

Effect of Glass Fiber Sheet in Adhesive on the Bond and Galvanic Corrosion Behaviours of CFRP-Steel Bonded System

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Abstract

Steel structures strengthened with CFRP composite may have potential galvanic corrosion issue. It was recommended that a layer of glass fiber sheet (GFS) be embedded in the adhesive layer to protect the CFRP-steel bonded system against galvanic corrosion. But the inclusion of GFS in the adhesive may negatively affect the bond behaviour between steel and CFRP. This paper investigated the effects of GFS on the corrosion behaviour and bond characteristics between steel and CFRP. Three types of experimental testing on CFRP-steel double strap joints with/without GFS were conducted, including accelerated corrosion testing, static and fatigue testing. Accelerated corrosion testing was carried out to justify the effectiveness of GFS in preventing galvanic corrosion of CFRP-steel bonded system. Static tension testing and fatigue testing were carried out to quantify the effect of GFS on the static and fatigue bond behaviour between steel and CFRP. The effects of GFS on the corrosion rate, failure mode, joint capacity and fatigue life were reported. Experimental results suggested that GFS may reduce the fatigue performance of the bond between steel and CFRP, although GFS may slightly improve the static bond behaviour. It is recommended that GFS can be included in the adhesive layer as an

additional protection against the galvanic corrosion hazard in the CFRP-steel bonded system, provided that the system has no concern of fatigue loading.

Keywords: Double strap joint; bond; CFRP; glass fiber sheet; galvanic corrosion

1. Introduction

Strengthening of steel structures using carbon fiber-reinforced polymer (CFRP) has attracted increasing interests in the construction industry [1-3]. It is convenient to install CFRP onsite due to its lightweight, and excellent strengthening performance can be achieved due to the high strength of CFRP composite [4-6]. Although CFRP itself has excellent corrosion resistance, when bonded to steel, the CFRP-steel system may be subjected to galvanic corrosion issue [7]. This is because CFRP and steel have very different electrical potentials. When CFRP is in contact with steel in the wet environment, the galvanic reaction takes place and the electric current is formed leading to corrosion of the steel substrate. This galvanic corrosion becomes worse in de-icing salts and other aggressive environmental conditions. Therefore, how to mitigate the potential galvanic corrosion issue becomes one of the key research questions for CFRP strengthening technique when applied to steel structures.

There have been research in the literature investigating the galvanic corrosion of CFRP-steel bonded system. Kim et al. [8] carried out an experimental program to investigate the effect of galvanic current on the physical and mechanical characteristics of CFRP-steel bonded joints. The specimens were exposed to galvanic current for different periods of time and then tensioned to failure. It indicated that the exposure time did not affect the failure mode but did influence the stress-slip behaviour of the joints. Tavakkolizadeh and Saadatmanesh [9] studied

the corrosion rates of CFRP-steel bonded samples with different thicknesses of epoxy bondline in different electrolytes. The experimental results showed that the rate of galvanic corrosion could be significantly decreased by epoxy layer. Dawood and Rizkalla [10] introduced a silane coupling agent and a glass fiber layer within the adhesive to enhance the durability of the CFRP-steel double lap joints. The research found that the glass fiber layer did not improve the durability of the bonded joints but helped to enhance the initial bond strength between CFRP and steel. Some other studies [11, 12] suggested that embedding a layer of glass fibers in the adhesive between steel and CFRP helped to prevent electrical contact between the two materials.

From the previous research, it seems that embedding a layer of glass fiber sheet (GFS) is recommended to reduce the potential galvanic corrosion of CFRP-steel bonded system. However, the effectiveness of this method in terms of corrosion mitigation has not been explicitly justified in the literature. In addition, the bond behaviour between CFRP and steel may be affected by the GFS in the adhesive, when the CFRP-steel bonded system is subjected to static or fatigue loading conditions. Unfortunately, there has been no information in the literature about how the bond will be affected by GFS layer in the adhesive.

This paper presents an investigation on how effective the GFS in the adhesive can be to mitigate the galvanic corrosion of CFRP-steel bonded system. The effects of GFS in the adhesive are also explicitly studied in this paper on the bond behaviour between CFRP and steel under static and fatigue loading conditions. Three types of experimental testing were conducted, including (a) accelerated corrosion testing on CFRP-steel bonded samples with/without GFS in the adhesive. This is to study whether GFS is effective or not to suppress

the potential galvanic corrosion of the CFRP-steel bonded system. (b) static tension testing on CFRP-steel bonded double strap joints with/without GFS in the adhesive. The effects of GFS on the bond strength and effective bond length are reported. (c) fatigue testing on CFRP-steel bonded double strap joints with/without GFS in the adhesive. The effects of GFS on the fatigue life, residue bond strength and stiffness after fatigue testing are presented. The experimental results suggest that the adhesive layer alone is sufficient enough to prevent galvanic corrosion of the CFRP-steel bonded system, while GFS can serve as an additional protection. This observation is only valid when the quality of the bonding process is well controlled and good. It is also found that GFS in the adhesive can marginally improve the bond strength and effective bond length of the CFRP-steel double strap joints. However, the inclusion of GFS in the adhesive may weaken the bond behaviour under fatigue loading. It is recommended that GFS can be used for CFRP strengthening of steel structures to provide additional protection against galvanic corrosion, provided fatigue loading is not a concern in such applications.

