Jordan Journal of Civil Engineering, Volume **10**, No. **3**, **2016**

Experimental Investigation of Bond Characteristics between CFRP and Steel under Tensile Loads

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ABSTRACT

Rehabilitation of damaged infrastructure has become a priority in recent years as an alternative to the daunting costs of rebuilding structures. Traditional strengthening methods have drawbacks, many of which can be overcome through the use of carbon fiber reinforced polymer CFRP. Considerable research has been directed to investigate the effectiveness of bond length and strength between CFRP and steel. Research results indicated that significant increase in strength due to CFRP strengthening can be obtained. Nevertheless, in-depth understanding of debonding failures along the steel-epoxy interface is still a challenging issue. This paper presents three different experimental models with new surface preparation to increase bond strength and control debonding failure between CFRP fabrics and steel. The experimental results indicated that debonding failure can be controlled to some extent with proposed surface preparation technology.

KEYWORDS: CFRP, Cold formed steel, Bond, Strengthening, Debonding.

INTRODUCTION

The number of structures deteriorated due to demand of increased live loads, installation of heavy machinery, vibration due to new designed vehicles, fire damage, severe environment effects and corrosion is increasing. These structures need to be strengthened. Over the past few decades, there has been increasing interest in applying CFRP for strengthening structures. Strengthening of cold formed steel structures with adhesively bonded carbon fiber reinforced polymer (CFRP) laminates has attracted much research attention in recent years (Yu et al., 2014; Zhao and Zhang, 2007; Teng et al., 2012; Wu et al., 2012). The results showed a considerable increase in strength due to CFRP strengthening (Heider et al., 2012; Kalavagunta et al., 2013; Kalavagunta et al., 2013; Kalavagunta et al., 2014; Kalavagunta et al., 2013; Nuno Silvestre et al., 2009; Bambach et al., 2009; Abdollahi Chahkand et al., 2013; Teixeira de Freitas et al., 2014). Bond is the interaction mechanism that enables the transfer of stresses between steel and the surrounding CFRP. The strength of the CFRP strengthened steel composite structures is completely dependent on the bond between the CFRP composites and steel (Lenwari et al., 2006; Fawzia et al., 2006; Al-Zubaidy et al., 2011; Harris and Beevers, 1999). In order to achieve a good bond, the surface of the steel must be clean, dry and free of all loose materials. Typical methods for steel surface preparation prior to the application of

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Received on 28/1/2015.
Accepted for Publication on 15/2/2015.

externally bonded CFRP systems are (Parker, 1994; Sykes, 1982; Allen et al., 1982; Schnerch et al., 2005; Buyukozturk et al., 2004; Xia and Teng, 2005; Liu et al., 2005; Yang et al., 2013):

- Grinding.
- Mechanical abrasion with a wire wheel.
- Hydro-blasting with high pressure water.

Force transfer between CFRP and steel is controlled by a bond at the interface between the two materials. Bond performance is influenced by several factors, such as the bonded length and width, adhesive and thickness of adhesive (Nguyen et al., 2012; Puigvert et al., 2014; Puigvert et al., 2014; Feng et al., 2014). The adhesive is the weak link in CFRP-steel bonded joints, provided that adhesion failure at the steel-adhesive interface and CFRP-adhesive interface is avoided by careful selection of the adhesive and appropriate surface preparation of the steel and CFRP. The determination of proper surface preparation is necessary for the design of the CFRP strengthened steel structures. The aim of this paper is to examine the proper surface preparation method in order to achieve good bond strength and control the debonding failure.

EXPERIMENTAL TESTING

Details of Specimens

Direct tension pullout tests were carried out for cold formed steel high strength (G550 with nominal yield strength of 550 MPa) steel specimens. In this test, steel specimens are gradually pulled in tension and transferred the tensile stresses to the surrounding CFRP materials. Tension test coupons were taken from the same batch of steel which was used to carry out axial compression ultimate strength tests and buckling test (Kalavagunta et al., 2013; Kalavagunta et al., 2013; Kalavagunta et al., 2014; Kalavagunta et al., 2013). The specimens designed for testing were 75 mm, 100 mm, 150 mm and 200 mm long and 50 mm wide of cold formed steel (F550 American Iron and Steel Institute (AISI) grade of steel plates) with thicknesses of 0.75 mm, 1.0 mm and 1.2 mm. The fiber sheets were cut into the same dimensions as for the tension test coupons; i.e., they were 75 mm, 100 mm, 150 mm and 200 mm long and 50 mm wide (Kalavagunta et al., 2014). The test specimens are given in Table 1 and Figures (1-2).

