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INVESTIGATING THE INFLUENCE OF STEEL SURFACE ROUGHNESS AND MULTIPLE CFRP LAYERS ON THE BONDING BEHAVIOUR OF A SINGLE-STRAP JOINT

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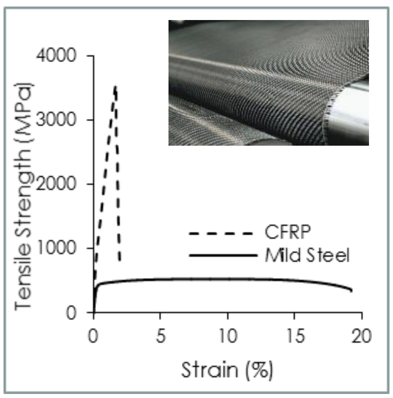
Graphical abstract



Tensile stress-strain relationships of steel and CFRP materials

Abstract

Three series of steel-plate single-strap joints bonded by Carbon-Fibre Reinforced Polymer (CFRP) sheets, which are used with an adhesive material, are investigated in this study. Experimental and finite element (FE) analyses using ABAQUS software are employed for this purpose. The main objective of this study is to provide further understanding of the bonding mechanism of strengthened single-strap joints under a pure-tension load. The experimental tests specifically investigated the effects of using multiple CFRP layers with normal/high steel surface roughness on the bonding failure mode, bond-load capacity, and effective bond length. Furthermore, the FE analysis was used to establish the shear stress-slip relationships of the suggested specimens. The results showed that the bond capacity (ultimate bond load) of single-strap joint did not increased much when the CFRP bonding length pass the effective bond length (limit). The bonding capacity (ultimate bond load) of single-strap joint increased only of about 14% when increase d the CFRP layers from two to four. Moreover, the behaviour of the shear stress-slip relationship was not significantly affected by increasing the number of CFRP layers.

Keywords: Single strap joint, CFRP, FE analysis, debonding failure, effective bond length

Abstrak

Tiga siri sendi satu tali plat keluli yang diikat oleh lapisan Polimer yang diperteguh dengan Gentian Karbon (CFRP) sheets, yang digunakan dengan sebagai bahan pelekat, dikaji dalam kajian ini. Analisis elemen eksperimen dan terhingga (FE) menggunakan perisian ABAQUS digunakan untuk tujuan ini. Objektif utama kajian ini ialah untuk memberi kefahaman yang lebih terhadap mekanisme ikatan sendi satu tali yang diperkukuhkan di bawah beban tegang. Ujian eksperimen mengkaji secara khusus kesan menggunakan pelbagai lapisan CFRP dengan kekasaran permukaan keluli biasa/tinggi ke atas mod ikatan gagal, kapasiti ikatan-beban, dan panjang ikatan yang efektif. Tambahan pula, analisis FE digunakan untuk menentukan perhubungan tegasan ricih-gelinciran spesimen yang dicadangkan. Hasilnya menunjukkan bahawa kapasiti (Beban bon muktamad) ikatan satu tali tunggal tidak banyak meningkat apabila panjang ikatan CFRP melepasi panjang (had) efektif. Kapasiti ikatan (beban ikatan muktamad) sendi tali tunggal meningkat hanya kira-kira 14% apabila meningkatkan lapisan CFRP dari dua hingga empat. Tambahan lagi, ciri-ciri perilaku perhubungan tegasan ricih-gelinciran tidak terjejas secara signifikan oleh bilangan lapisan CFRP.

Kata kunci: Sendi satu-tali, CFRP, analisis FE, kegagalan nyah-ikatan, panjang ikatan yang efektif

1.0 INTRODUCTION

Recently, steel members have been highly recommended for use in several modern structures. This type of structural member has been widely applied in the construction of warehouses, aircraft hangars, multi-story buildings, and car/walkway bridges. Steel members may require repairs for various reasons, such as degradation as a result of aging, environment, fatigue, fire, and/or upgrade out of necessity to carry extra loads. However, the conventional methods of repairing and strengthening existing steel members by replacing or adding new steel parts through welding/bolting leads to increased project costs because these methods require heavy equipment and considerable working time, also could be increase the possibility of fatigue problems [1]. Therefore, Carbon-Fibre Reinforced Polymer (CFRP) composite material has become the most suitable solution for repairing and upgrading steel structural members [2]. This type of composite material has a tensile-strength capacity and elastic modulus that are higher than those of steel on the basis of its weight ratio. Furthermore, CFRP sheets perform effectively in resisting environmental degradation, and CFRP is a flexible material that can be shaped any member.

