Failure modes of carbon fiber reinforced polymer plate - steel joints with ductile or brittle adhesives

Guijun Xian[1], Jun He[2]

[1] Key Lab of Structural Dynamic Behavior and Control (Harbin Institute of Technology), Ministry of Education, Harbin, China
[1] School of Civil Engineering, Harbin Institute of Technology, Harbin, China
gjxian@hit.edu.cn, xianguijun@163.com
[2] Key Lab of Structural Dynamic Behavior and Control (Harbin Institute of Technology), Ministry of Education, Harbin, China
[2] School of Civil Engineering, Harbin Institute of Technology, Harbin, China
tdtuhejun@163.com

Key words: failure modes; delamination; ductile or brittle adhesive

Abstract: The failure modes of the CFRP-steel joints were critical determining the performances of the strengthened structures. Generally, cohesive failure was considered as an ideal failure mode, leading to ductility of the structures. In the present article, a series of single slap bond tests were conducted on CFRP-steel joints with three different adhesives with brittle or ductile properties. The CFRP-steel joints exhibited cohesive failure or CFRP delamination due to the varied properties of the adhesives. From the load-displacement curves tested with the single slap bond tests, the CFRP delamination failure can lead to large displacement, and thus the delamination failure is also acceptable compared to the cohesive failure. The failure mode of the joint depended on the relative strain value between CFRP and adhesive. When the ultimate strain of the adhesive is greater than the CFRP ultimate strain, the CFRP delamination failure tended to occur. Otherwise, the cohesive failure happens. From the bond-slip curves, the ductile adhesive has an approximately trapezoidal shape with an obvious plateau. However, the brittle adhesives have a bi-linear shape for the CFRP delamination failure mode. Finally, a prediction model of maximum shear stress is proposed for CFRP delamination failure mode.

1 Introduction

Using fiber reinforced composites (FRP) have been demonstrated as a successful technique to increase the strength and stiffness of structure elements [1]. Debonding of CFRP from steel surface is an important issue in the field of strengthening of steel structures with CFRPs [2]. For FRP-to-steel, the weak link has many possibilities [3], such as:

(a) Adhesion failure at FRP/adhesive interface
(b) Adhesion failure at Steel/adhesive interface
(c) Cohesive failure in adhesive
(d) CFRP delamination (separation of some carbon fibers from the resin matrix)

A schematic views of the failure modes are given in Fig. 1. Failure modes (a) and (b), the bonding strength results from both chemical bonding and mechanical bonding between the two adherents [4, 5]. Failure mode (c) and (d), the bonding strength depends on the material properties.

Table 1 summarizes the failure modes for the CFRP laminates - steel joints [3, 6-11]. As can be seen, the cohesive (c) and delamination (d) failure are very common. However, failures between adhesive-FRP (a) and steel - adhesive (b) are very rare. The debonding between FRP-adhesive can be avoided by use of a clean and fresh FRP surface. The debonding between steel- adhesive

Excerpt from ISBN 978-3-00-053387-7

can be avoided by abrading and cleaning the steel surface before bonding [12].

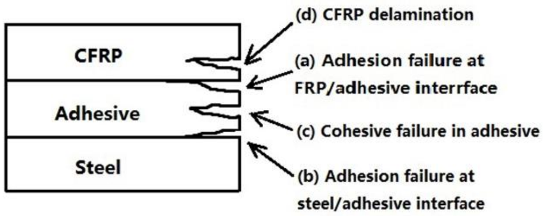

Figure 1. Possible failure modes of FRP-to-steel bonded joints.

So far, to the best knowledge of the authors, no systematic research work was reported on the CFRP delamination failure of the FRP-to-steel joints. Therefore, the present article aims to study the CFRP delamination failure mechanisms of a CFRP-steel joint through application of adhesives with different ductility.

Table 1. Recent results of CFRP laminates and steel bonds in literature.

Failure mode	Joints	Adhesive	Reference
Cohesive	Single lap joint	Sika 30	T. Yu, D. Fernando, J.G. Teng [3, 7, 8]
		Araldite 2015	
	Double strap joint	Sika 30	Chao Wu, Xiaoling Zhao [10]
Delamination	Single lap joint	Sika 330	T. Yu, D. Fernando, J.G. Teng [3, 8, 11]
		Araldite 420	
	Single lap joint	Adhesive A	Ibrisam Akbar [6]
	Double strap joint	Araldite420	Chao Wua, Xiaoling Zhao [10]
	Double strap joint	CNT-epoxy	Asghar H. Korayem [9]
Adhesive-FRP	Single lap joint	Adhesive B	Ibrisam Akbar [6]
Steel-FRP	Double strap joint	Pure-epoxy	Asghar H. Korayem [9]

2 Experimental

2.1 Materials

Pultruded unidirectional CFRP plates with a thickness of 1.44 mm and a width of 25 mm were used in the present study. The average Young's modulus and the tensile strength are 185 GPa and 1970 MPa, respectively, measured according to the ASTM D 3039.