2. Accelerated Corrosion Testing

2.1 Materials

CFRP plate was 1.32 mm thick and 30 mm wide. The steel plate was hot rolled structural steel Q345 with a thickness of 15 mm and a width of 30 mm. A two-part epoxy, Araldite 420, was used as the adhesive to bond CFRP on steel. The material properties of CFRP, steel and adhesive were measured through coupon tests according to ASTM D3039, ASTM E8 and ASTM D638-01 [13-15], respectively. The detailed dimensions of the coupons are shown in Fig. 1, and the tested material properties are listed in Table 1.

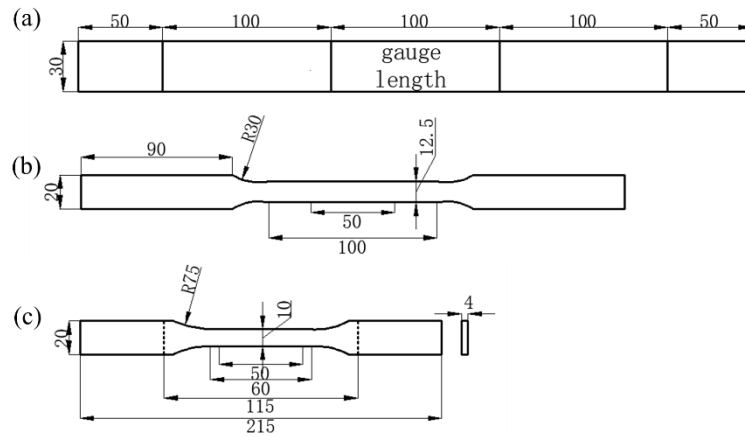


Fig. 1. Coupon test specimens of (a) CFRP plate; (b) steel plate and (c) adhesive (dimension in mm, not to scale)

Table 1 Material properties of CFRP, steel and adhesive

Properties	CFRP	steel	Araldite 420
Tensile strength (MPa)	2659	539	30
Yield stress (MPa)	N/A	381	N/A
Tensile modulus (GPa)	155.9	219.6	1744

2.2 Specimens

Three types of coupons were prepared to find out the effect of the adhesive and GFS on the anti-corrosive behaviour of CFRP-steel joints. As for the control specimen, the CFRP was directly put on the steel surface without adhesive or GFS, as shown in Fig. 2a. The epoxy, Araldite 420, was employed to bond the CFRP plate and GFS to the steel substrate. For the bonded specimens, a thin layer of adhesive as large as the steel surface was firstly applied. For all the bonded specimens, the steel surface was sandblasted with grade 80 sand and 0.4MPa pressure at first and then cleaned with acetone before applying the adhesive to get a better bonded surface. For the specimen without GFS in the adhesive, after the first layer of adhesive was applied, another thin layer of adhesive was evenly applied with CFRP plate laid on top. For the specimen with GFS in the adhesive, after the first layer of adhesive was applied, the

GFS was laid on top. Then the adhesive and CFRP were applied as the same procedures as the specimen without GFS in the adhesive.

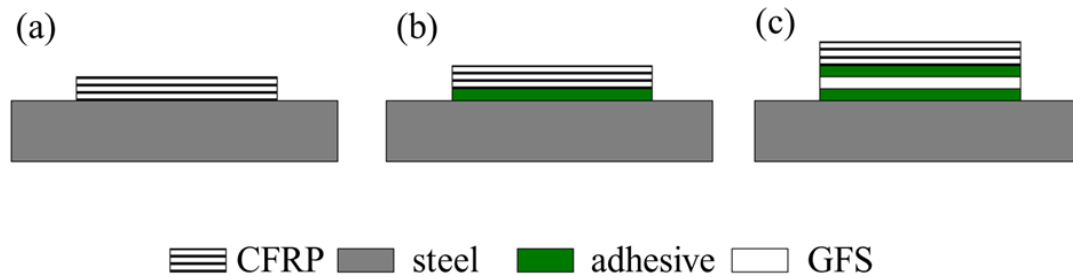


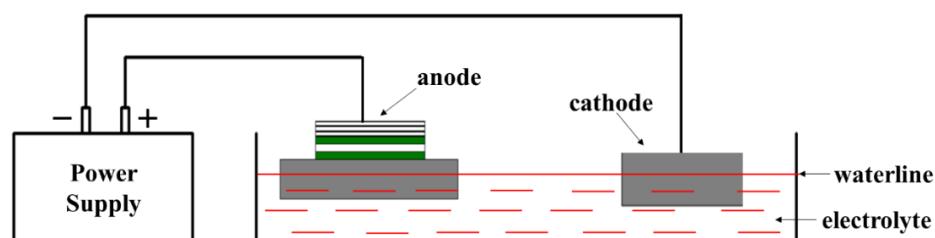
Fig. 2. Schematic view of specimens for corrosion tests (a) control specimen with CFRP directly put on top of the steel plate; (b) CFRP was bonded on top of the steel plate without GFS in the adhesive layer; (c) CFRP was bonded on to the steel plate with GFS in the adhesive layer

2.3 Test setup

Four essential elements are required for the galvanic corrosion to take place, including anode, cathode, electrolyte, and electrical connection. Therefore, galvanic corrosion becomes an issue for steel structures strengthened with CFRP composite especially when corrosive environment exists. It has been proposed to embed a layer of GFS in the adhesive before bonding CFRP on steel to completely separate them to avoid potential galvanic corrosion. However, few experimental evidences have been reported to verify the effectiveness of this method. In this paper, accelerated corrosion tests were conducted to show how effective it could be to suppress galvanic corrosion.

