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.

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] and [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.

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. 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.

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 5mm 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 7 days and post-cured for one day at 70^{o}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 (2004) [15]. A schematic view of the specimen is shown in Figure 1. The observed failure mode for the normal modulus CFRP was bond failure. Table 2 gives test results for different bond length.

EFFECTIVE BOND LENGTH

The ultimate load carrying capacity is plotted in Figure 2 against the bond length L_1. It can be seen from Figure 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.

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

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 Figure 3. Loading was applied through displacement increments to simulate the uniform displacements along the loaded edges of the steel plates in the experiments.

Strand7 uses information about the nominal size of the structure to automatically give a reasonable displacement scale, one that clearly shows the deformation. Figure 4 shows bond failure of the CFRP sheets. In case of experiment the failure mode was similar as with the FE. Figure 5 shows a typical experimental bond failure. This is similar to those observed previously from similar tests on normal modulus CFRP and steel tubes [20].

MATERIAL PROPERTIES

The properties including tensile strength, strain and modulus can be found from Table 1. In the FE model, 3 layers of CFRP together with 2 layers of adhesive were considered as full CFRP layer having an equivalent thickness. The equivalent modulus of this layer was taken equal to 117 GPa. This was calculated from:

$$E_{e,CFRP} = \frac{E_a t_a + E_f t_f}{t_a + t_f}$$

where E_a and E_f are the tensile moduli of the adhesive and carbon fibre, respectively. The terms t_a and t_f represent the total thickness of the adhesive and carbon fibre layers, respectively.

COMPARISON OF THE RESULTS

Examination of Figures 6 and 7 shows that the zones of maximum Von Mises stress in the adhesive layer increase with the increase of load, indicating progressive bond failure as found experimentally.

Figures 8,9,10 and 11 show the comparison between load vs deflection of experiment and FE analysis. The term SN stand for normal modulus CFRP, Exp is for experiment and FE stands for finite element.

Table 3 gives a comparison of the ultimate load achieved from FE and experiment. A mean ratio of 1.072 is achieved with a coefficient of variation (COV) of 0.033. The analytical load carrying capacity was found to be in close agreement with that obtained experimentally.

Fawzia et al. [15] proposed a modification to an existing model derived by Hart-Smith [25] to predict the effective bond length and ultimate load capacity of double-strap joints. The modified model is compared with the experimental and FE results as shown in Figure 2. A good agreement is evident.

DISTRIBUTION OF STRAIN ALONG THE BOND LENGTH

The strain distribution measured in the specimens along the bond lengths are plotted in Figures 12 and 13. At each load level, the distributions show a gradual decline from the peak near the loaded edge to the other end. As the load increases, the strain at the first and second gauges increases significantly. The distributions have the steepest slope near the loaded edge. The distribution of strain after the third gauge is very small and becomes almost zero at a distance 75mm from the loaded edge. This phenomenon clearly indicates the concept of effective bond length which is the distance over which the maximum strain decreases to near zero.

The FE results were evaluated by comparing the predictions with test data. The strains predicted by the model, at known locations in the specimen, were compared with measured strain in the specimen as shown in Figure 14. It is evident that the distributions of strain agree well with those measured experimentally.

CONCLUSIONS

The CFRP bonded steel plate has been simulated by using the FE method. The model was evaluated by comparing the predictions with test data. The following conclusions and observations are made based on the FE analysis:

- The analytical load carrying capacity was found to be in close agreement with that obtained experimentally with a mean ratio of 1.072 and a coefficient of variation (COV) of 0.033.

In FE analysis the zone of maximum Von Mises stress in the adhesive layer increases sharply with the increase of the load indicating progressive bond failure as found experimentally.

- Comparison of the predicted strain distribution from FE analysis agrees well with experimental results.