Three kinds of two-part, room-temperature curable adhesives (designated as T1, Tc and Ts), developed at our laboratory were used to bond CFRP plate to steel substrate. The tensile stress-strain curves for those three adhesives are presented in Fig. 2. T1 and Ts are relative brittle adhesives. The average tensile modulus is 3.13 GPa for T1 and 11.3 GPa for Ts, and the tensile strength is 50 MPa for T1 and 27.3 MPa for Ts. The tensile strain-stress curves are linear for both T1 and Ts. Tc is a ductile nonlinear adhesive. The average tensile modulus is 1.5 GPa and the tensile strength is 25.69 MPa. When the stress reaches the maximum value, the strain ε_0 is approximately 2.55%, while the ultimate break strain is about 6.97%.

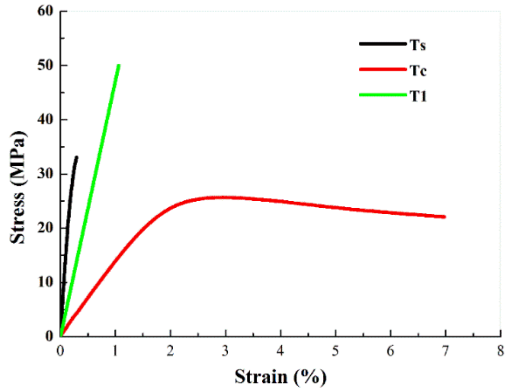

Figure 2. Tensile stress-strain curves of three adhesives.

2.2 Specimen preparation

The steel surfaces were de-rust by abrasive paper and then cleaned with acetone firstly. All specimens were treated by 0.1 mm alumina grit in order to avoid adhesion failure at the adhesive/steel interface. CFRP plates (also roughed with sand paper) were then bonded to the steel substrate within 24 hours after grit blasting. In order to keep all the specimens consistent, two 1 mm steel spacer were used to make sure the same adhesive thickness (1 mm). The adhesives were then cured at room temperature for at least one week before testing.

2.3 Instrumentation and loading procedure

Single lap shear test (Fig. 3) was adopted in the present study. A CFRP plate was bonded to one surface of a square steel tube with one kind of adhesive (Fig. 3). The square steel tube is 100 mm x 100 mm rectangular hollow sections with the thickness of 5 mm as illustrated in Fig. 3. Twelve samples were prepared.

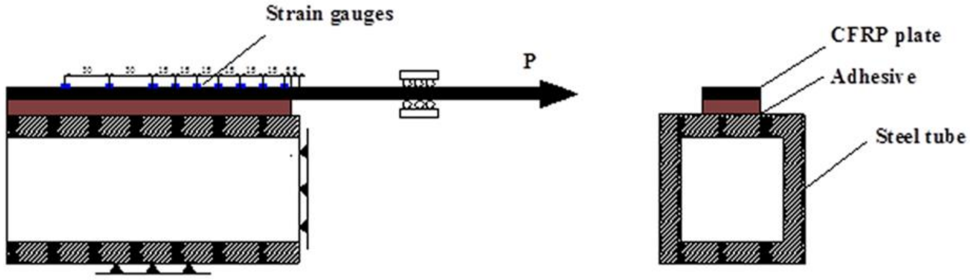

Figure 3. Tensile stress-strain curves of three adhesives.

Excerpt from ISBN 978-3-00-053387-7

Nine strain gauges with a gauge length of 5 mm were attached on the top surface of the CFRP plate. Loading was applied using a universal tensile testing machine (Shang Hai HY-10080) by displacement control at a loading rate of 0.05 mm/min until full failure of the joint.

3 Results and discussion

3.1 Failure modes

Two types of failure modes were observed for the current joints: cohesive failure and CFRP delamination failure. A typical CFRP delamination failure mode is shown in Fig. 4. Note, the debonded adhesive surface is black, because some of CFRP plate was delaminated and attached on the adhesives. At the load end, there was nearly no carbon fiber on it.