Several studies have discussed the strengthening behaviours of steel members using FRP materials in general. Zhao and Zhang [2] prepared a qualified review article that included the bond test methods, bond strength, bond-slip relationship, and bond failure modes of CFRP and steel. Further research specifically investigated the bonding interaction behaviours (bond mechanism) between CFRP sheets and steel plates under static and/or dynamic tension loads [3-17], for example. So far, few studies have investigated particularly the single-strap steel joints that are bonded using CFRP sheets [4-6]. Further parameters that are expected to directly affect the bonding behaviour of single-strap joints needs deep investigation, such as multiple CFRP layers, various CFRP thicknesses, CFRP types, adhesive types, adhesive curing conditions, and steel surface's roughness.

Therefore, the main objective of this study is to specifically investigate the influence of using multi-CFRP layers to bond a steel-plate single-strap joint, which has normal and high surface roughness with regard to the ultimate load, failure mode, and effective bond length. A number of steel specimens bonded along various lengths have been tested experimentally under direct tensile loads in the structural laboratory of Universiti Kebangsaan Malaysia (UKM). Finite element (FE) analysis was adopted as well using ABAQUS software to implement the shear stress-slip relationship of this joint type, which bonded with 2 and 4 CFRP layers. The results were compared to the existing theoretical approach given by Xia and Teng [18].

2.0 METHODOLOGY

To investigate the effects of the bonding behaviour of a single-strap joint, three series of CFRP-steel specimens were subjected to pure tension loading. A total of 20 specimens were suggested to study the effects of multiple CFRP layers (2 and 4 layers) bonded along steel plates with normal and high interaction surface's roughness. The steel surface roughness was increased by providing artificial tiny scratches/grooves to improve the mechanical bond that interlocks with the adhesive material. Each specimen was prepared mainly from two pieces of steel plates with a total length of 500 mm, a width of 25 mm, and a thickness of 8 mm, as shown in Figure 1. Each steel plate was prepared from two steel plates (4 mm thick for each), where welded together along full of their lengths from both sides. The fixed length (L2) was suggested to be sufficiently long (250 mm) to ensure that failure would occur on the side with various bonding/lapping lengths (L1) which is rating from 20 mm to 140 mm.

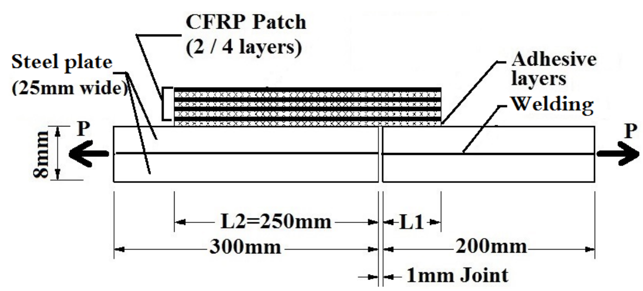


Figure 1 Geometry of the specimens

2.1 Material Properties

Steel plates of 4 mm thickness and 25 mm width were tested in accordance to ASTM-E8/E8M (2009) [19]. The average values of the steel-yielding strength, ultimate tensile strength, and modulus of elasticity that were recorded from the tensile tests of two coupons were 322 MPa, 463 MPa, and 196 GPa, respectively.

A SikaWrap-231C unidirectional CFRP sheet of 0.13 mm thickness manufactured by Sika Kimia-Malaysia was chosen for this experimental study. Three coupons were prepared in accordance to ASTM-D3039 (2000) [20] and were tested under a direct tensile load. The average results of the coupon tests were 3224 MPa, 1.65%, and 228.8 GPa for ultimate tensile strength, strain at break fibre, and modulus of elasticity, respectively, whereas, the nominal properties from the manufacturer were 4900 MPa, 2.1%, and 230 GPa.

