# Modeling and Analysis of CFRP Strengthened Steel Joints

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Abstract: This paper highlights the performance of carbon fiber reinforced polymers (CFRP) strengthened steel joints. An accurate simulation of the joint was presented using a nonlinear 3-D finite element model. Both material and geometrical nonlinearities were considered. The interface between the steel plate and the FRP laminate was modeled using a bi-linear and a tri-linear bond slip relationships representing the contact and bond behavior between the components. The model was utilized to investigate the most effective parameters on the specimen's performance. The studied specimens were strengthened using normal to ultra-high modulus FRP laminates. Different bond lengths between the steel plate and CFRP laminate were studied. The adhesive thickness affected the slippage between the components of the specimen, while the FRP thickness affected its load carrying capacity.

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**Keywords**: Steel plate, FRP (Fiber Reinforced Polymer), Strengthening, Finite element analysis.

## 1. Introduction

The use of FRP material for the repair and rehabilitation of steel members has numerous benefits over the traditional methods of bolting or welding of steel plates. Strengthening steel structures using FRP composites has many advantages over using steel plates such as its high strength-to-weight ratio, ease and speed of transportation and installation, reducing disturbance to services and traffic. Another significant advantage is the ability of such FRP laminates to follow curved and irregular surfaces of a structure, which is difficult to achieve using steel plates. In addition, carbon fibers show the greatest resistance to fatigue. As a rough indication, if the loads in carbon reinforced composites are below half of the long term strength then fatigue is unlikely to be a problem **(Moy, 2001)**

During the last twenty years, many experimental and analytical approaches were conducted to examine strengthening concrete structures with FRP materials; **(Lu et.al., 2005, Mohamed et.al., 2008, Lau and Pam 2010 and** P. Cornetti and Carpinteri **2011).** However, strengthening steel structures using FRP composites experienced limited developments. This was due to the need of a strong strengthening material with steel because of its high strength values compared to concrete **(Teng et.al., 2012).**

Few researches were performed to study the bond-slip relationship between FRP and steel elements. **Xia and Teng (2005)** noticed some errors in the interfacial stresses and strains when the strain gauges were installed on the CFRP surface instead of the adhesive surface. The accuracy of the results can be affected by the distance between the adjacent strain gauges as well. However, the load displacement curves and the effective bond-length showed true results with the new places of the strain gauges. They proposed a simple bi-linear bond-slip relationship shown in Figure 1. This relationship consists of a linear ascending branch followed by a linear descending one. They noted the need for more studies to determine the parameters of this model. **Fawzia et al. (2010)** presented relations between the values of $\delta_1$, $\delta_f$ in Figure 1 and the thickness of adhesive layer.

A number of researchers **(Xia and Teng 2005, Fawzia et.al., 2005 and Dawood and Rizkalla 2006)** noticed that the slope of elastic part in Figure 1 obtained from experimental results is smaller than the stiffness calculated from the elastic properties of the adhesive. They claimed that this difference was due to ignoring the nonlinear properties of the adhesive in the bilinear model. **Dehghani et al., (2012)** proposed a new tri-linear numerical bond-slip model by adding a plastic part to the conventional bi-linear model, as shown in Figure 2. This was to resolve the difference between the experimental results and the calculated elastic stiffness. He concluded that the ultimate debonding load is independent from the adhesive thickness.

The main objective of this paper is to develop an efficient nonlinear 3-D finite element model to study the effective parameters which influence the bond between CFRP laminates and steel plates. This was achieved using the finite element program ANSYS**.** The obtained results from the finite element analysis were verified against the test results performed by **Fawzia et al. (2006) and Xia and Teng (2005).** Parametric studies were carried out to investigate the effect of the changes in the CFRP elastic modulus, CFRP thickness, bond length, adhesive elastic modulus and adhesive thickness.