Table 1. Sectional dimensions for testing

Material	Grade (N/mm^2)	Length (mm)	Width (mm)	Thickness (mm)
Cold formed steel plate	F550	75	50	0.75, 1.0 and 1.2
		100	50	
		150	50	
		200	50	
CFRP polymer sheet	F550	75	50	0.166 1. Single layer 2. Double layer 3. Triple layer
		100	50	
		150	50	
		200	50	

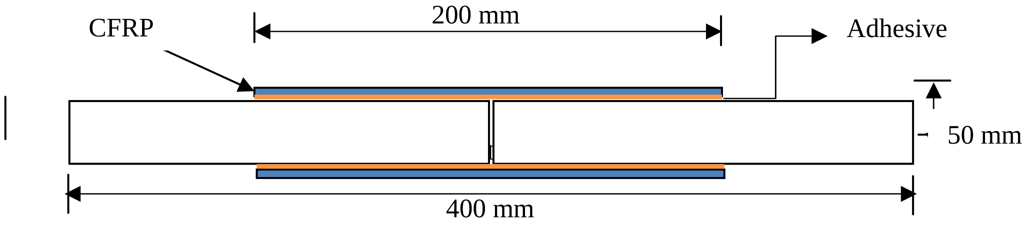

Figure (1): Tension test samples

Figure (2): Grinding the sample

Surface Preparation

Although the surface preparation and interlock between steel-adhesion-CFRP are already known, these methods generate bonding strengths that are considerably low compared with the combined strength. The new surface preparation was introduced in order to ensure a better interlocking between cold formed steel and carbon fiber reinforced polymer. This is a new method of surface preparation compared to the methods available based on recent research (Parker, 1994; Sykes, 1982; Allen et al., 1982; Schnerch et al., 2005; Buyukozturk et al., 2004; Xia and Teng, 2005; Liu et al., 2005; Yang et al., 2013). The mechanical disk and the surface preparation are shown in Figure 3. The degree of surface roughness of steel has been determined by visual observations. All samples were cleaned with smooth cloth in order to get rid of dust particles. The methods followed for surface preparation were as follows (Park and Jang, 1998; Abdel-Jaber et al., 2007):

- Surface thoroughly degreased to remove oils and other contamination;
- Grot blasting performed to remove paint and surface corrosion;
- Surface preparation using mechanical disk as shown in Figure 3.

Figure (3): Cleaning with cotton after surface

preparation to remove dust

Preparation of Adhesive

Adhesive MC-DUR 1280 (MC-Bauchemie) epoxy resins have been prepared as per manufacturer guidelines. One third of the hardener was mixed with glues and placed in the cleaned plate. By using the hand mixer, the hardener and glues are mixed thoroughly as shown in Figure 4 and Figure 5.

Figure (4): Mixing

Figure (5): Prepared adhesive

Bonding of High Modulus CFRP Sheet to CFS Sections

In this study, high strength carbon fiber Sheets MapeWrap C UNI-AX manufactured by MAPEI Malaysia SdnBhd were used in this experimental program. The technical specifications of MapeWrap C UNI-AX are uni-directional carbon fiber fabrics, characterized by a high tensile strength of 230,000 MPa. The perfect installation of high modulus CFRP polymers is essential to obtain full composite action between CFRP and steel. Two steel plates were aligned in position. Then, a thin coat of adhesive was uniformly applied on steel surfaces as shown in Figure 6. Mechanical scale and roller were used to maintain the same thickness. It is important and required to maintain a uniform thickness of the adhesive. The thickness of the adhesive has a direct effect on the load carrying capacity of the test specimen. The CFRP was carefully and evenly layered as shown in Figure 7 and Figure 8. The entire specimen was cured at room temperature for at least 15 days and then a second layer of CFRP sheet was applied and cured similarly. The same procedure was repeated for the third layer. The geometry and dimensions of the test specimen were as shown in Figure 1.