Sikadur-330 adhesive material (epoxy) was used in this study as an adhesive material. This type of epoxy mainly consists of two parts resin: hardener mixed with a ratio of 4:1 (by weight). The nominal properties are a 30 MPa tensile strength, 3.8 GPa flexural E-modulus and 0.9% elongation at break (as given in the manufacturer data sheet).

2.2 Specimen Preparation and Test Setup

Usually, the grit blasting it has to be used for cleaning and preparing the surface of steel members before apply the epoxy and CFRP materials. However, with absence of this facility (grit blasting), a low-speed grinder with sandpaper disc (grit #24) was used to grind and clean the steel samples from one side along the overall bonding lengths (L2 + L1). The specimens selected to have high surface roughness were prepared by creating tiny artificial scratches/grooves using the sharp head of a steel hammer. After the surfaces of the specimens were prepared and before the CFRP sheets were applied, the surfaces were cleaned with acetone to remove all contaminants, including dust, rust and oil, as shown in Figure 2.

The adhesive material was mixed as per the manufacture recommendations, then applied uniformly along the bonding lengths of steel plates. The first layer of the CFRP sheet was laid on top of the adhesive layer and then lightly pressed using a ribbed roller to ensure uniform adhesive thickness as much as possible, also to remove the voids remaining in the adhesive layer. This procedure was repeated for each CFRP layer. Transverse wrapping was applied along the fixed length side (L2) for some samples to provide extra strength, specifically for those with long bond lengths (L1). All of the samples were left for curing at room temperature for approximately 14 days till the day of testing. The average thickness of the overall adhesive layers of each specimen was measured after the curing, which was performed by calculating the total thickness of the specimen and then subtracting this value from the thicknesses of the steel plate and CFRP layers. After that, the average thickness of each adhesive layer was estimated by dividing the thickness of the overall adhesive layers by the total number of adhesive layers. Each specimen was subjected to direct tensile load using a 100 kN universal testing machine, as shown in Figure 3. The load was applied using a constant displacement rate of 1 mm/min. The failure mode and value of the maximum load were recorded for each of the tested specimens.

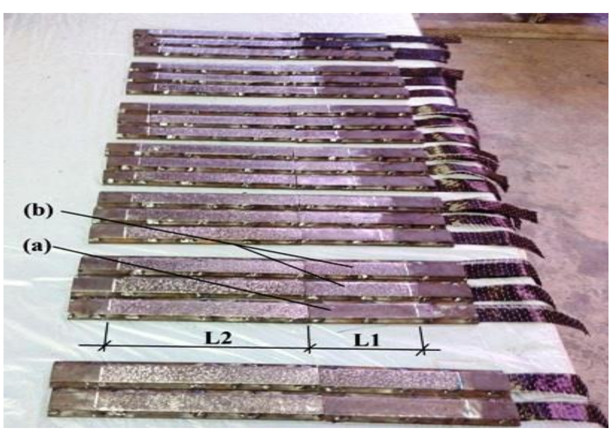


Figure 2 Test specimens of (a) grinded surface only (b) grinded surface with artificial scratches

Figure 3 Test setup

2.3 Finite Element Modelling

In this research, Nonlinear FE analysis was used to perform tensile testing simulations on steel plate single-strap joints that were bonded with multiple CFRP layers, also to implement the shear stress-slip relationship for this type of joints. The FE model (FEM) was developed using the ABAQUS/CAE 6.9 software. Each FEM has three different materials that represent the actual specimens (steel, CFRP sheets, and adhesive materials). The steel was modelled with the element type C3D8R, a 3-D solid element with an eight-node linear brick-reduced integration, whereas the element type S4R was selected for the CFRP patch (2 and 4 layers).