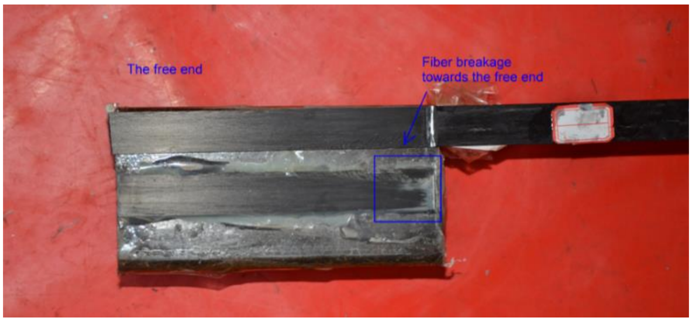

Figure 4. CFRP delamination failure mode.

Xia and Teng [11] found that the failure modes of the CFRP-steel joints depended on the thickness of the adhesive layer. When the adhesive thickness is less than 2mm, cohesive failure dominates, but for thicker adhesive layer (e.g., beyond 2mm), CFRP delamination failure occurs. Wu and Zhao [10] found that CFRP plate axial rigidity also can affect the failure mode. For an ultra high modulus CFRP laminate, CFRP rupture was observed. In the present study, the normal modulus (lower than 210GPa) CFRP laminates and 1mm thick adhesive were used. From Table 2, it appears that the failure modes depend mainly on the properties of the adhesives. Careful comparison between Ts, T1 and Tc indicated that the ultimate strain of the adhesive is greater than the CFRP ultimate strain, the CFRP delamination failure tended to occur. Otherwise, the cohesive failure happens.

3.2 Load-displacement Behavior

Teng et al. [3, 13] suggested that the ideal failure mode is the cohesive failure due to the better ductility, because cohesive failure brings in a long plateau on the load–displacement curves. In Asghar H. Korayem's paper [9], however, the delamination of CFRP was also reported to bring in a plateau on the load-displacement curve, and the joint can be considered to be ductile. In view of this, the delamination of CFRP plate is considered to be acceptable.
Fig.5 shows the load–displacement curves of joints with T1 and Tc adhesives. Note both joints failed with CFRP delamination. For comparison, Fig. 7 also presents the typical load–displacement curve for adhesive cohesive failure (with Ts adhesive).

Excerpt from ISBN 978-3-00-053387-7

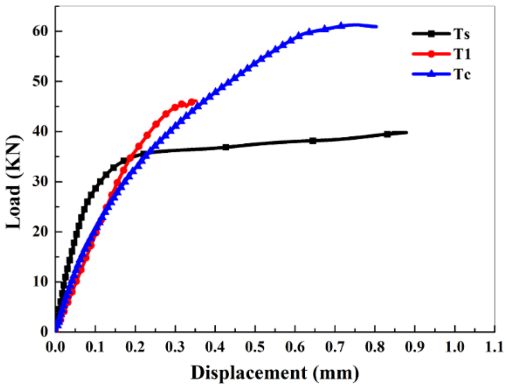

Figure 5. Load-displacement curves.

3.3 Bond slip relationship

Bond-slip relationship refers to the relationship between the local shear stress and the corresponding slip along the bond line of the joint. Bond–slip relationship is independent of geometric conditions, and therefore a local bond-slip model may be appropriate to measure the bond performance [10]. Although considerable research works have been conducted on the bond-slip model of CFRP -steel joints for cohesive failure, the bond slip models for CFRP-steel joints with FRP delamination failure received much less attention.

The interfacial shear stress and the slip can be found from readings of the strain gauges attached on the surfaces of the CFRP plate using the following equations [3]:

$$\tau_{i-1/2} = \frac{\varepsilon_i - \varepsilon_{i-1}}{L_i - L_{i-1}} E_p t_p \tag{1}$$

$$\delta_{i-1/2} = \frac{(\varepsilon_i + \varepsilon_{i-1})}{4}(L_i - L_{i-1}) + \frac{(\varepsilon_{i-1} + \varepsilon_{i-2})}{2}(L_{i-1} - L_{i-2}) + \sum_{i=3}^{i} \frac{(\varepsilon_{i-2} + \varepsilon_{i-3})}{2}(L_{i-2} - L_{i-3}) \tag{2}$$

where ε_i is the reading of the ***i*** th strain gauge counted from the free end of the CFRP plate, with $\varepsilon_0 = 0$; L_i is the distance of the ***i*** th strain gauge from the free end of the CFRP plate, with $L_0 = 0$; E_p and t_p are the elastic modulus and thickness of the CFRP plate respectively; $s_{i-1/2}$ and $\delta_{i-1/2}$ are the shear stress and slip at the middle point between the ***i*** th strain gauge and the ***i-1*** th strain gauge [3].