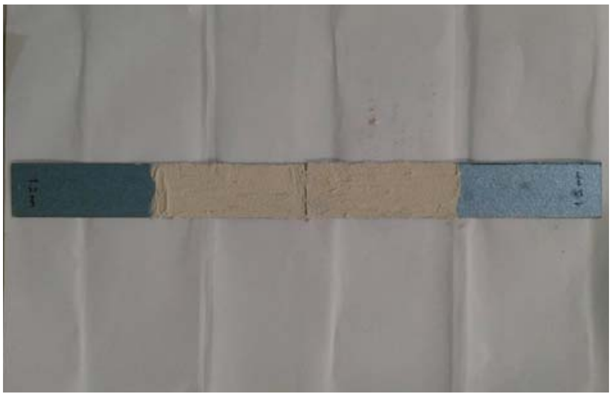

Figure (6): Specimen with applied adhesive

Figure (7): Application of CFRP on specimen

Figure (8): Test specimens ready for testing

Testing Procedure

In conducting the standard pull out tension test, both the test specimen and the support of the test specimen were pulled in tension simultaneously. The tests were carried out by using a universal testing machine available in UNITEN structural testing laboratory (Figure 9). The load was applied for pull out test with a rate of 0.5 mm per minute. The load was increased gradually until failure of specimen. The automated load *vs.* deflection graphs were generated by the UTM machine. The micrometer screw gauge was set up to measure the readings. All the specimens were tested, and the load carrying capacities and corresponding deflections were recorded. The load and strain were automatically recorded at one second intervals by using an auto data recorder. Every specimen was tested twice and the average values were taken into consideration.

Figure (9): CFRP test specimen's tension test arrangements

RESULTS AND DISCUSSION

The test results obtained from the experimental investigation are tabulated in Tables 2-6. The major challenge of CFRP strengthened steel structures is the bond performance. Surface preparation and method of bonding the composite section play an important role in strengthening. The results are graphically represented in Figures (10-14) to identify the bond strength corresponding to the number of CFRP layers. Figure 15 shows the overall load carrying capacity of CFRP strengthened single, double and triple layers of CFS sections.

An analytical procedure for determining the bond strength was developed and compared with the experimental test results. The basic stress-strain principles are employed to develop the equation (Eq. 1) to calculate the strength of materials. The stress is the ratio of applied load to the cross-sectional area of the plate element under tensile force.

Load at failure stage = FYLD x A; (Eq. 1)

where
FYLD = Yield strength of steel.
A = Cross-sectional area.

This analytical model is widely used in structural engineering for the calculation of tensile strength of materials including composites.

The analysis includes the steel yield strength and excludes the CFRP tensile strength. This is to aim that the adhesive strength should gain at least the yield strength of the steel. The equation above was developed based on the following assumptions as per simple bending theory:

- The composite section made up of CFRP and cold formed steel is initially strained, unstressed and symmetric.
- The composite material of the plate is linearly elastic.

- Young’s modulus for the composite material is considered for steel only.
- Plane cross-section before loading remains plane after loading.

Table 2. Single layer results (experimental *vs.* analytical)

Layers	**Specimen thickness (mm)**	**Max. load at 75 mm (kN)**	**Max. load at 100 mm (kN)**	**Max. load at 150 mm (kN)**	**Max. load at 200 mm (kN)**
Single Layer	0.75	13731.32	14307.64	13948.06	14951.42
	1	15665.79	16967.61	15318.48	16216.05
	1.2	12584.28	7522.01	9778.09	8708.8
Analytical	0.166-CFRP	6847.5	9130	13695	18260