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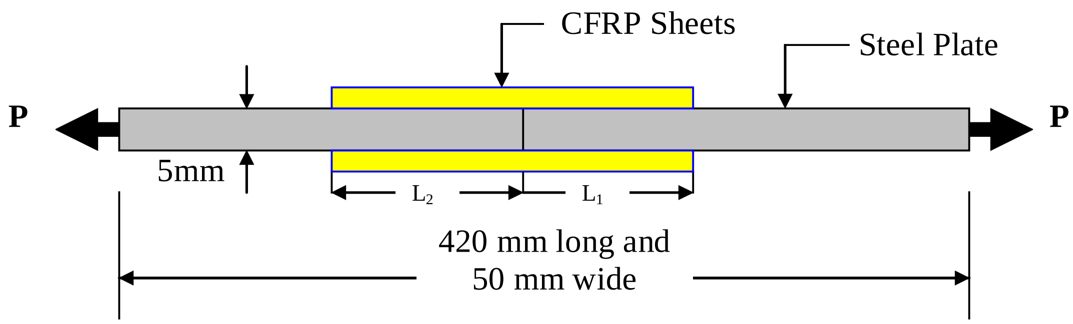

Figure 1: A schematic view of specimen (not to scale).

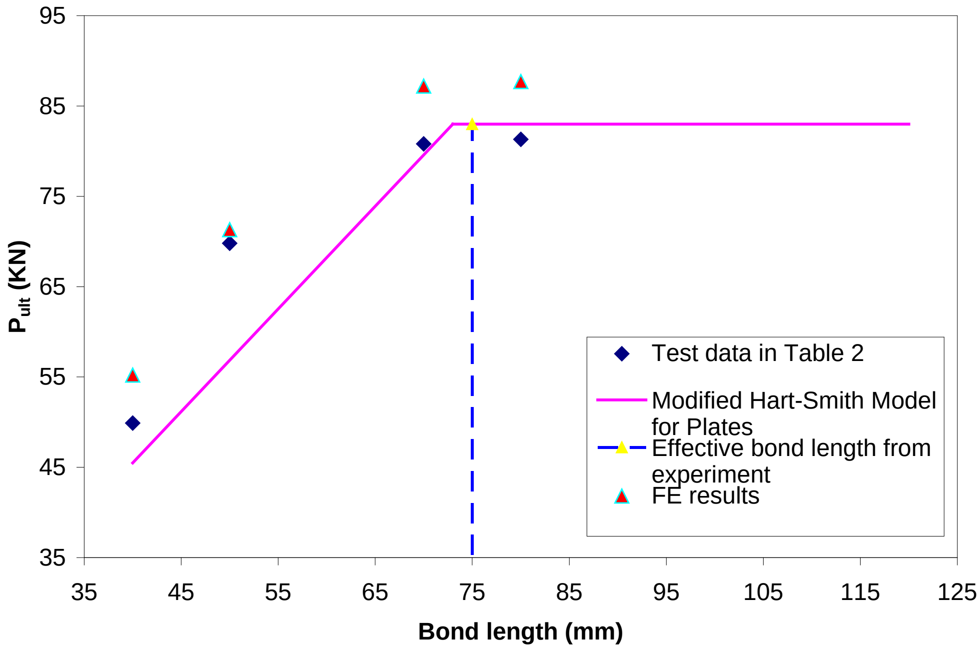

Figure 2: Effective bond length for normal modulus CFRP joint