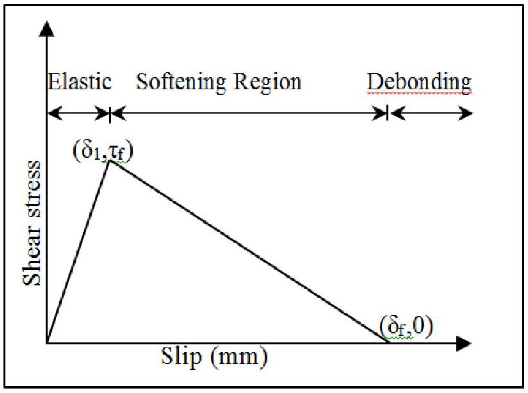


**Figure 1**. Bilinear Bond-Slip Model, [7]

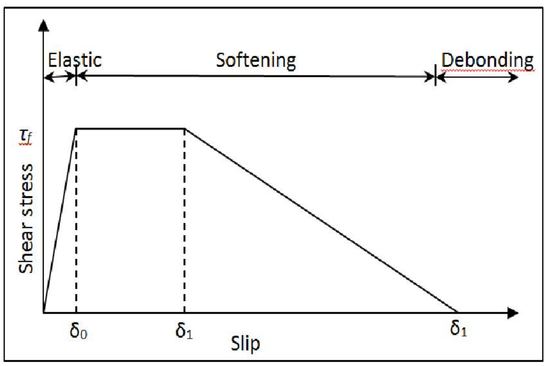


**Figure 2**. Tri-linear Bond-Slip Model, [11]

## 2. Finite Element Modeling and Material Properties

The simulation was implemented using Finite Element Program ANSYS. A three dimensional model was constructed taking into consideration material and geometric nonlinearities. A typical shape of the finite element model is shown in Figure 3.

### 2.1. Steel

The steel sections were modeled using a three dimensional 8-Node Structural Solid Shell element. It is used for simulating shell structures with a wide range of thickness (from thin to moderately thick). It has three translational degrees of freedom at each node. The element has many features which helped in simulating the studied material; ANSYS **program [12].** The number of solid elements representing the steel plates was significantly increased to avoid large aspect ratio and obtain the desired accuracy. This in turn increased the computational time, however it was reasonable and never been too long. The material behavior of the steel sections was isotropic with properties as stated in the compared researches.

### 2.2. CFRP

The CFRP was modeled as an orthotropic material. The same three dimensional 8-node structural solid shell element was utilized to model the CFRP laminate. The CFRP is primarily stressed in the fiber direction, so the modulus in the fiber direction is the more important parameter. The values of the moduli were taken from the compared researches.

### 2.3. CFRP–Steel Interface

Special attention needs to be paid when modeling adhesive bonding between steel and FRP. The adhesive layer was modeled as spring elements with specified load-slip curves. In addition, contact elements were utilized to insure separation and prevent penetration between the different elements of the model. Two techniques were utilized for the spring element to identify the best in representing the bond-slip relationship. The first model is a simple bi-linear bond-slip relationship presented by **Xia and Teng (2005)**, while the second is a tri-linear bond-slip relationship presented by **Dehghani et al., (2012).**

In the first model; the first branch of the relation was a linear ascending line representing a linear elastic state with a high initial stiffness. At the end of this stage, the ultimate load was attained. Initiation of the interfacial softening stage means that the load continues to increase as the length of the softening zone increases. The second branch was a linear descending line, until the maximum slip is reached. The relationship depended mainly on three parameters; $\tau_f$, $\delta_1$, $\delta_f$. Where $\tau_f$ is the adhesive maximum shear stress (MPa), $\delta_1$, $\delta_f$ are the initial and maximum slip (mm) respectively, as shown in Figure 1. This model was represented by the coordinates of the peak and the ultimate points were derived from the experimental data of **Xia and Teng (2005).** The maximum shear stress in the adhesive $\tau_f$ was taken about 80% of maximum tensile strength.

$$\tau_f = 0.8 f_{t,a} \ldots\ldots\ldots\ldots(1)$$

where $f_{t,a}$ is the maximum tensile strength of adhesive. The second model is a tri-linear bond-slip model as shown in Figure 2. The slop of the ascending part in the model was calculated based on the elastic properties of adhesive. The yield displacement ($\delta_0$) was calculated by equation (2). Where $G_a$ and $t_a$ are modulus of elasticity and thickness of adhesive. The fracture displacement ($\delta_f$) and the displacement corresponding to the start of softening part; ($\delta_1$) were calculated according to equations (3) and (4). **Dehghani et al., (2012)** found experimentally that the ultimate debonding force does not change by adhesive thickness variation.

Consequently, the area under the bond-slip curve should be independent of the adhesive thickness. The empirically calculated interfacial fracture energy equals to this area.

$$\delta_0 = \frac{\tau_f}{G_a} t_a \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

$$\delta_f = \frac{3G_f}{2\tau_f} + \frac{3}{4}\delta_0 \ldots\ldots\ldots\ldots\ldots\ldots(3)$$

$$\delta_1 = \delta_f/3 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4)$$