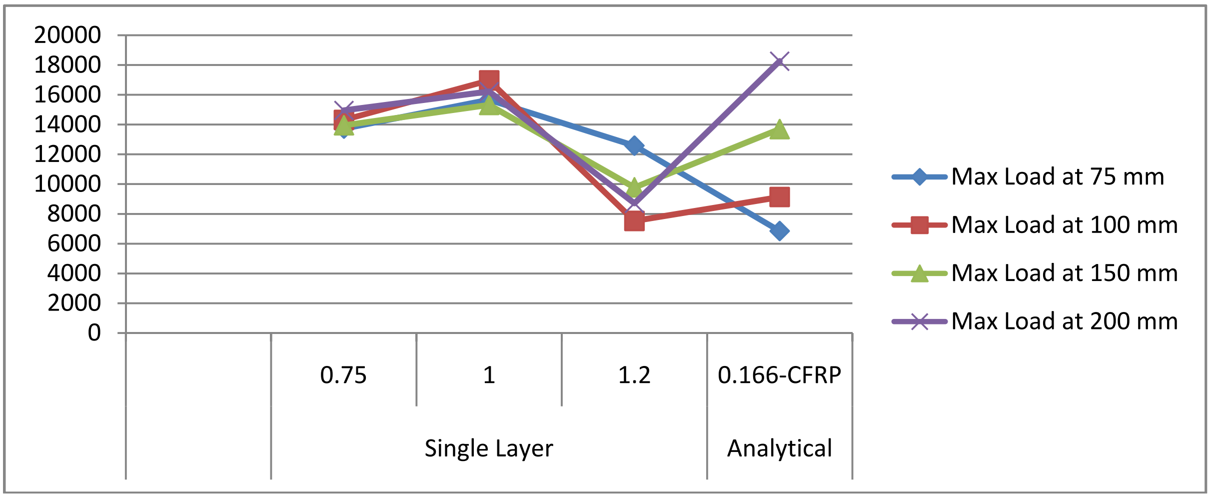

Figure (10): Single layer results (experimental *vs.* analytical) (thickness *vs.* load)

Table 3. Double layer results (experimental *vs.* analytical)

Layers	**Specimen thickness (mm)**	**Max. load at 75 mm (kN)**	**Max. load at 100 mm (kN)**	**Max. load at 150 mm (kN)**	**Max. load at 200 mm (kN)**
Double Layer	0.75	17225.41	17948.34	18397.03	15325.14
	1	19970.61	17920.32	24256.03	24508.27
	1.2	21578.75	26612.6	27728.07	27488.37
Analytical	0.166X2-CFRP	13695	18260	27390	36520

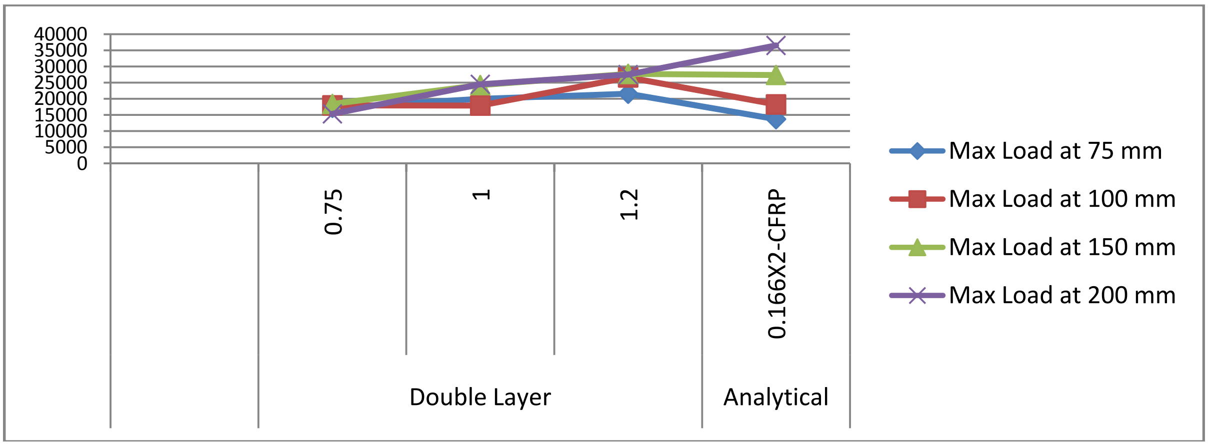

Figure (11): Double layer results (experimental *vs.* analytical) (thickness *vs.* load)