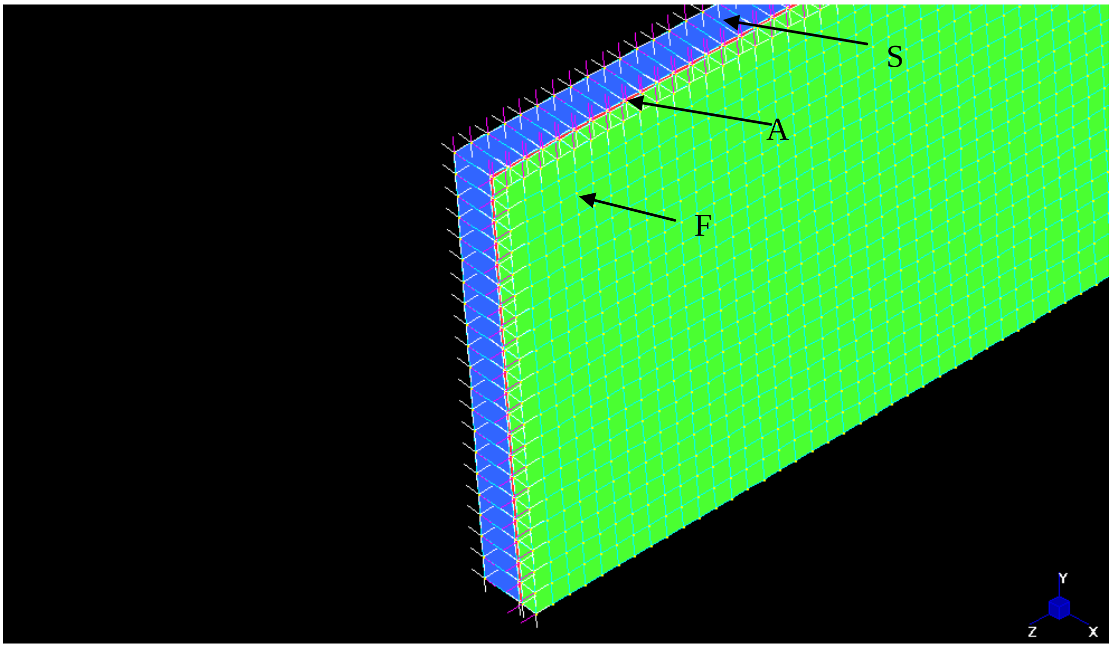

Figure 3: Details of the boundary conditions of the model (Failure edge). S=Steel, A=Adhesive, F=CFRP.

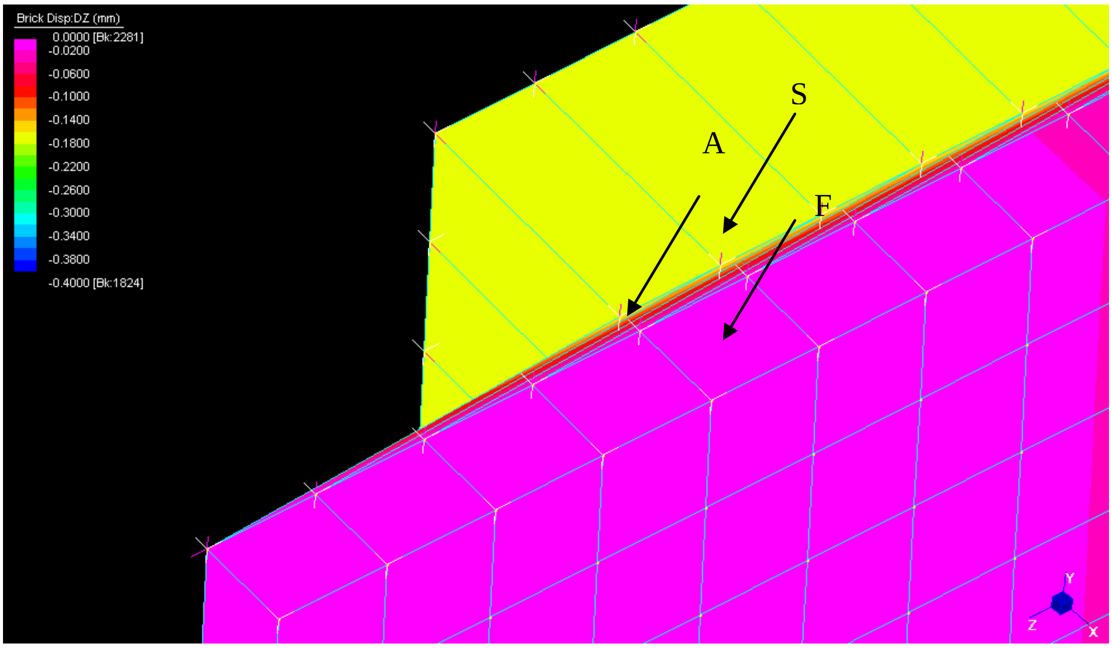

Figure 4: Bond failure of the specimen (Failure edge). S=Steel, A=Adhesive, F=CFRP.