### 3. Model Verification

This model was verified by comparing the results of the suggested model with the experimental tests performed by **Fawzia et al. (2006) and Xia and Teng (2005)** with the load applied to the steel plate and the FRP layer respectively. In the first specimen, mild steel plates (210 mm in length, 50 mm in width and 5 mm in thickness) were strengthened by three layers of CFRP on each side. The adhesive was applied between the steel plates and the CFRP, and between the different layers of the CFRP sheets. Since the common mode of failure was bond failure, the three CFRP layers together with two layers of adhesive were considered as one layer having an equivalent thickness and equivalent modulus calculated by equation (5) as suggested by **Fawzia et al. (2006).**

$$E_{e,CFRP} = \frac{E_a t_a + E_f t_f}{t_a + t_f} \quad \ldots\ldots\ldots\ldots\ldots(5)$$

Where $E_a$ and $E_f$ are the tensile moduli of the adhesive and CFRP, respectively, while , $t_a$ and $t_f$ are the total thickness of the adhesive and carbon fibre layers respectively.

The second specimen; tested by **Xia and Teng (2005)**; composed of a steel block formed by welding steel plates to two rectangular hollow sections. The steel plates dimensions were 355 mm long × 118 mm wide × 12 mm thick. CFRP plate with modulus of elasticity of 165 Gpa and with dimensions 350 mm long × 50 mm wide × 1.2 mm thick was bonded to the steel plate using adhesive thickness of 2mm. The tensile strength of the adhesive was 22.53 Mpa, the young's modulus was 4013 Mpa while the Poisson's ratio was 0.36.

The analysis showed that using the bilinear load-slip relation produced less accurate results than the tri-linear load-slip relation. This is due to the difference in the slope of the elastic part of the load-slip curves between the experimental and the proposed bilinear relation. The comparison depended mainly on the load-displacement relation and the ultimate load. The ultimate loads of the two analyzed specimens obtained from the finite element models were 1.025 and 0.97 of the corresponding experimental results. Figures 4 and 5 show the load-displacement curves. These reasonable results insure the reliability of the model.

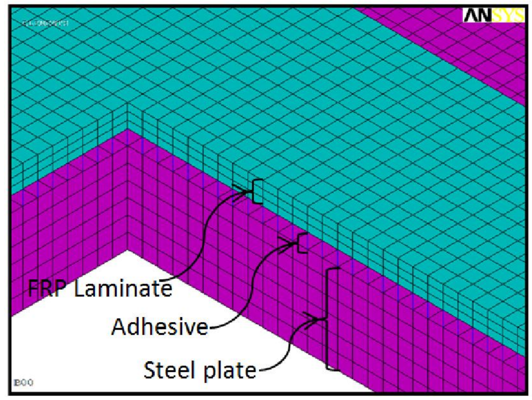


**Figure 3**. Finite Element Model of CFRP Strengthened Steel Joint

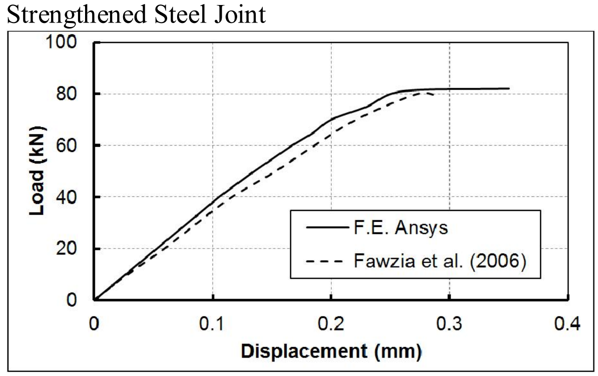


**Figure 4**. Comparison of Load-Displacement Curves with **Fawzia et al., (2006)**

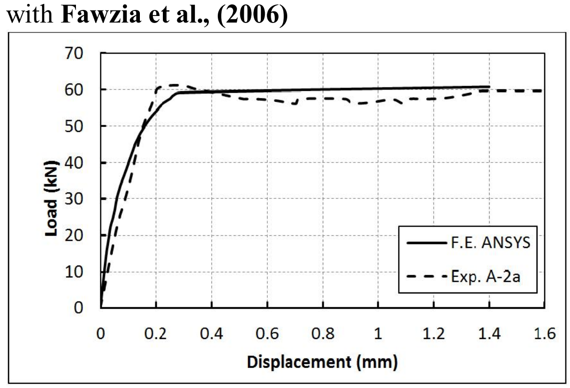


**Figure 5.** Comparison of Load-Displacement Curve with **Dehghani et al., (2012)**

### 4. Parametric Analysis

#### 4.1. CFRP Thickness

The thickness of the CFRP layer was varied from 0.5 mm to 3 mm in 0.5 mm increments as detailed in Table 1. Failure was noticed in the CFRP layer in specimens with CFRP thickness 0.5 and 1.0 mm. with the increase of the fiber thickness, the failure was directed to the adhesive layer with approximately equal failure load, as shown in Figure 6.