Table 4. Triple layer results (experimental *vs.* analytical)

Layers	Specimen thickness (mm)	Max. load at 75 mm (kN)	Max. load at 100 mm (kN)	Max. load at 150 mm (kN)	Max. load at 200 mm (kN)
Triple Layer	0.75	18825.69	18613.31	20268.92	18236.43
	1	20310.6	24759.32	24643.55	24381.84
	1.2	17117.62	23167.07	25428.83	30390.36
Analytical	0.166X3-CFRP	20542.5	27390	41085	54780

After comparing the experimental results with the analytical results, it was found that double layer experimental results are the closer results to the analytical ones. This indicates that after two layers, any increase in the number of CFRP layers will not cause an increase in the load carrying capacity as expected. The reason behind this is the debonding of CFRP layers from steel.

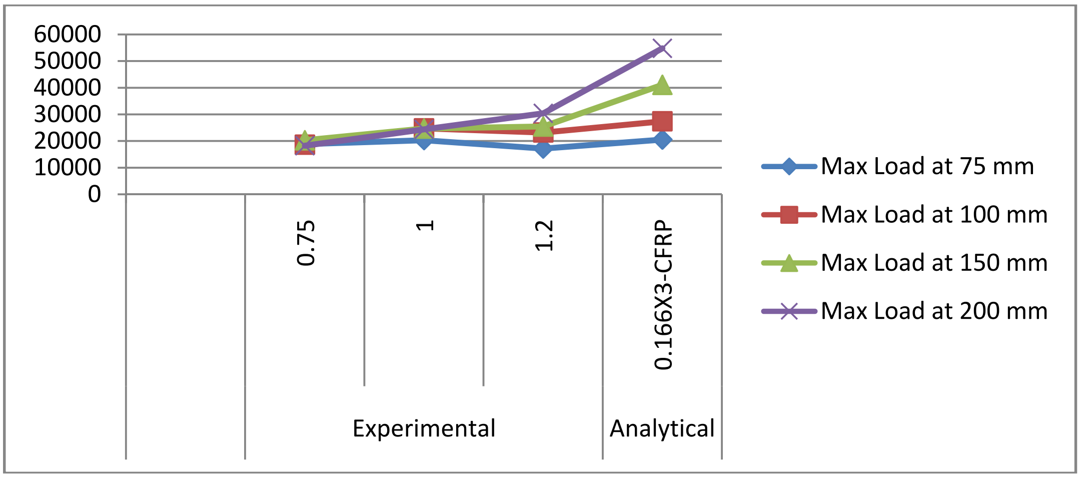

Table (12): Triple layer results (experimental *vs.* analytical) (thickness *vs.* load)

Table 5. Comparison of single layer vs. double layer experimental results

Layers	Specimen number	Specimen thickness (mm)	Max. load at 75 mm (kN)	Max. load at 100 mm (kN)	Max. load at 150 mm (kN)	Max. load at 200 mm (kN)
Single Layer	1	0.75	13731.32	14307.64	13948.06	14951.42
	2	1	15665.79	16967.61	15318.48	16216.05
	3	1.2	12584.28	7522.01	9778.09	8708.8
Double Layer	4	0.75	17225.41	17948.34	18397.03	15325.14
	5	1	19970.61	17920.32	24256.03	24508.27
	6	1.2	21578.75	26612.6	27728.07	27488.37