Figure 5: Bond failure of the specimen(Experiment)

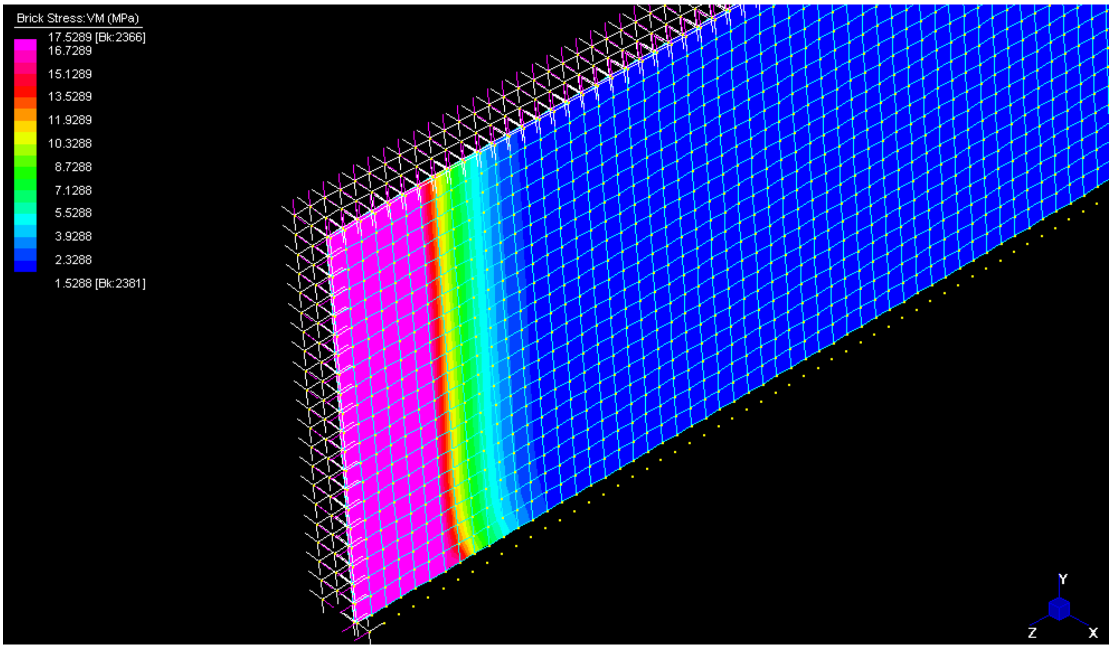

Figure 6: Maximum Von Mises stress for adhesive layer at low load level.