The test setup is shown in Fig. 3, which has been used in similar research [16,17] in the literature to investigate the effect of galvanic current on the physical and mechanical

characteristics of CFRP sheets bonded to a steel substrate. In order to accelerate the corrosion of the CFRP-steel specimens, an external power resource was provided with the CFRP-steel specimen connected to the anode. And another pure steel block was connected to the cathode. The specimen and the steel block were immersed in an electrolyte which was a 3.5% sodium chloride solution. It should be noted in Fig. 3 that, for the CFRP-steel specimen, only the steel adherent was partially immersed in the electrolyte while the CFRP and adhesive were not in contact with the electrolyte. Also, the anode of the power source was connected to CFRP layer of the specimen and not in contact with the steel adherend. In this way, galvanic corrosion will occur to the steel adherend if the CFRP contacts the steel. On the other hand, the steel adherend will not corrode if the CFRP and steel are successfully separated by the adhesive layer with/without GFS. This is because the path for the flow of electrons is cut. The steel block is connected to the cathode so it will never corrode. Each corrosion test was carried out at room temperature and lasted for 48 hours. During the test, the electric current in the system was recorded by an electrochemical workstation (CHI 660e) which was used to represent the corrosion speed.



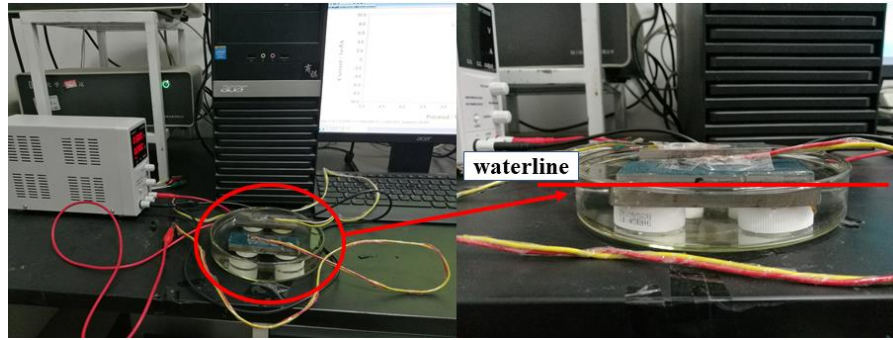


Fig. 3. Setup of accelerate corrosion test

2.4 Results and discussions

The bottom surfaces of the steel adherends of all specimens after the tests are shown in Fig. 4. It is obvious that the specimen with CFRP directly contacting steel (no adhesive, no GFS) was severely corroded. On the other hand, very little corrosion was observed on the other two specimens with CFRP bonded to steel using adhesive with/without GFS. These observations indicate that both adhesive layer and GFS were very effective to suppress the corrosion of the steel adherend. In other words, if carefully prepared, the adhesive layer alone can sufficiently separate CFRP and steel without using GFS. In engineering practice, the inclusion of GFS in the adhesive layer can provide another protection to galvanic corrosion.

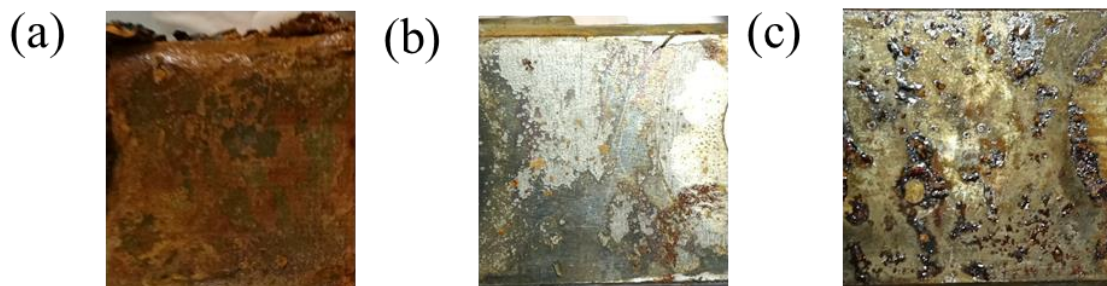


Fig. 4. Corrosion status of the steel adherends after the corrosion test: (a) control specimen with CFRP in direct contact with steel plate; (b) specimen with CFRP separated from steel

plate by adhesive layer; (c) specimen with CFRP separated from steel plate by both adhesive and GFS

The electric current in the system was recorded to analyse the corrosion speed. According to the Faraday's law [18], the corrosion speed can be calculated as:

$$Cr = C \frac{Mi}{n\rho} \quad (1)$$

where Cr is the corrosion speed in mm/year; C is a conversion constant (0.00327 for mm/year [19]); M is the atomic weight in g/mol which is 55.9 g/mol for steel; i is the electric current density in $\mu\text{A}/\text{cm}^2$; n is the number of electrons for the iron ion which is 2 for Fe^{2+} ; and ρ is the density of the steel which is 7.85 g/cm^3 .

The corrosion speed Cr curves of the three specimens are plotted in Fig. 5. For the specimen with CFRP in direct contact with steel, the corrosion speed initially increased fast with time up to a peak. After the peak the corrosion speed slowed down. This is because with the corrosion progressed, the rust gradually accumulated on the surface of the steel adherent which became a protection layer and impeded electrochemical reaction. For the specimens with CFRP separated from steel through adhesive with/without GFS, the corrosion speed was maintained almost zero with time. This indicates that there was almost no electric current in the system thus the corrosion is much less than that of specimen with direct contact between CFRP and steel. Therefore, it can be said that both adhesive and GFS are effective to mitigate the galvanic corrosion hazard of CFRP-steel bonded system.