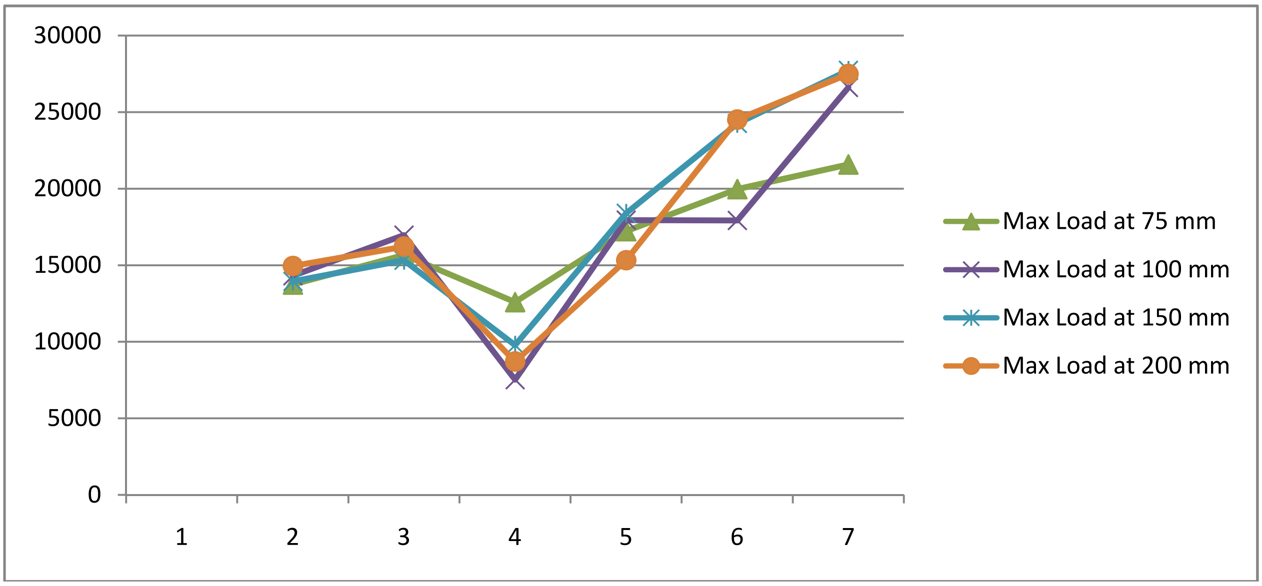

Figure (13): Graph of single layer *vs.* double layer experimental results (specimen number *vs.* load)

Table 6. Comparison of double layer *vs.* triple layer experimental results

Layers	Specimen number	Specimen thickness (mm)	Max. load at 75 mm (kN)	Max. load at 100 mm (kN)	Max. load at 150 mm (kN)	Max. load at 200 mm (kN)
Double Layer	1	0.75	17225.4	17948.3	18397	15325.1
	2	1	19970.6	17920.3	24256	24508.3
	3	1.2	21578.8	26612.6	27728.1	27488.4
Triple Layer	4	0.75	18825.7	18613.3	20268.9	18236.4
	5	1	20310.6	24759.3	24643.6	24381.8
	6	1.2	17117.6	23167.1	25428.8	30390.4