### 4.2. FRP Bond Length

The study was carried out for specimens with bond lengths of 40, 60, 80, 100, 120, 150, 200 mm, as detailed in Table 1. It was noticed that the strains were very high near at the edge and decreases gradually along the strip as shown in Figure 7. The effective bond length of the studied specimens was about 100 mm. This length was the distance at which the strain almost vanished. The maximum sustained load by the specimen noticeably increased with the increase of the bond length then the rate of increase was decreased, as shown in Figure 8. This indicates that increasing the bond length more than the effective bond length does not have a significant enhancement on the specimen behavior.

### 4.3. FRP Elastic Modulus

Four specimens of steel strengthened joints with CFRP laminates were analyzed using different CFRP elastic modulus varying from ultra-high modulus to normal modulus, as detailed in Table 1. It was found that the reinforced steel specimens with ultra-high modulus laminate have a lower ultimate load in tension as compared to plates strengthened with normal modulus laminates, as shown in Figure 9. This is due to the inverse relation between the elastic modulus of the FRP laminates with their tensile strengths.

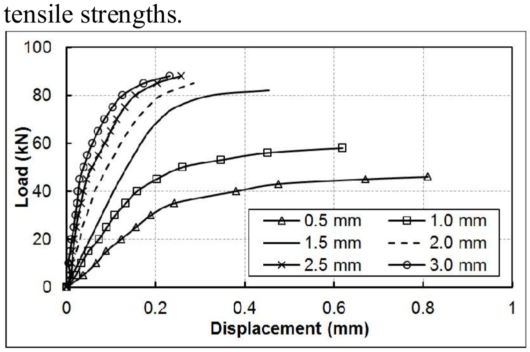


**Figure 6**. Effect of Changing CFRP thickness

### 4.4 Adhesive Elastic Modulus

The adhesive modulus of elasticity was varied from about 2 Gpa to 14 Gpa, as summarized in Table 1. The thickness of the adhesive layer was maintained at 1.5 mm. Since the controlling failure material in the steel specimens strengthened with the FRP layers is the adhesive, it was noticed that the magnitude of the failure load and the peak stresses were increased with the increase of the adhesive modulus of elasticity. The adhesive which has low modulus of elasticity shows small initial and maximum slip than others with high modulus of elasticity.

**Table 1.**

| Specimen | FRP | | Adhesive | | Bond length (mm) |
|---|---|---|---|---|---|
| | t mm | E Gpa | t mm | E Gpa | |
| A01 | 0.5 | 215 | 0.2 | 2 | 80 |
| A02 | 1.0 | 215 | 0.2 | 2 | 80 |
| A03 | 1.5 | 215 | 0.2 | 2 | 80 |
| A04 | 2.0 | 215 | 0.2 | 2 | 80 |
| A05 | 2.5 | 215 | 0.2 | 2 | 80 |
| A06 | 3.0 | 215 | 0.2 | 2 | 80 |
| B01 | 1.5 | 215 | 0.2 | 2 | 40 |
| B02 | 1.5 | 215 | 0.2 | 2 | 60 |
| B03 | 1.5 | 215 | 0.2 | 2 | 100 |
| B04 | 1.5 | 215 | 0.2 | 2 | 120 |
| B05 | 1.5 | 215 | 0.2 | 2 | 150 |
| B06 | 1.5 | 215 | 0.2 | 2 | 200 |
| C01 | 1.5 | 165 | 0.2 | 2 | 80 |
| C02 | 1.5 | 300 | 0.2 | 2 | 80 |
| C03 | 1.5 | 460 | 0.2 | 2 | 80 |
| D01 | 1.5 | 215 | 0.2 | 4 | 80 |
| D02 | 1.5 | 215 | 0.2 | 6 | 80 |
| D03 | 1.5 | 215 | 0.2 | 8 | 80 |
| D04 | 1.5 | 215 | 0.2 | 10 | 80 |
| D05 | 1.5 | 215 | 0.2 | 12 | 80 |
| D06 | 1.5 | 215 | 0.2 | 14 | 80 |
| E01 | 1.5 | 215 | 0.4 | 2 | 80 |
| E02 | 1.5 | 215 | 0.6 | 2 | 80 |
| E03 | 1.5 | 215 | 0.8 | 2 | 80 |
| E04 | 1.5 | 215 | 1.0 | 2 | 80 |
| E05 | 1.5 | 215 | 1.2 | 2 | 80 |