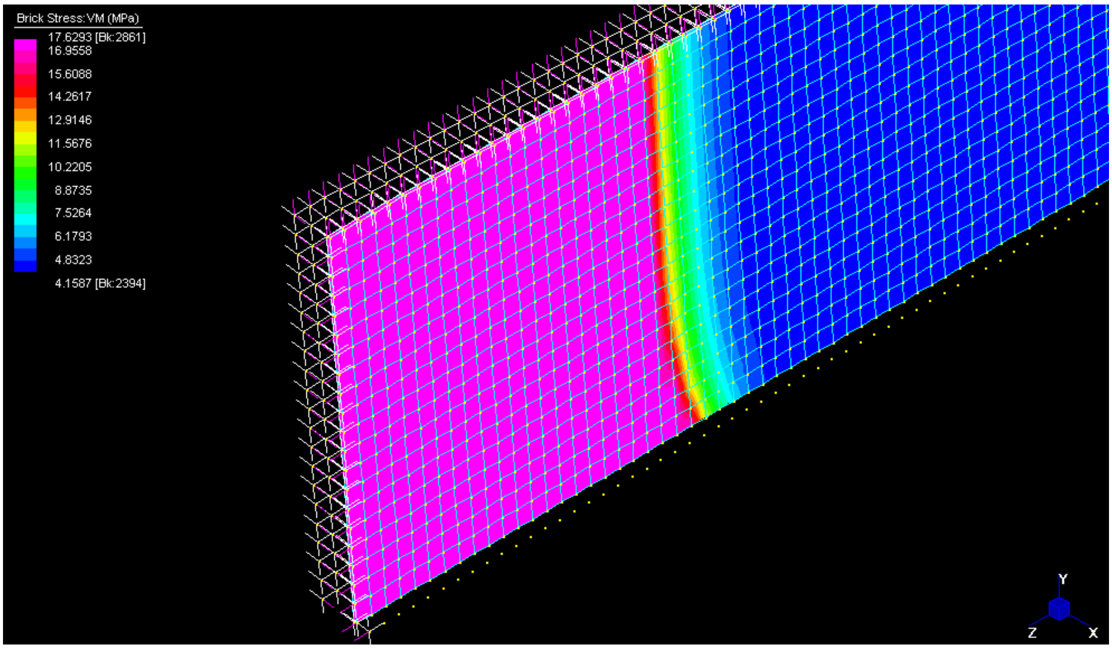

Figure 7: Maximum Von Mises stress for adhesive layer at a high load level.

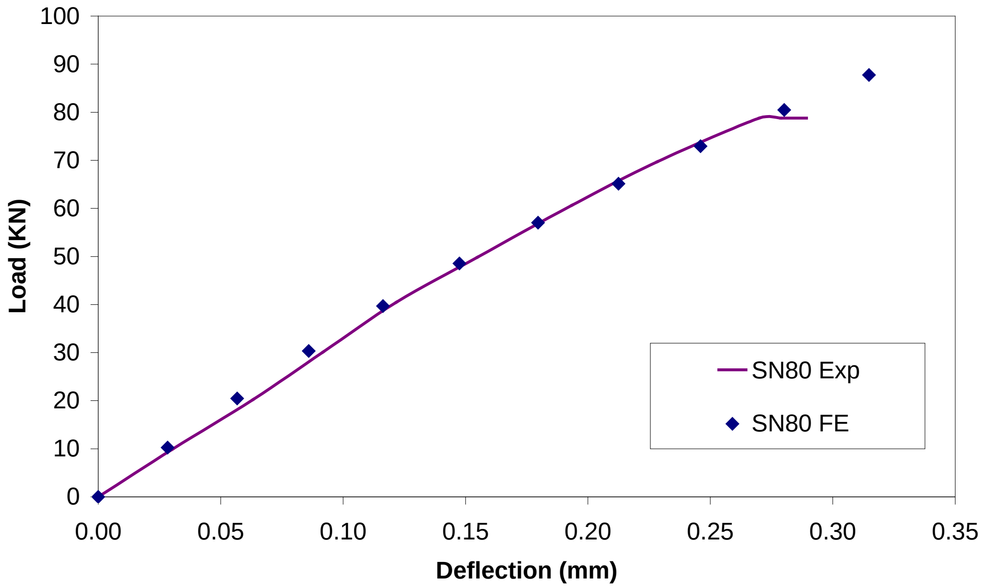

Figure 8: Load vs Deflection for bond length 80mm.