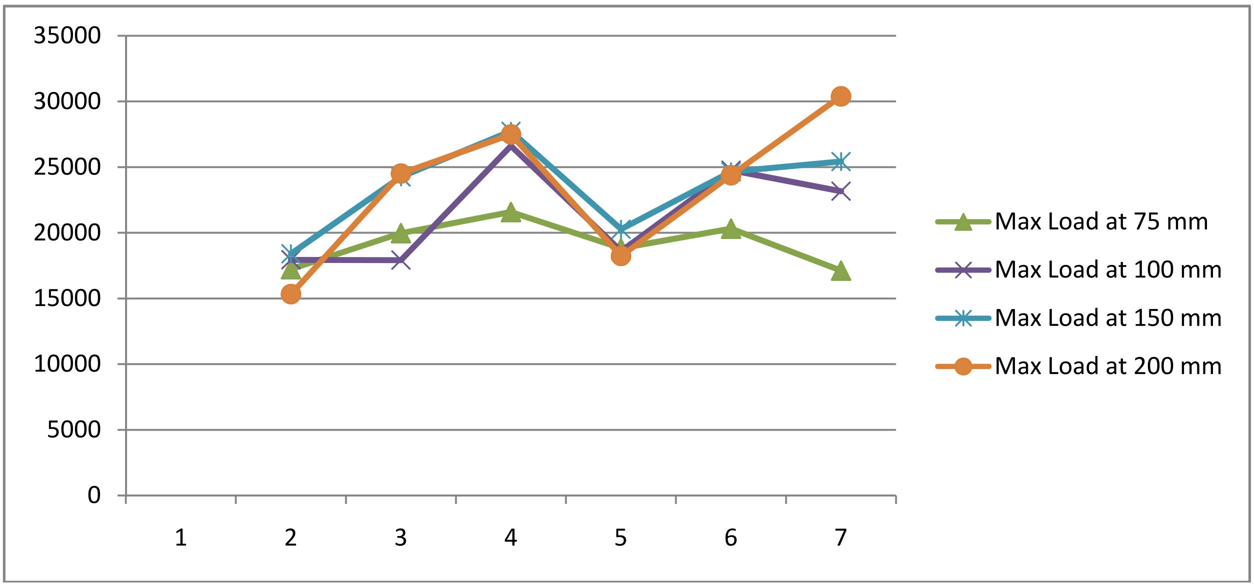

Figure (14): Graph of double layer *vs.* triple layer experimental results (specimen number *vs.* load)

The results shown in Table 5, Table 6, Figure 13 and Figure 14 indicate that the double layer results are optimum to achieve greater strength of a given composite section. The effective bond strength of 26kN with CFRP rupture indicates that full strength of composite action has been achieved.

Table 7. Experimental results

Layers	Specimen number	Specimen thickness (mm)	Max. load at 75 mm (kN)	Max. load at 100 mm (kN)	Max. load at 150 mm (kN)	Max. load at 200 mm (kN)
Single Layer	1	0.75	13731.32	14307.64	13948.06	14951.42
	2	1	15665.79	16967.61	15318.48	16216.05
	3	1.2	12584.28	7522.01	9778.09	8708.8
Double Layer	4	0.75	17225.41	17948.34	18397.03	15325.14
	5	1	19970.61	17920.32	24256.03	24508.27
	6	1.2	21578.75	26612.6	27728.07	27488.37
Triple Layer	7	0.75	18825.69	18613.31	20268.92	18236.43
	8	1	20310.6	24759.32	24643.55	24381.84
	9	1.2	17117.62	23167.07	25428.83	30390.36

The overall experimental results (Figure 15) show that double layer and 150 mm bond strength comparatively give higher strength compared to single and triple layered CFRP strengthened CFS steel sections. The results show the failure of most of the specimens due to rupture rather than peeling of CFRP from cold formed steel. This indicates that the new surface preparation gives better interlock among CFRP- adhesive-steel. This will help increase cold formed steel strength due to CFRP strengthening.

There are some differences in results due to surface preparation, but this can be controlled by careful detailing. The thickness of adhesive layers with single layer, double layer and triple layer results also confirmed that bond strength might decrease if the number of layers increases. The results also indicate that the development length is directly depending on surface preparation and CFRP layer orientation. The new method of surface preparation using mechanical disk shows perfect bonding between CFRP and cold formed steel.