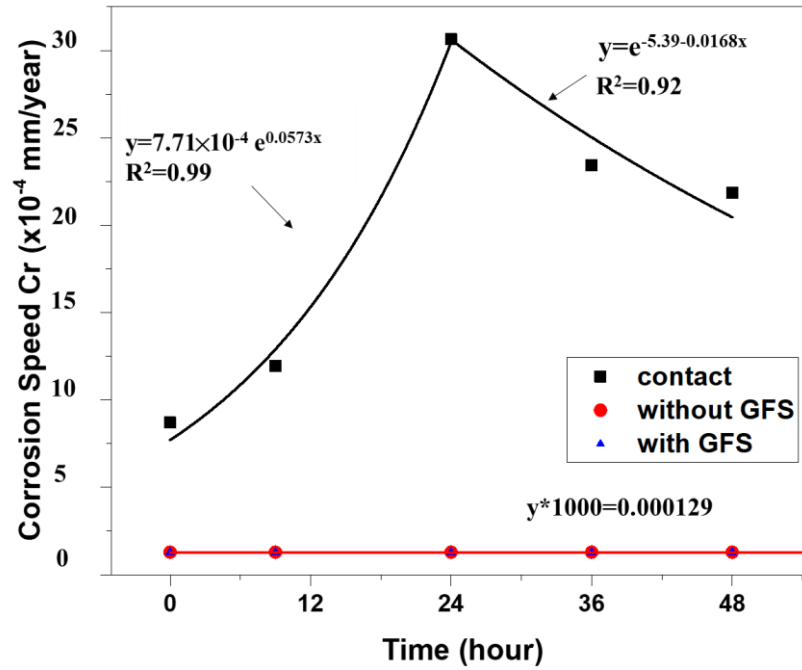


Fig. 5. Corrosion speed curves of different CFRP-steel specimens

3. Static Tension Testing of CFRP-Steel Double Strap Joints

The experimental results of the accelerated corrosion tests in Section 2 have shown that GFS can be effective to suppress the potential galvanic corrosion of CFRP-steel bonded system. However, the inclusion of GFS in the adhesive layer may affect the bond behaviour between CFRP and steel. In this study, static tension tests were conducted on CFRP-steel double strap joints with/without GFS in the adhesive layer. This is to experimentally quantify the effect of GFS on the static bond behaviour between CFRP and steel.

3.1 Specimens and test setup

Two types of CFRP-steel double strap joints with/without GFS in the adhesive were prepared as shown in Fig. 6. All the steel plates are 30 mm wide and 15 mm thick. Both types of specimens were prepared with five different bond lengths (L_1 in Fig. 6), including 50 mm, 70 mm, 90 mm, 110 mm and 130 mm. The bond length L_2 in Fig. 6 on the other side of the joint

was 1.5 times of L_1 in order to ensure that the failure only occurred on one side of the joint (L_1 side). The details of two types of joints are shown in Figs. 6a and b. All the specimens are listed in Table 2. The specimen ID starts with a letter of 'C' or 'G', with 'C' referring to joint without GFS and 'G' meaning specimen with GFS embedded in the adhesive. The digit after the first letter of the specimen ID means the bond length of the joint. For the same joint, three identical specimens were tested for repeating purpose. The repeating time is indicated by the last digit of the specimen ID. For example, specimen C70-3 means the third repeating specimen of a joint with a bond length of 70 mm, and without GFS in the adhesive.

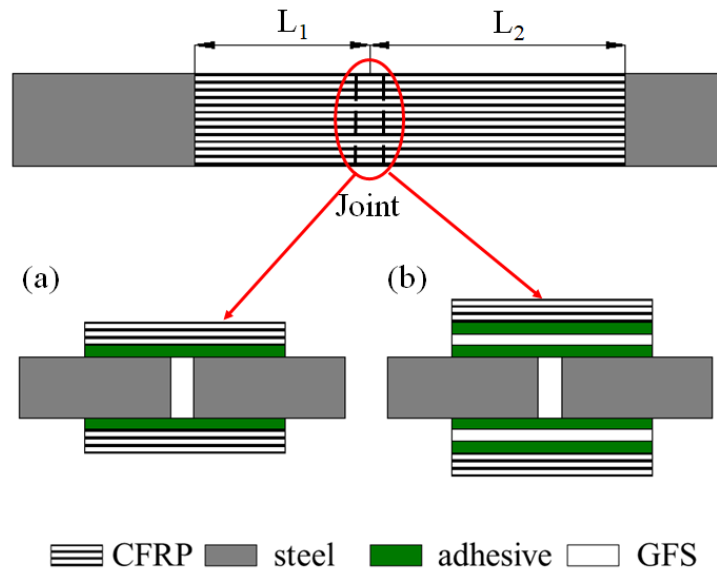


Fig. 6. Schematic view of the typical double strap joint specimen (a) with and (b) without GFS in the adhesive

The materials of CFRP, GFS, steel and adhesive of the double strap joints are the same as those of the specimens in the accelerated corrosion tests. The material properties can be found in Table 1. For the specimen preparation, the same process as introduced in [20] was used. Firstly, two steel plates were sand blasted and aligned in position on a flat table after

which a thin layer of adhesive was uniformly applied on the steel surfaces. For specimens without GFS, CFRP plate was directly attached on the steel plates with adhesive. While for specimens with GFS, the GFS was impregnated with Araldite 420 and placed on top of the first adhesive layer. Then the CFRP plate was placed on top of GFS. After the adhesive became hardened after 24 hours, the other side of the two steel plates was prepared following the same procedure. The whole specimen was then cured at room temperature for at least one week before test. The adhesive thickness of every specimen was measured with the method mentioned in [20] and listed in Table 2. It can be seen in Table 2 that the adhesive thickness of every specimen was consistent because all specimens were prepared using the same procedure. All the specimens were tested in tension using an Instron 8802 hydraulic testing machine by displacement control at a loading rate of 1 mm/min. The test was continued until the failure of the specimen.