In Figs. 6, bond-slip curves were obtained for each CFRP-steel joint using readings from strain gauges at different locations. It is evident from Figs. 6 that the curves for different locations of the same interface are consistent, except near the loaded end. For the CFRP delamination failure, adhesive T1 (a linear adhesive) and adhesive Tc (a nonlinear adhesive) bring in much different bond–slip curves as shown in Figs. 6: the former have an approximately bi-linear shape, but the latter have an approximately trapezoidal shape with an obvious plateau.

Excerpt from ISBN 978-3-00-053387-7

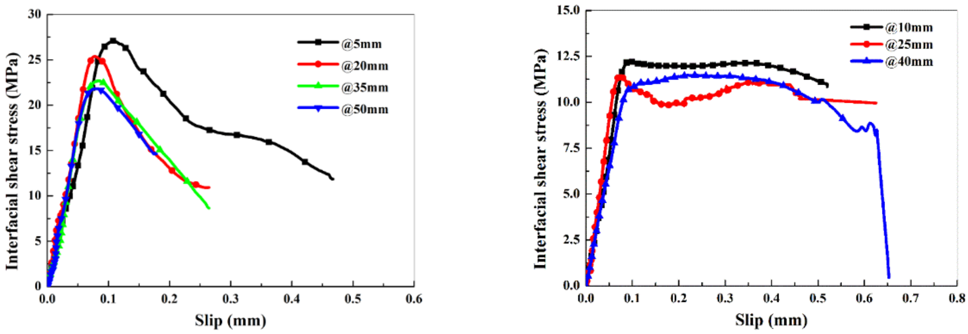

Figure 6. Bond-slip relationship curve for T1 and Tc in CFRP delamination failure.

4 Prediction of the maximum shear stress τ_f

In the present study, based on Xia and Teng's model [11], a new model were developed for the CFRP delamination failure which will be applied to predicting the maximum shear stress τ_f firstly. Xia and Teng's [11] model is suit to the case of cohesive failure because of the crack growth in the adhesive layer. Xia and Teng [11] found that the value of the local bond strength τ_f varies with the type of the adhesive but does not vary significantly with the adhesive thickness. Based on the experimental local bond strengths from those joints which experienced cohesive failure in the adhesive layer, the local bond strength can be reasonably closely approximated:

$$\tau_f = 0.8 f_{t,a} \tag{3}$$

Where $f_{t,a}$ is the tensile strength of the adhesive.

An important difference between the delamination failure and cohesive failure is the exact location of the interfacial failure. For the CFRP delamination failure, the interfacial failure generally occurs in the substrate CFRP laminate; for another case, the interfacial failure occurs in the adhesive. The initial crack of CFRP delamination is the fiber breakage and then crack propagate along the resin between fibers, which is parallel to the fiber direction. Therefore, the fiber fracture criterion should be investigated.

CFRP laminate fractures because it reaches the ultimate strain $\varepsilon_{FRP,u}$. Given that the strain is uniform along the thickness direction of the adhesive. The adhesive and the CFRP plate which has been fractured connect together, so they reach the same strain level. This means that the strain of the adhesive is equal to the fractured CFRP plate:

$$\varepsilon_{adhesive} = \varepsilon_{FRP,u} \tag{4}$$

Where $\varepsilon_{adhesive}$ is the strain of the adhesive.

For linear adhesive, the stress of the adhesive is:

$$f_a = E_a \varepsilon_{adhesive} \tag{5}$$

Where E_a is the elasticity modulus of adhesive.

$$E_a = \frac{f_{t,a}}{\varepsilon_{adhesive,u}} \tag{6}$$

Excerpt from ISBN 978-3-00-053387-7

Combining Eqs. (5) and (6),

$$f_a = f_{t,a} \frac{\varepsilon_{FRP,u}}{\varepsilon_{adhesiv,u}} \tag{7}$$

The adhesive is not broken and the tensile stress does not reach the ultimate stress, so $f_{t,a}$ should be instead by f_a, see Eq. (3)

$$\tau_f = 0.8 f_a \tag{8}$$

Combing Eqs. (7) and (8),

$$\tau_f = 0.8 f_{t,a} \frac{\varepsilon_{FRP,u}}{\varepsilon_{adhesiv,u}} \tag{9}$$

In the current study, the ultimate strain $\varepsilon_{FRP,u}$ = 1.06% for CFRP plate, and the ultimate strain $\varepsilon_{adhesive,u}$ = 1.6%, $f_{t,a}$ = 50 MPa for T1. Put those data into Eq (9), the τ_f is predicted to be 26.5 Mpa. Note, the measured value τ_f =27.1 MPa, very close to the predicted value. Similarly, for Tc, the predicted τ_f is 11.79 Mpa, and the experimental value τ_f = 11.4 MPa. In addition, as indicated in Korayem's paper [9], the tested value τ_f = 23.8 MPa. With the above model, the predicted τ_f is 24 MPa. A typical comparison of the maximum shear stress is shown in Fig. 7, which illustrates that the predicted values agree well with the tested values. Since the available data is limited, and the model need to be further validated.