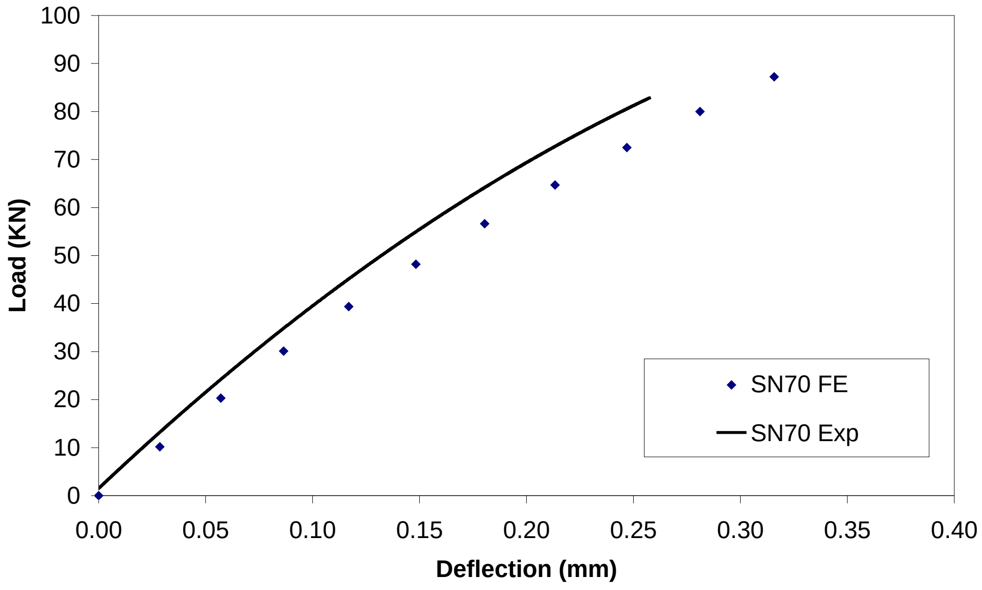

Figure 9: Load vs Deflection for bond length 70mm.

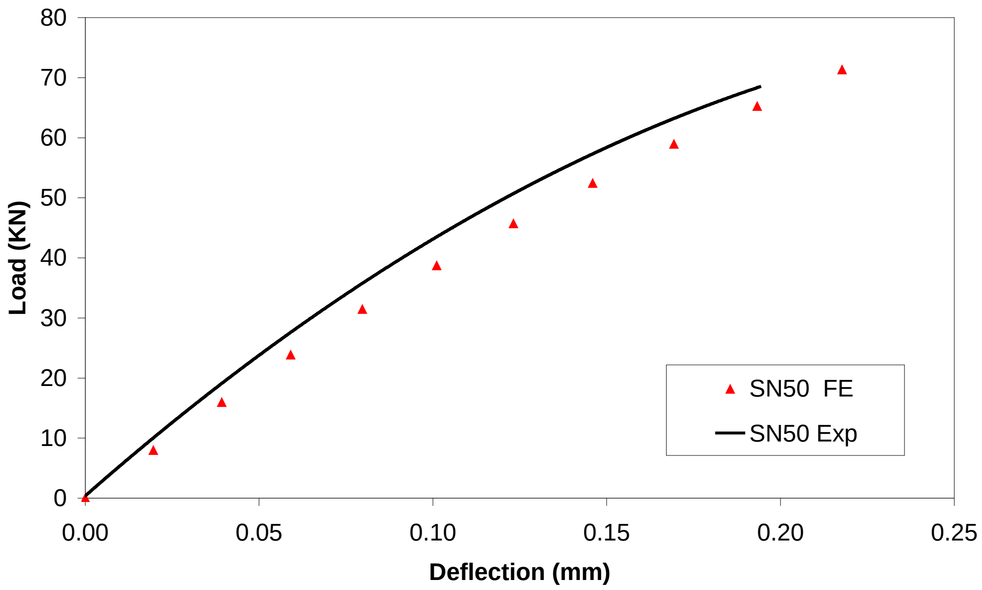

Figure 10: Load vs Deflection for bond length 50mm.