Only one fourth (quarter model) of the specimen was modelled because of the specimen is symmetric, as shown in Figure 4. The uniform displacement increment was applied along the steel plate's edge to simulate the tensile loading (P) which was done in the experiments. The CFRP sheets was bonded to the surface of the steel plate from the top side. Each layer of CFRP has a thickness of 0.13 mm, as indicated by the manufacturer. The average thickness of each adhesive layer used in the FEM was 0.85 mm, as measured after the preparation of the specimen was completed. The CFRP patch technique is proposed here to represent the multiple CFRP layers, including the intermediate adhesive layers, by transferring them to one equivalent layer (CFRP patch), as adopted in similar valid numerical studies [21-23]. However, the adhesive layer laid between the steel plate and the CFRP patch was modelled independently in the FEM as a 'Cohesive Behavior' interaction, which is available in ABAQUS. This type of interaction enables the nodes located along the surface between the two adherent materials (steel and CFRP patch) to break after achieve the ultimate shear and/or tension stress limits of the adhesive material (epoxy), which is perfectly can representing the actual CFRP-steel debonding failure. In this study, the same adhesive modelling criteria had been used in the previous researches of the same authors [22, 23]. In general, the equivalent thickness, ultimate tensile strength and modulus of elasticity for each CFRP patch which is related to the multilayer sheets and intermediate adhesive layers can be evaluated as follows:

$$t_{cfrp.patch}=n.t_{cfrp}+t_{ad}.(n-1) \quad (1)$$

$$S_{cfrp.patch}=((n.t_{cfrp}.S_{cfrp})+t_{ad}.S_{ad}.(n-1))/t_{cfrp.patch} \quad (2)$$

$$E_{cfrp.patch}=((n.t_{cfrp}.E_{cfrp})+t_{ad}.E_{ad}.(n-1))/t_{cfrp.patch} \quad (3)$$

where, $t_{cfrp.patch}$, t_{cfrp} and t_{ad} are the equivalent thickness of CFRP patch, thickness of single CFRP sheet and the thickness of single adhesive layer, respectively. The $S_{cfrp.patch}$, S_{cfrp}, and S_{ad} are the equivalent ultimate tensile strength of CFRP patch, strength of single CFRP sheet and the strength of single adhesive layer, respectively. While, the $E_{cfrp.patch}$, E_{cfrp} and E_{ad} are the modulus of elasticity of CFRP patch, single CFRP sheet and adhesive layer, respectively

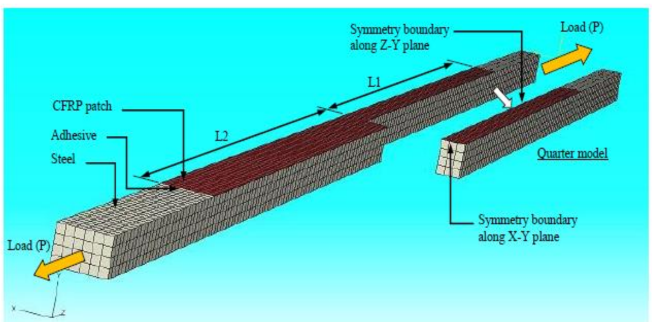
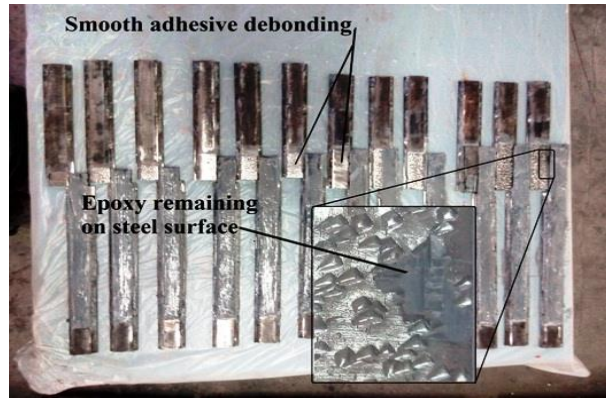


Figure 4 3D-FE model of CFRP-steel single-strap joint with boundary conditions

3.0 RESULTS AND DISCUSSION

3.1 Failure Modes

In general, the results of the tensile tests showed that the failure modes are almost the same for all specimens, and debonding failure was recorded along the steel-adhesive interface along the shorter bonding length (L1). A small amount of epoxy remained stuck on the steel surface of some samples, specifically, those with high surface roughness; this condition occurs because the mechanical bond that interlocks between the steel surface and adhesive material was improved a little as a result of the artificial scratches, as shown in Figure 5.