Table 2. Experimental results of double strap joints in static tensile tests

Specimen label	Measured t_a mm	L_1 mm	F_{ult} kN	Average $F_{u,average}$ kN	failure mode
C50-1	0.38	50	73.50	75.79	steel and adhesive interface debonding & CFRP delamination
C50-2	0.34	50	75.26		steel and adhesive interface debonding & CFRP delamination
C50-3	0.41	50	78.61		CFRP delamination
C70-1	0.44	70	107.41	109.62	steel and adhesive interface debonding & CFRP delamination
C70-2	0.44	70	113.92		CFRP delamination
C70-3	0.48	70	107.54		CFRP delamination
C90-1	0.40	90	125.04	122.93	CFRP delamination
C90-2	0.46	90	120.92		CFRP delamination
C90-3	0.42	90	122.84		CFRP delamination
C110-1	0.42	110	118.49	121.41	CFRP delamination
C110-2	0.42	110	123.19		CFRP delamination

C110-3	0.45	110	122.55		CFRP delamination
C130-1	0.50	130	117.23	128.26	CFRP delamination
C130-2	0.41	130	136.08		CFRP delamination
C130-3	0.42	130	131.47		CFRP delamination
G50-1	0.32	50	74.91	80.03	steel and adhesive interface debonding & CFRP delamination & GFS fragments
G50-2	0.44	50	84.71		steel and adhesive interface debonding & CFRP delamination & GFS fragments
G50-3	0.46	50	80.48		steel and adhesive interface debonding & CFRP delamination & GFS fragments
G70-1	0.44	70	109.40	107.93	CFRP delamination & GFS fragments
G70-2	0.43	70	110.96		CFRP delamination & GFS fragments
G70-3	0.45	70	103.43		CFRP delamination & GFS fragments
G90-1	0.45	90	128.18	125.97	CFRP delamination & GFS fragments
G90-2	0.41	90	120.80		CFRP delamination & GFS fragments
G90-3	0.44	90	128.93		CFRP delamination & GFS fragments
G110-1	0.41	110	142.90	134.70	CFRP delamination & GFS fragments
G110-2	0.47	110	136.14		CFRP delamination & GFS fragments
G110-3	0.44	110	125.05		CFRP delamination & GFS fragments
G130-1	0.49	130	142.56	139.74	CFRP delamination & GFS fragments
G130-2	0.45	130	140.01		CFRP delamination & GFS fragments
G130-3	0.41	130	136.64		CFRP delamination & GFS fragments
G150-1	0.43	150	128.13	134.50	CFRP delamination & GFS fragments
G150-2	0.42	150	134.58		CFRP delamination & GFS fragments
G150-3	0.43	150	140.79		CFRP delamination & GFS fragments

215

216 3.2 Failure mode

217 Two failure modes of double strap joints were observed as shown in Fig. 7. The failure mode
218 of each specimen was also recorded in Table 2. It can be seen in Table 2, for specimens with a
219 short bond length of 50 mm, the failure mode was a mixture of steel and adhesive interface
220 debonding and CFRP delamination (see Figs. 7a and c). For specimens with longer bond length,
221 only CFRP delamination was observed (see Figs. 7b and d). This observation was the same for
222 both specimens with/without GFS in the adhesive layer, which indicates that the failure mode
223 of the CFRP-steel joint was not affected by the GFS. It should also be noted that GFS fragments

can be observed on the fracture surface of specimens with CFRP delamination failure mode (see Figs. 7c and d). This indicates that the GFS fractured in the test which may affect the bond strength of the joint. This will be further discussed in the following sections.

