives the results for specimens with thickness of CFRP sheet 0.176 and 0.352 mm. It can be seen that the effective length is not affected by the CFRP sheet thickness.

4.2. Effect of adhesive layer thickness

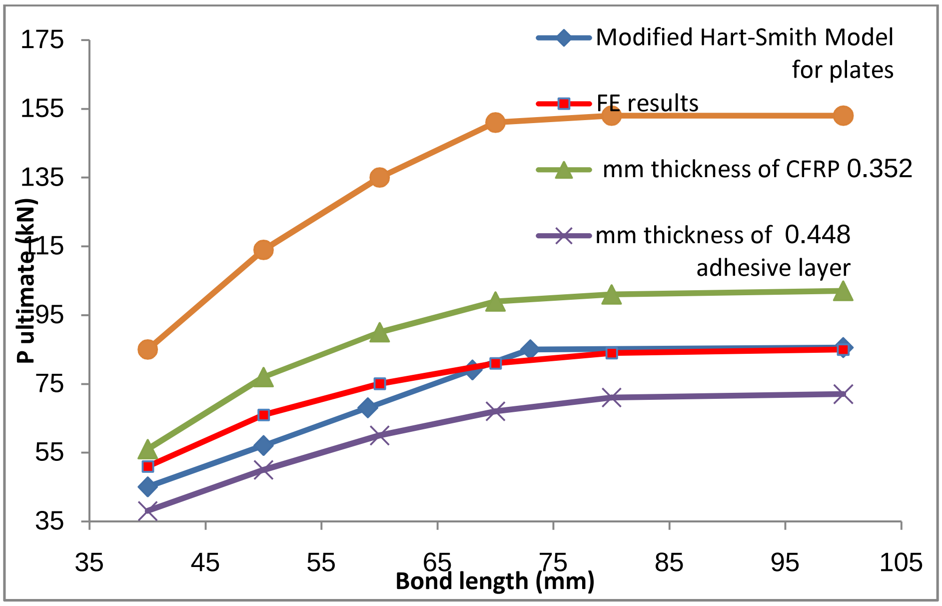

Figure 9. Effective bond length for CFRP joint

The thickness of the adhesive layer has a significant effect on the failure mode for CFRP laminate strengthening [15]. A parametric study has been conducted to investigate the effect of bond line thickness. Figure 9 shows the results from two different models using 0.224 and 0.448 mm adhesive thickness. Results show that the slip is directly proportional to adhesive thickness. Results also show that both models have same effective length.

4.3. Effect of steel plate thickness

Figure 9 shows the results of two thicknesses of steel plate (5 and 10 mm). Results show that no significant effect of the effective length.

4.4 Effect of CFRP layers

Finite element analysis has been carried out for different numbers of CFRP sheet 1, 2, 3, 4, and 5 layers with the same tensile strength value and CFRP sheet thickness. Figure 10 gives the results for specimens compared with Hart-Smith model. It can be seen that the number of CFRP sheet layers have a little effect on the effective length. The effective length increases to 80 mm when use one or two layers and become about 75 mm when use three layers, the using of more than three layers reduce effective length to 70 mm.

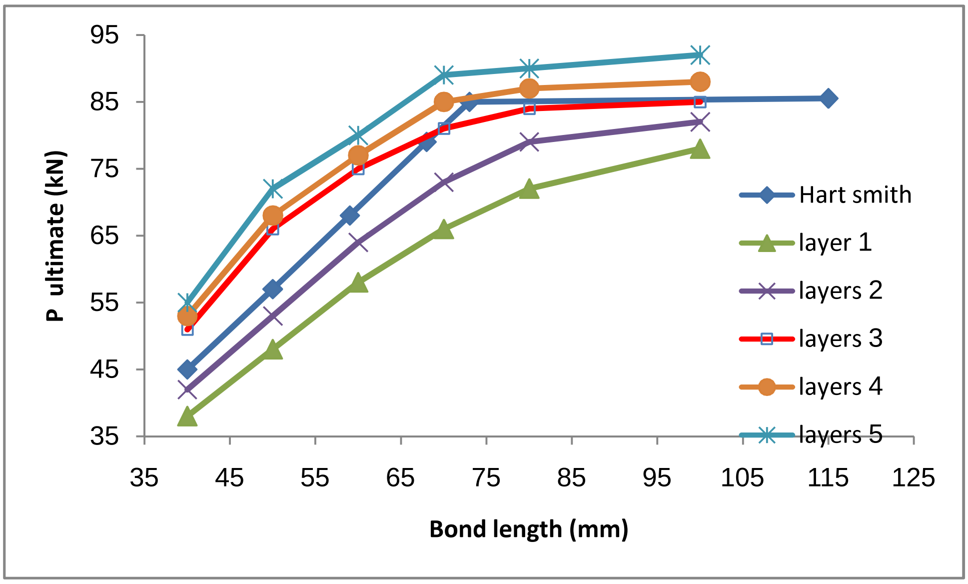

Figure 10. Effect of CFRP sheet layers number on effective bond length for CFRP joint

5. CONCLUSION

Numerical methods have been used to analyze the response of double strap joint between steel plates and normal modulus CFRP. The numerical model was evaluated by comparing the predictions with test data. The following conclusions and observations are made based on the numerical analysis:

1- The numerical load carrying capacity was found to be in close agreement with that obtained experimentally

2- Comparison of the predicted strain distribution from numerical agrees well with experimental results.

3- The effective length is not affected by the thickness of CFRP sheet, adhesive layer, and steel plate.

4- The number of CFRP sheet layer has significant effects on the effective length.

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