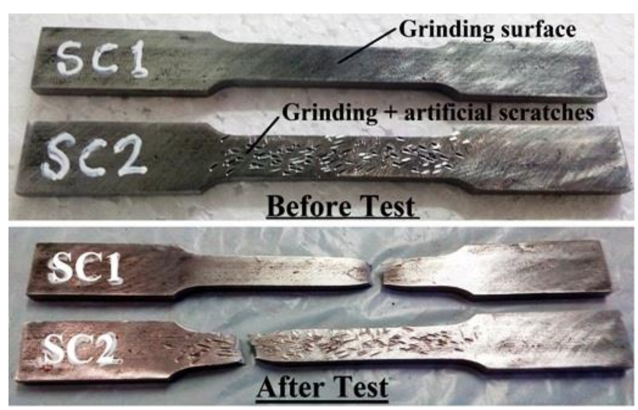
(a) CFRP-steel debonding failure

(b) CFRP rupture failure

Figure 5 Failure modes of tested specimens

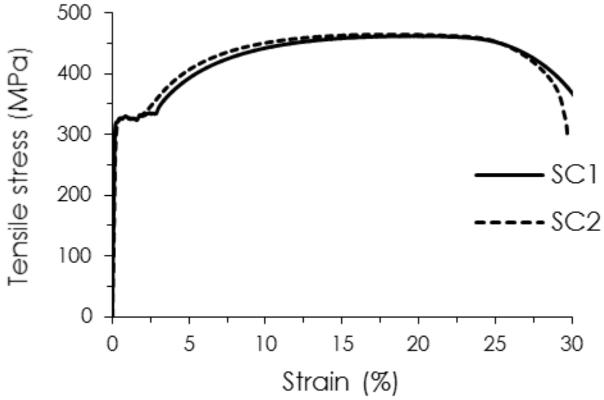
3.2 Effects of Scratches on the Steel Plate Properties

To investigate the effect of the suggested grinding action with/without providing artificial scratches on the steel plate capacity, a tensile test was performed for two coupons of 4-mm thick steel plates. One coupon was grinded only using the sandpaper (SC1), and the second coupon was prepared with artificial scratches after grinding (SC2). The results of these two coupons are presented as a tensile stress-strain relationship in Figure 6, which showed that the tiny artificial scratches did not affect the physical properties of the plates.



(c) Steel coupons

(a)



(d) Tensile stress-strain relationship
(b)

Figure 6 Tensile tests of grinded steel plates with/without artificial scratches

3.3 Effects of the Steel Surface Roughness

The effect of the steel surface roughness was investigated on the bond load capacity with reference to the same bond length (L1). The ultimate loads obtained from the experimental (Exp.) tests of specimens bonded with two CFRP layers (2L) along various L1 are presented in Table 1 and Figure 6. The ultimate bonding loads of the steel specimens with normal surface roughness (NR) are compared to those obtained from specimens with high surface roughness (HR) (the specimens with artificial scratches). This comparison shows that the ultimate bond loads of the HR-2L specimens are higher than those obtained from the NR-2L specimens in general, because of they achieved better mechanical bonds interlocking with the adhesive material.

In general, increasing the bonding length (L1) between the steel plate and CFRP sheets gradually led to increase the bonding strength (bond capacity) up to certain limit, after this bonding length limit, the bond capacity value remains almost constant with no more increment, where this bonding length limit usually called "effective bond length", as shown in Figure 6. The effective bond length and maximum bond loads for both types of specimens (NR-2L and HR-2L) were found to be very close at approximately 80 mm and 13.5 kN, respectively, (see Figure 7). The gap between the ultimate bond loads of NR-2L and HR-2L specimens was observed clearly when their bonding lengths are less than the effective bond length. This gap begins to decrease gradually for specimens with increasing lengths of L1. Therefore, it can be concluded that increasing the degree of surface roughness will not much improve the bonding load capacity, especially when the bonding lengths pass the effective bond limit.