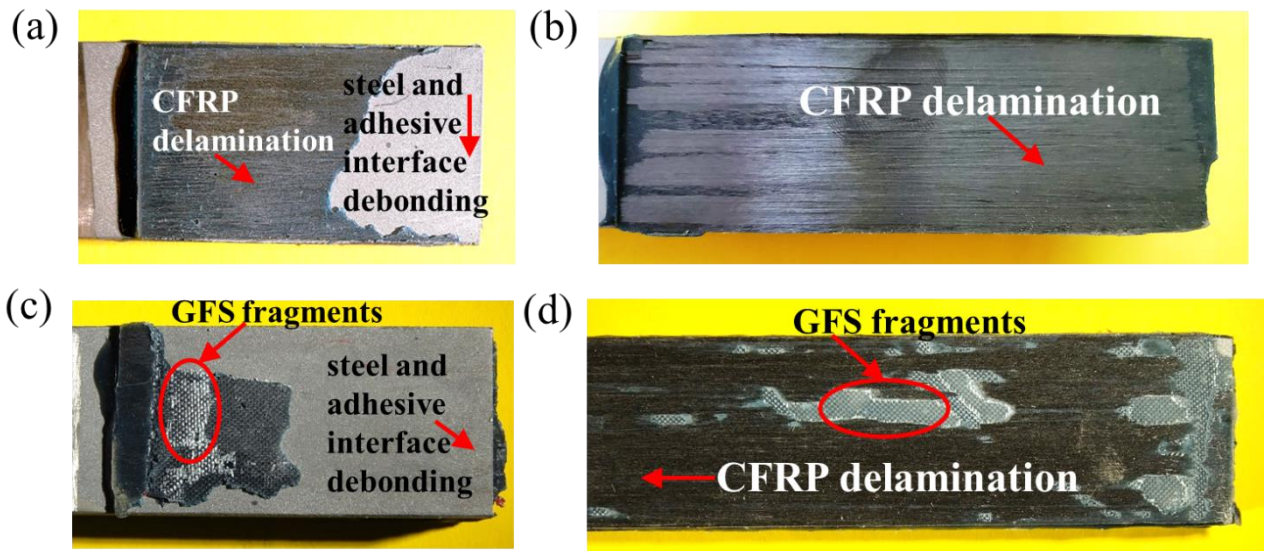


Fig. 7. Typical failure modes of CFRP-steel double strap joints (a) short bond length without GFS (C50); (b) long bond length without GFS (C130); (c) short bond length with GFS (G50); (d) long bond length with GFS (G150)

3.3 Bond strength and effective bond length

The bond strength is defined as the ultimate failure load of the double strap joint (F_{ult}). The bond strengths of all the specimens are plotted against the corresponding bond lengths in Fig. 8. It can be seen for all specimens with/without GFS in the adhesive, the bond strength initially increased with the bond length and then reached a plateau. The bond length beyond which no more bond strength can be achieved is defined as ‘effective bond length’ or L_e . As can be seen in Fig. 8., L_e is approximately 110 mm for CFRP-steel joints with GFS, which is longer than that of joints without GFS (90 mm).

It can also be observed in Fig. 8 that the bond strength of the joints with GFS is a little higher than that of specimens without GFS, especially for specimens with a bond length longer than L_e . For example, the average bond strength of G130 is 139.74 kN which is 8.95% higher than that of C130 (128.26 kN). Therefore, it indicates that the inclusion of GFS in the adhesive may have positive effect on the bond behaviour between CFRP and steel, i.e. longer L_e and higher bond strength. This may be related to the failure mode of joint with GFS. As shown in Figs. 7c and d, GFS fragments can be observed on the fracture surface of the bond, indicating GFS fracture in the test. Therefore, GFS may contribute to the load carrying mechanism of the bond thus the bond strength of joint is slightly increased.

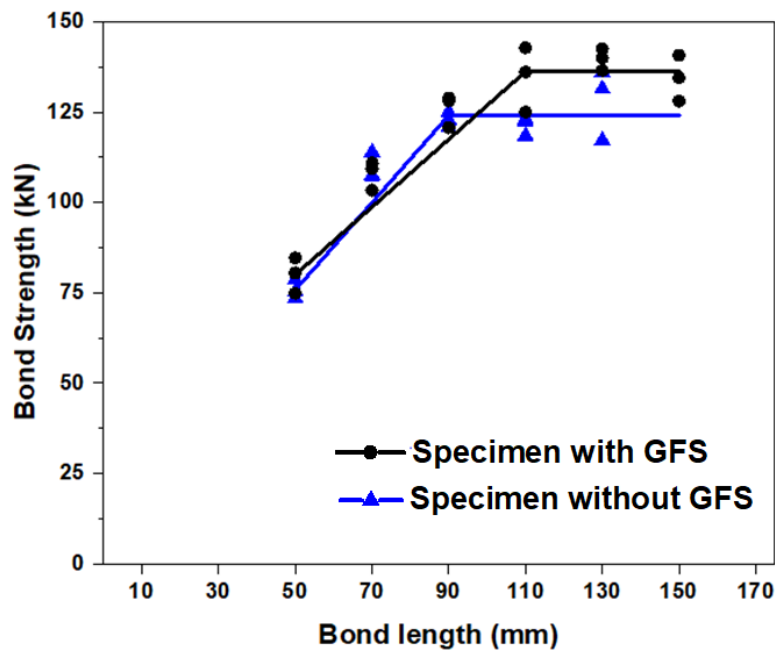


Fig. 8. Relationship of bond strength and bond length of double strap joints with/without GFS

4. Fatigue Testing of CFRP-Steel Double Strap Joints

From the experimental results of the static tension testing, it can be seen that inclusion of GFS in the adhesive is beneficial to increase the bond strength and effective bond length of CFRP-

steel joint. It is also necessary to understand how GFS will affect the bond between CFRP and steel under fatigue loading. Two types of fatigue tests were conducted to evaluate the effect of GFS on the bond behaviour between CFRP and steel under fatigue loading. In the first fatigue tests, CFRP-steel double strap joints with/without GFS were tested under fatigue loading with various load ranges until failure of the specimens. The fatigue lives of specimens with/without GFS were compared to see how GFS would affect the fatigue life of CFRP-steel joints. In the second fatigue tests, CFRP-steel double strap joints with/without GFS were tested under the same fatigue loading but with different number of cycles. When the fatigue loading stopped, the specimens were statically tensioned to failure. The failure load was defined as the residual bond strength. By comparing the experimental results of joints with/without GFS, the effect of GFS on the residual bond strength and residual bond stiffness between CFRP and steel can be investigated.