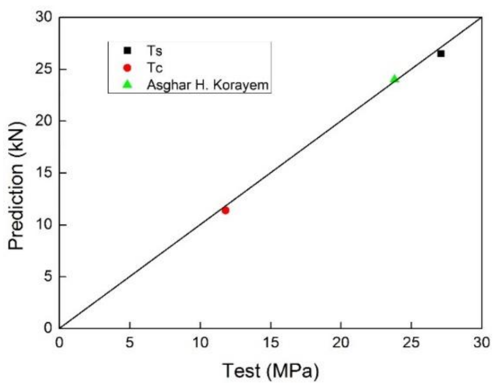

Figure 7. Comparison between the test and predicted maximum shear stress

5 Conclusions

In this paper, the following conclusions can be drawn based on the testing results and analysis.

(1) The failure mode depend on the relative strain value between the CFRP and adhesives. When the ultimate strain of the adhesive is greater than that of the CFRP plate, the delamination failure in CFRP occurs. Otherwise, the cohesive failure happens.

(2) From the bond-slip curves shape, the ductile adhesive leads to an approximately trapezoidal shape with an obvious plateau. However, the brittle adhesives brings in a bi-linear shape for the CFRP delamination failure mode.

Excerpt from ISBN 978-3-00-053387-7

(3) Based on the existed models for cohesive failure, a new prediction model of the maximum shear stress is proposed for the failure mode of CFRP delamination.

Acknowledgements

This work is financially supported by the NSFC with Grant Nos. 51178147 & 51478145, and the National Key Basic Research Program of China (973 Program) with Grant No. 2012CB026200.

References

[1] Gholami M, Sam ARM, Yatim JM, Tahir MM. A review on steel/CFRP strengthening systems focusing environmental performance. Construction and Building Materials. 2013;47:301-10.

[2] Dehghani E, Daneshjoo F, Aghakouchak A, Khaji N. A new bond-slip model for adhesive in CFRP–steel composite systems. Engineering Structures. 2012;34:447-54.

[3] Yu T, Fernando D, Teng J, Zhao X. Experimental study on CFRP-to-steel bonded interfaces. Composites Part B: Engineering. 2012;43:2279-89.

[4] Baldan A. Adhesively-bonded joints and repairs in metallic alloys, polymers and composite materials: adhesives, adhesion theories and surface pretreatment. Journal of materials science. 2004;39:1-49.

[5] Encinas N, Oakley B, Belcher M, Blohowiak K, Dillingham R, Abenojar J, et al. Surface modification of aircraft used composites for adhesive bonding. International Journal of Adhesion and Adhesives. 2014;50:157-63.

[6] Akbar I, Oehlers DJ, Ali MM. Derivation of the bond–slip characteristics for FRP plated steel members. Journal of Constructional Steel Research. 2010;66:1047-56.

[7] Fernando D, Yu T, Teng J-G. Behavior of CFRP laminates bonded to a steel substrate using a ductile adhesive. Journal of Composites for Construction. 2013.

[8] Fernando ND. Bond behaviour and debonding failures in CFRP-strengthened steel members: The Hong Kong Polytechnic University, 2010.

[9] Korayem AH, Li CY, Zhang QH, Zhao XL, Duan WH. Effect of carbon nanotube modified epoxy adhesive on CFRP-to-steel interface. Composites Part B: Engineering. 2015;79:95-104.

[10] Wu C, Zhao X, Duan WH, Al-Mahaidi R. Bond characteristics between ultra high modulus CFRP laminates and steel. Thin-Walled Structures. 2012;51:147-57.

[11] Xia S, Teng J. Behaviour of FRP-to-steel bonded joints. Proceedings of the International Symposium on Bond Behaviour of FRP in Structures (BBFS 2005)2005. p. 411-8.

[12] Teng J, Fernando D, Yu T, Zhao X. Debonding failures in CFRP-strengthened steel structures. Proceedings of the Third Asia-Pacific Conference on FRP in Structures2012.

[13] Teng J, Fernando D, Yu T. Finite element modelling of debonding failures in steel beams flexurally strengthened with CFRP laminates. Engineering Structures. 2015;86:213-24.

Excerpt from ISBN 978-3-00-053387-7