Table 1 Ultimate bond loads of specimens with different surface roughness - 2 CFRP layers

Bond length (L1) (mm)	Ultimate bond load (kN)		Load's ratio (HR-2L / NR-2L)
	Exp. (NR-2L)	Exp. (HR-2L)	
20	5.28	7.70	1.460
40	9.61	11.26	1.172
60	11.67	12.58	1.078
80	14.28	13.76	0.964
100	14.34	12.33	0.860
120	12.81	14.13	1.103
140	13.62	13.74	1.009
Mean value			1.092

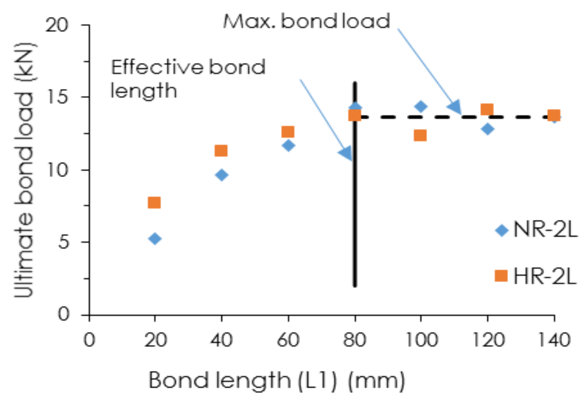


Figure 7 Ultimate bond load - bond length relationship - specimens with different surface's roughness (2 CFRP layers)

3.4 Effects of Multiple CFRP Layers

The effects of using multiple layers of CFRP sheets on the bonding behaviours are investigated in this section. The ultimate bond loads of the specimens have the same surface roughness (HR), but different CFRP layers, as presented in Table 2, with reference to their bonding length (L1). Generally, Table 2 shows that the specimens that bonded with 4 CFRP layers (HR-4L) featured bond loads a little higher than those obtained from specimens that bonded with 2 CFRP layers (HR-2L). The overall mean value of the increasing load ratio (HR-4L/HR-2L) was approximately 1.148. Figure 8 shows that the maximum bond loads of specimens increased from 13.50 kN to 15.4 kN when the CFRP layers increased from 2 to 4, respectively, achieving a load's improvement of about +14.0%. Meanwhile, the effective bond length was not significantly affected by the increasing CFRP layers, which remained at approximately 80 mm. Therefore, it can be concluded that the single-strap joint that bonded with the 4 CFRP layers did not double the bond load capacity of the same specimen that bonded with 2 CFRP layers, and increasing the CFRP layers would not increase/decrease the effective bond length.

Table 2 Ultimate loads of specimens bonded with multiple CFRP layers

Bond length (L1) (mm)	Ultimate bond loads (kN)		Load's ratio (HR-4L / HR-2L)
	Exp. (HR-2L)	Exp. (HR-4L)	
20	7.70	9.32	1.210
40	11.26	12.53	1.112
60	12.58	13.76	1.094
80	13.76	16.20	1.177
100	12.33	15.20	1.233
120	14.13	14.98	1.060
Mean value			1.148