4.1 Fatigue life testing of CFRP-steel double strap joints

CFRP-steel double strap joints with/without GFS were prepared. All specimens had a bond length of 50 mm, which was shorter than the corresponding L_e . The selection of this bond length was to eliminate the effect of L_e on the fatigue behaviour of the joints. For the fatigue loading, a stress ratio of 0.1 was adopted which is the ratio between the min and max fatigue loads (F_{min} and F_{max}) applied on the joint. Two load ratios of 0.5 and 0.8 were used which is the ratio between the max fatigue load (F_{max}) and the ultimate static failure load (bond strength F_{ult}) of the joint.

The specimens for testing the fatigue lives are listed in Table 3. The name of each specimen consists of three parts. The first letter of 'C' or 'G' represents specimens with or

without GFS in the adhesive layer respectively. The following number after the first letter means the load ratio of the fatigue loading. The last digit stands for the repeating time of the same specimen. For repeating purpose, three identical specimens were tested under the same loading condition.

Table 3 Specimens and experimental results for fatigue life testing of double strap joints

Specimen label	Measured t_a mm	Fatigue load range kN	Fatigue life cycles	Average fatigue life	Failure mode
C0.5-1	0.49	3.79-37.90	20201	24812	CFRP delamination & cohesive failure
C0.5-2	0.47	3.79-37.90	30998		CFRP delamination & cohesive failure
C0.5-3	0.49	3.79-37.90	23238		CFRP delamination & cohesive failure
C0.8-1	0.42	6.06-60.64	1346	1191	CFRP delamination & cohesive failure
C0.8-2	0.48	6.06-60.64	1043		CFRP delamination & cohesive failure
C0.8-3	0.43	6.06-60.64	1184		CFRP delamination & cohesive failure
G0.5-1	0.41	4.00-40.02	19540	15363	cohesive failure & GFS fragments
G0.5-2	0.42	4.00-40.02	12598		cohesive failure & GFS fragments
G0.5-3	0.41	4.00-40.02	13952		cohesive failure & GFS fragments
G0.8-1	0.44	6.40-64.02	523	631	cohesive failure & GFS fragments
G0.8-2	0.43	6.40-64.02	685		cohesive failure & GFS fragments
G0.8-3	0.41	6.40-64.02	684		cohesive failure & GFS fragments

4.1.1 Failure modes

As shown in Fig. 9, the failure mode of each specimen is a mixture of CFRP delamination, steel-adhesive interface debonding. Cohesive failure was observed for all specimens regardless with/without GFS. CFRP delamination was only observed for specimens without GFS (Fig. 9a). While for specimens with GFS, the fragmentation of GFS can be clearly observed on the fracture surface (Fig. 9b). The fracture surfaces of all failed double strap joints were finally investigated using a BJMICRO industrial digital camera. Typical microscope images of fracture surfaces are shown in Figs. 9(c) and (d) for specimens without and with GFS, respectively. From Fig. 9(c), delaminated carbon fibers and exposed adhesive can be observed on the fracture surface of specimen without GFS. The delaminated carbon fibers are uniformly distributed on the surface in the loading direction. On the other hand, in Fig. 9(d), the glass fibers from GFS can be clearly observed in addition to the delaminated carbon fibers. In GFS, the glass fibers are woven in orthotropic directions. Therefore, the fibers vertical to the loading direction in Fig. 9(d) are glass fibers from GFS. It can be seen in Fig.9(d) that, carbon fibers become nonuniform and interrupted by glass fibers, indicating that the integrity of the bondline was violated by GFS and defects are introduced into the interface.