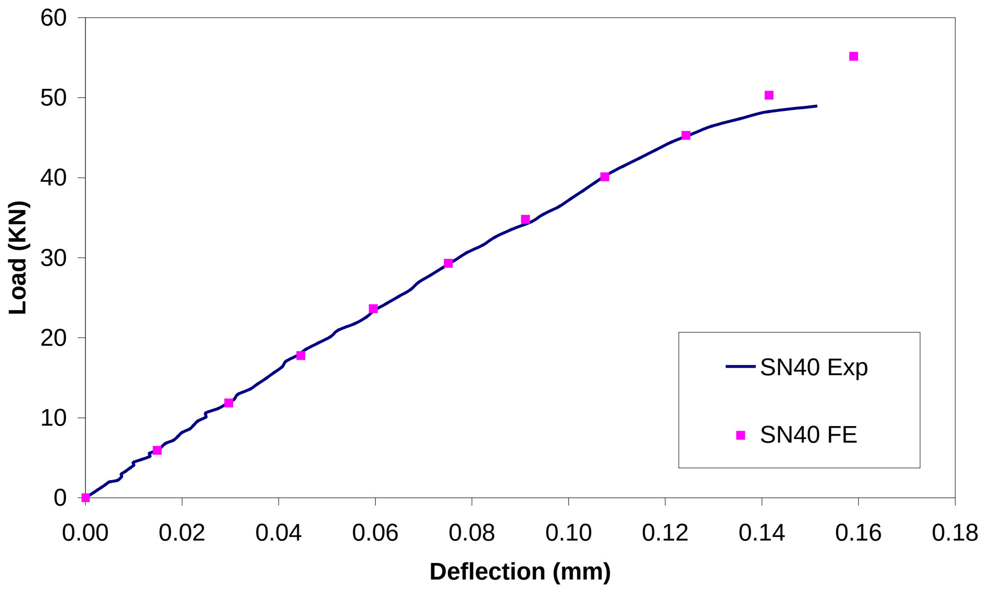

Figure 11: Load vs Deflection for bond length 40mm.

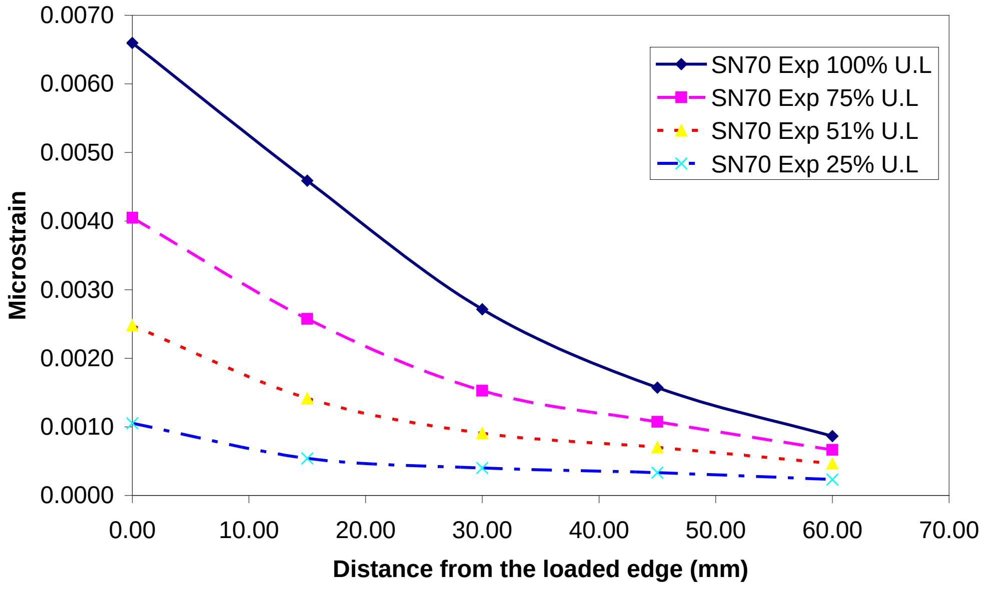

Figure 12: Distribution of strain along the distances from the loaded edge for bond length 70mm.