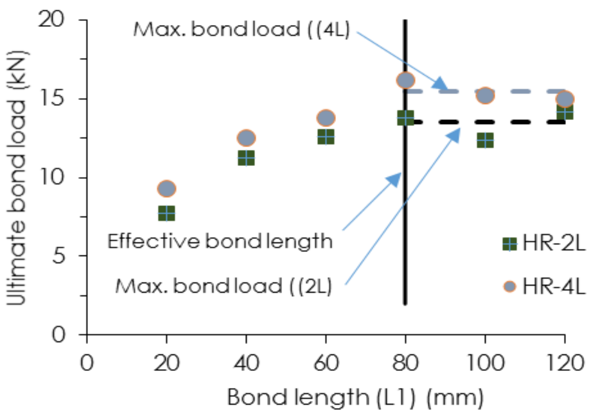


Figure 8 Ultimate bond load - bond length relationship - multiple CFRP layers

3.5 Validating the FE Analysis

The results of the ultimate bond loads achieved by the FEMs are validated by using the experimental (Exp.) results, as presented in Tables 3 and 4 for the models with 2 and 4 CFRP layers, respectively. In general, the results of the FE analysis overestimated the experimental results but still within the acceptable limit. Table 3 shows that the mean value of the load ratios of FEM/HR-2L was about 1.061 with a coefficient of variation (COV) of 0.176, for the specimens bonded with 2 CFRP layers that have high surface roughness. From the same table, the mean value and COV of the load ratios of FEM/NR-2L were equal to 1.136 and 0.129, respectively. Table 4 shows mean value of 1.101 was achieved with a COV of 0.140 for the load ratios (FEM/HR-2L) of specimens bonded with 4 CFRP layers. Moreover, the debonding failure mode was achieved in the FE analytical study as well as the experimental tests, as shown in Figure 9 for one of the FEMs as an example. Therefore, it can conclude that the bond load capacities and failure modes achieved numerically were found in good agreement with those obtained experimentally.

Table 3 Comparison of ultimate loads of FEM with Exp. specimens - 2 CFRP layers

Bond length (L1) (mm)	Ultimate bond load (kN)			Load's ratio	
	Exp. (NR-2L)	Exp. (HR-2L)	FEM	FEM/ (NR-2L)	FEM/ (HR-2L)
20	5.28	7.70	6.58	1.247	0.854
40	9.61	11.26	9.04	0.940	0.803
60	11.67	12.58	12.10	1.037	0.962
80	14.28	13.76	14.20	0.995	1.032
100	14.34	12.33	15.63	1.090	1.268
120	12.81	14.13	16.85	1.315	1.192
140	13.62	13.74	18.05	1.325	1.313
Mean value				1.136	1.061
Standard Deviation				0.147	0.187
Coefficient of Variation (COV)				0.129	0.176

Table 4 Comparison of ultimate loads of FEM with Exp. specimens - 4 CFRP layers

Bond length (L1) (mm)	Ultimate bond load (kN)		Load's ratio
	Exp. (HR-4L)	FEM	FEM/(HR-4L)
20	9.32	8.21	0.881
40	12.53	12.50	0.998
60	13.76	14.80	1.076
80	16.20	17.20	1.062
100	15.20	18.92	1.245
120	14.98	20.16	1.346
Mean value			1.101
Standard Deviation			0.154
Coefficient of Variation (COV)			0.140

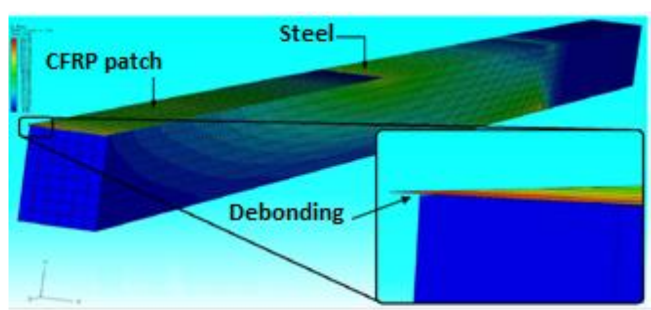


Figure 9 Typical CFRP debonding failure of FE models (4 CFRP layers with L1 = 80 mm)

3.6 Shear Stress-Slip Relationship

The shear stress-slip relationships are determined numerically in this section using the validated FE models. The bond load-slip relationships of each FEM of single-strap joint bonded with 2 CFRP layers are shown in Figure 10, as an example. The top point of each curve shown in this figure refers to the ultimate bond load of FEM that was summarized earlier in Table 3, in which the middle numbers shown in the designations of the FE models are denoted as the bond length (L1). Figure 11 presents the shear stress-slip relationships of FE models bonded with 2 and 4 CFRP layers. In this figure, the curves represent the average shear stress obtained from the models that have already passed the effective bond length (L1 = 80 mm and greater), where the value and behaviour of shear stress will not be greatly affected when the bond length passes the effective bond length [8, 15]. Figure 11 also illustrates that the maximum shear stress value of FEM with 4 CFRP layers is slightly higher than FEM with 2 layers (as established in Table 2). Moreover, both curves have the same behaviour, which trends as a bilinear shape. The shear stress-slip relationships for both models (FEM-2L and FEM-4L) were found to be in good agreement compared to the bilinear curve that was prepared based on the theoretical approach given by Xia and Tang [18]. Therefore, it can be concluded that increasing the number of CFRP layers from 2 to 4 does not change the behaviour of the shear stress-slip relationship in which both curves satisfy the three main stages of the bilinear shape, which are the linear elastic, softening, and debonding stages, as shown in Figure 12.