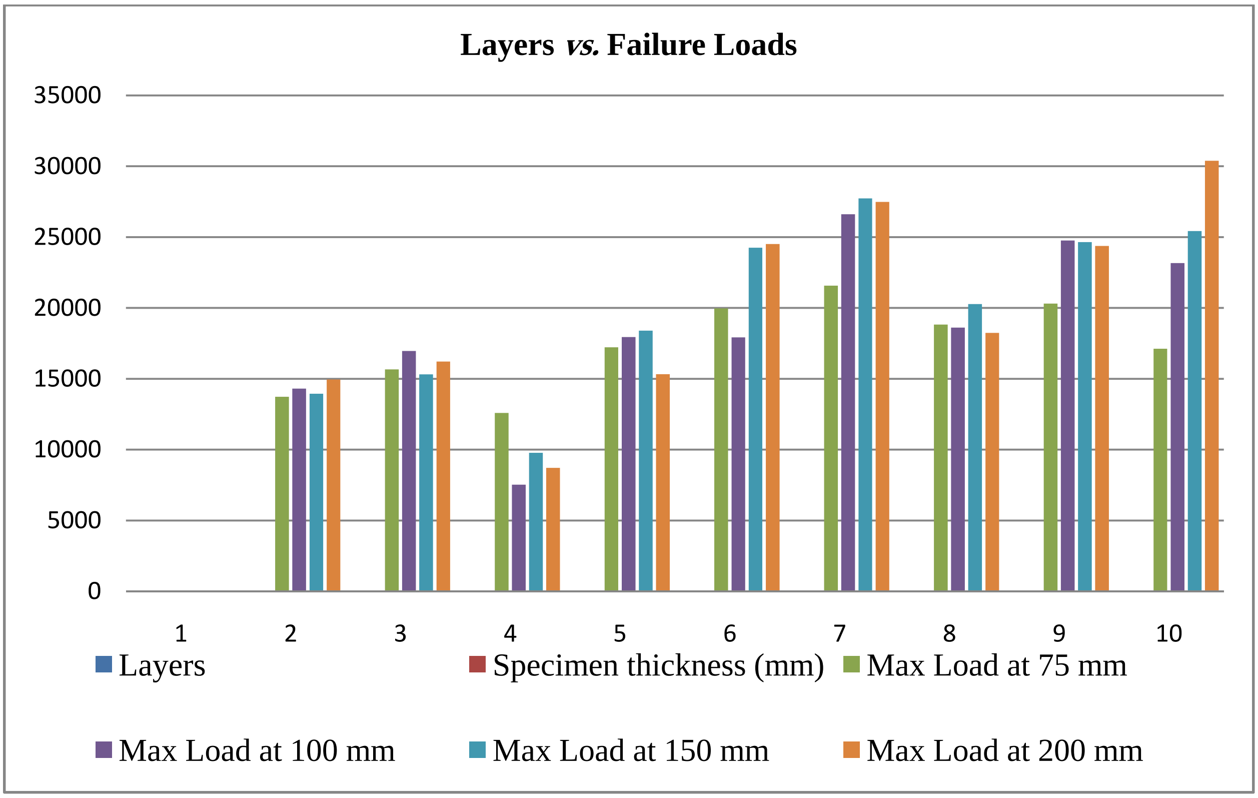

Figure (15): Load carrying capacity of experimental results (specimen number *vs.* load)

CONCLUSIONS

This paper presents an experimental investigation to calculate the effective bond strength between cold formed steel and single, double and triple layers of 0.166 thick CFRP polymer sheet. Both numerical and experimental investigations were conducted and the results were compared. Based on the findings of this experimental investigation, the following observations are made.

- The new surface preparation method provides better interlock among CFRP-adhesive-cold formed steel.
- The experimental results have been validated with a mathematical equation.
- The specimens using the 150 mm development length were found to have achieved full utilization of the carbon fiber material using MC-DUR 1280 epoxy adhesive.
- The results show that there is no increase in strength due to increasing the number of layers above two.

The results from tension coupon tests showed that bond length of 150 mm is effective in producing maximum bond strength. The 150 mm bond length gives full utilization of CFRP MapeWrap C UNI-AX unidirectional, MC-DUR 1280 epoxy adhesive for a given surface preparation and hence is optimal in terms of bonding. Future research is needed to develop a more standard approach to achieve perfect bond between CFRP and cold formed steel. The following are some recommendations for future work.

- A broader parametric work should be performed with different thicknesses, grades of steel, adhesive and CFFRP materials.
- Standardized surface preparation should be investigated.
- Practical design guidelines need to be developed.
- CFRP-adhesive-cold formed composite models need to be developed and tested for compression, bending and fatigue to evaluate design rules.
- Methods of bonding and guidelines need to be investigated.

Acknowledgements

The authors would like to acknowledge BlueScope Lysaght Malaysia SdnBhd for giving support by providing cold formed steel sheets and MC-Bauchemie International for providing MC-DUR 1280 adhesive.

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