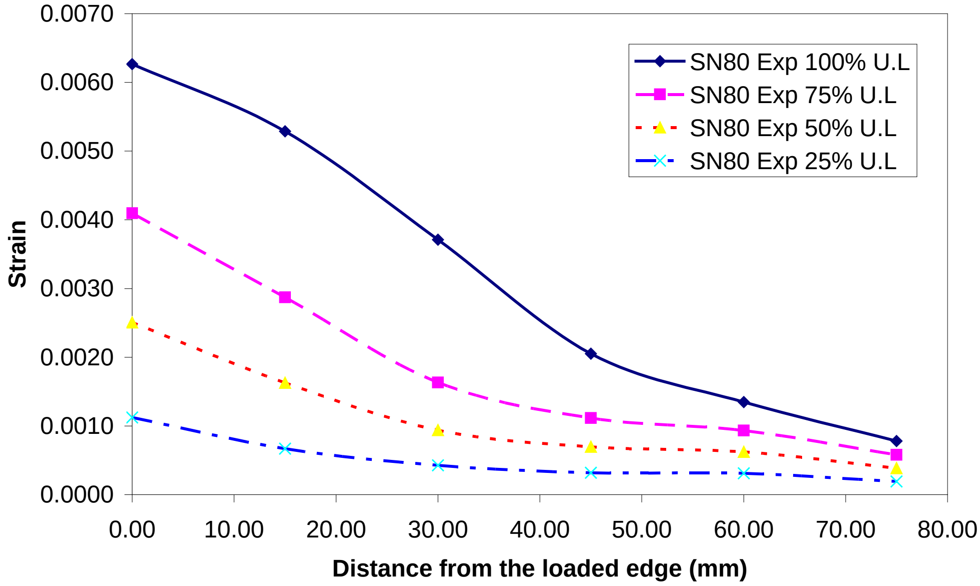

Figure 13: Distribution of strain along the distances from the loaded edge for bond length 80mm.

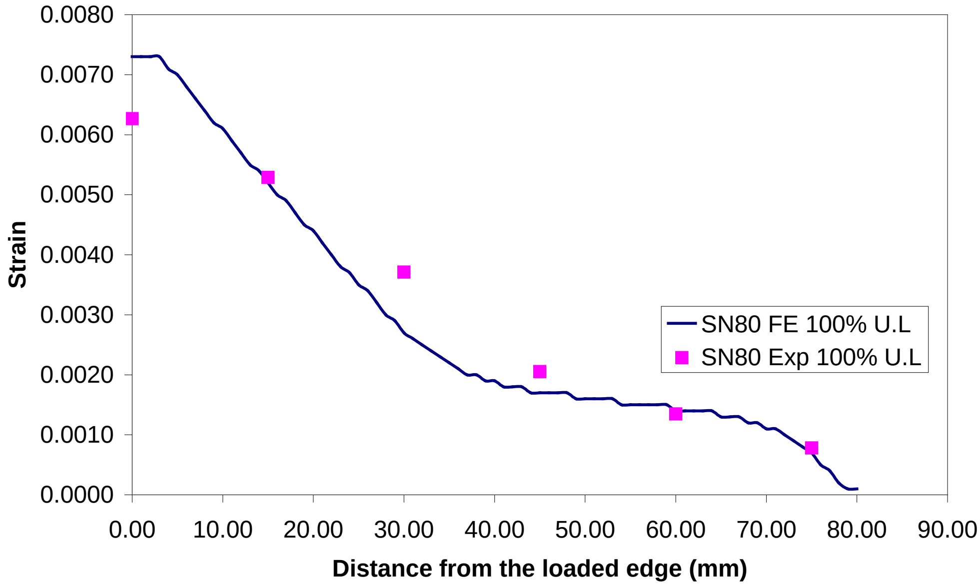

Figure 14: Comparison of experimental strain distribution with FE along the distances from loaded edge for bond length 80mm (at 100 % U.L)

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

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

Table 3: Comparison of experimental and FE results

Bond length (mm)	Experimetal failure load P_{exp} (kN)	Finite element failure load P_{fe} (kN)	P_{fe}/P_{exp}
40	49.9	55.2	1.106
50	69.8	71.3	1.022
70	80.8	87.2	1.080
80	81.3	87.7	1.079
Mean			1.072
COV			0.033