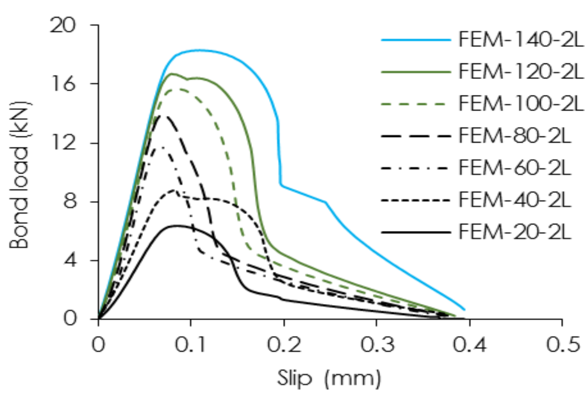


Figure 10 Bond load-slip relationships of FEM with 2 CFRP layers

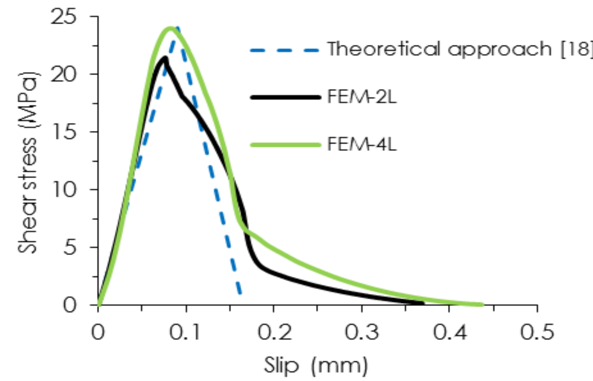


Figure 11 Shear stress-slip relationships of FEM from current study compared to the theoretical approach [18]

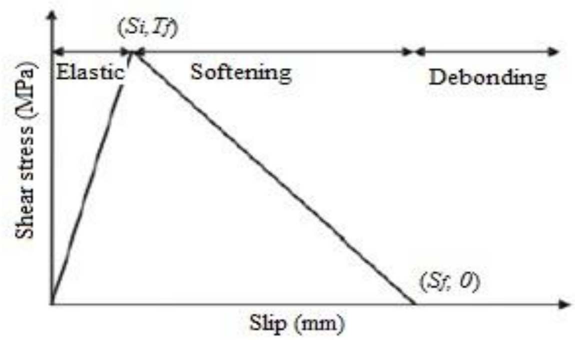


Figure 12 Theoretical model of bilinear bond-slip [18]

4.0 CONCLUSION

In general, the conclusions of the test results are summarized as following:

The debonding failure mode that occurs along the CFRP-steel interface was not significantly affected by the increasing number of CFRP layers and/or the degree of steel surface roughness.

Increasing the steel surface roughness does not necessarily increase the bonding capacity (ultimate bond load) of the single-strap joints that bonded with multi CFRP layers, specifically when the bonding lengths achieve and/or pass the limits of the effective bond length. However, minor improvement in the bonding capacity was observed when the bond length is less than the limits of the effective bond length.

The bonding capacity of a single-strap joint that bonded with 2 CFRP layers probably expected will be doubled when bonded with 4 layers. However, the results of the experimental and FE analyses showed that the bonding capacity increased by about 14% only when doubling the number of CFRP layers.

In general, the behaviour of the shear stress-slip relationships did not change when increased the CFRP layers to bond the steel-plate single-strap joint, which remain as bilinear shapes.

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