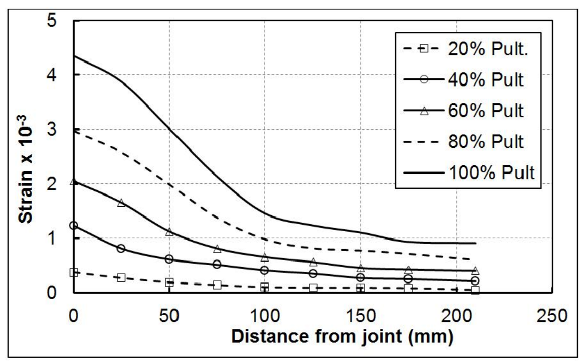


**Figure 7**. Strain Distribution along the Bond Length

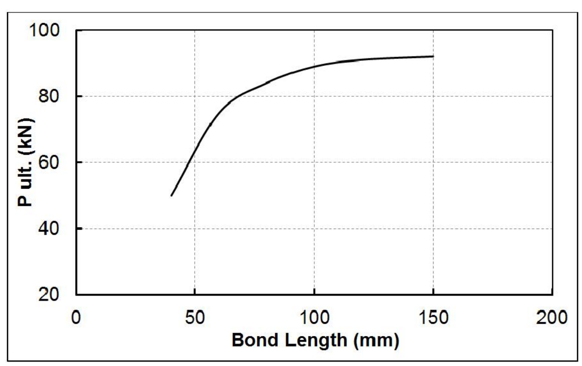


**Figure 8**. Relation between bond length and maximum load

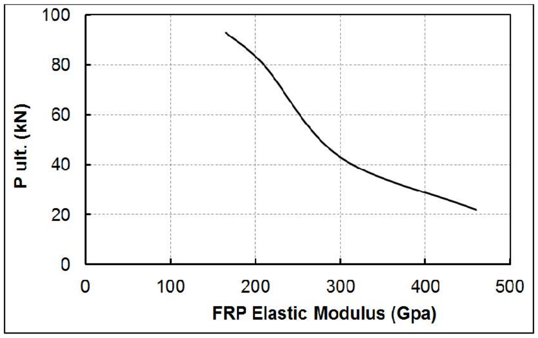


**Figure 9**. Effect of CFRP Elastic Modulus on the Ultimate Load

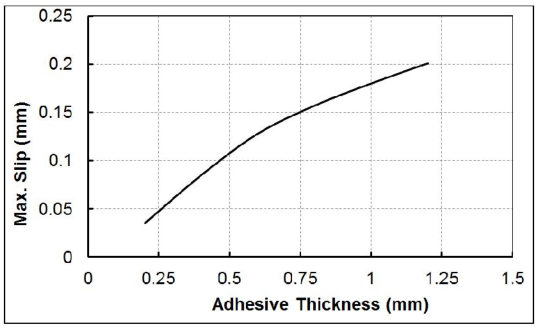


**Figure 10**. Effect of Adhesive Thickness

### 4.5 Thickness of Adhesive layer

The most noticeable effect of the thickness of the adhesive layer was on the slippage values between the FRP and the steel plate. Six specimens with adhesive thicknesses of 0.2, 0.4, 0.6, 0.8, 1.0 and 1.2 mm were analyzed. A directly proportional relation between the adhesive thickness and the slippage was found and the relation was plotted in Figure 10. In experimentally tested specimens, increasing the adhesive thickness affects the failure mode of the specimen. It might direct the failure to happen in the adhesive layer (cohesive failure). However in the finite element analysis, increasing the thickness of the adhesive layer did not influence the specimen in the same way.

## 5. Conclusion

A 3-D nonlinear finite element model for FRP strengthened steel joints was presented. The interfaces between the steel plates and the FRP laminates have been considered allowing the contact and bond behavior to be modeled. The bi-linear bond-slip relation shoed acceptable results at the beginning of loading stages, however the tri-linear model was more accurate.

In CFRP strengthened steel joints, failure is controlled by the CFRP thickness. Increasing the CFRP thickness directs failure to occur at the adhesive layer. A direct proportional relation between the thickness of the adhesive layer and the slippage between the components of the joint.

Normal elastic modulus CFRP laminates showed a better performance than ultra-high modulus CFRP laminates in specimens subjected to tensile stresses, since a large strain increment in the steel beneath the laminate edge are expected to occur, and due to the inverse relation between the elastic modulus of the CFRP laminates with their tensile strengths as well.

Increasing the bond length higher than the effective bond length has a negligible effect on the specimen carrying capacity. On the other hand, the magnitude of the failure load and the peak stresses of the strengthened joint is noticeably enhanced with the increase of the adhesive modulus of elasticity.

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