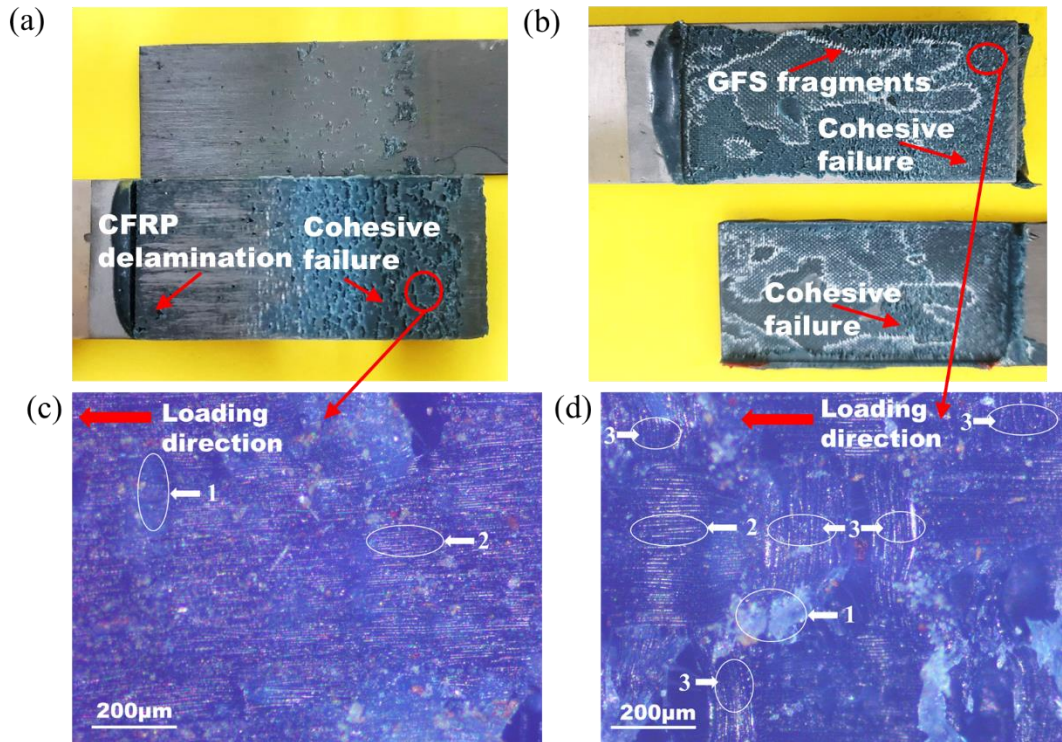


Fig. 9. Typical failure modes of CFRP-steel double strap joints under fatigue loading (a) without GFS, (b) with GFS, (c) microscope image of fracture surface without GFS, (d) microscope image of fracture surface with GFS. The numbers in the figures mean: number 1 is exposed adhesive in the bondline, number 2 is carbon fiber delamination from CFRP plate, number 3 is glass fibers delamination from GFS

4.1.2 Fatigue lives

The number of loading cycles until failure (i.e., fatigue life) for each specimen in the fatigue tests are presented in Table 3. The fatigue lives of specimens with/without GFS are compared in Fig. 10. It can be seen in Fig. 10 that, under the same load ratio, the specimens with GFS generally exhibited shorter fatigue life comparing to specimens without GFS. For example, the average fatigue life of G0.5 was 15363 cycles and that of G0.8 was 631 cycles. They were 61.5% and 88.7% shorter than the average fatigue lives of C0.5 (24812cycles) and C0.8 (1191

cycles) respectively. It can be found that when the load ratio increased to 0.8, the fatigue lives of specimens with/without GFS decreased by 95.89% and 95.12%, respectively. This phenomenon indicates that regardless of GFS in the adhesive, the fatigue lives of the joints always sharply decrease when undergoing extreme load level (0.8 of ultimate static failure load). It should be noted that in real structures, the load ratio of 0.8 will not be experienced in service condition. Therefore, the short fatigue lives of 1191 and 631 in Table 3, which are outside the high cycle fatigue region, are only for comparison purpose in the current study.

Therefore, from the experimental results shown in Fig. 10, it seems the GFS has negative effect on the fatigue behaviour of the bond between CFRP and steel. This may be associated with the failure modes shown in Fig. 9. Because of the inclusion of GFS in the adhesive, more defects at the interfaces between GFS and adhesive were introduced in the bond. Under fatigue loading, the damage may accumulate at the interfaces between GFS and adhesive and propagates until the fracture of the GFS within the joint. Although the fragment of GFS is helpful to increase the static bond capacity, the fatigue behaviour of the bond seems more sensitive to the bond defects introduced by GFS.

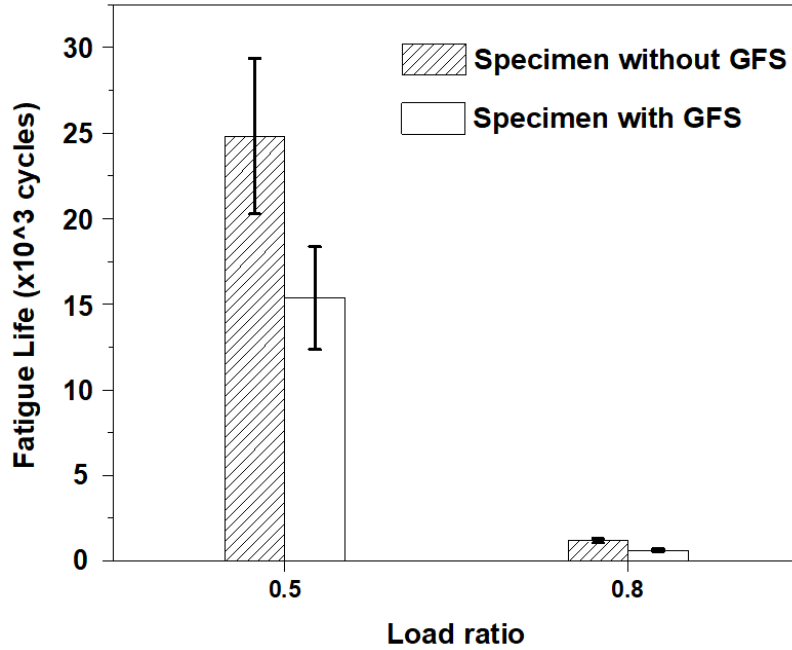


Fig. 10. Fatigue lives of double strap joints with/without GFS

4.2 Residual strength and stiffness testing of CFRP-steel double strap joints

The same CFRP-steel double strap specimens with/without GFS as those in the first batch fatigue tests were prepared with a 50 mm bond length. Firstly, all specimens were statically tensioned upto 50% of corresponding joint capacity then unloaded. This loading and unloading process was repeated for three times. This first step was to measure the static stiffness of the joint before it was put under fatigue loading. Then all specimens were tested under a fatigue loading with a load ratio of 0.5 and a stress ratio of 0.1. After a certain number of fatigue cycles, the fatigue tests were stopped and all the specimens were statically tensioned to failure. By comparing the static behaviour before and after the fatigue loading, the effect of GFS on the residual bond behaviour between CFRP and steel could be investigated. All specimens are listed in Table 4. The names of the specimens have two parts. The first part, 'C_{ft}' or 'G_{ft}', refers

to joints with or without GFS respectively. Two identical specimens were tested for repeating purpose.

4.2.1 Failure modes

Typical failure modes of specimens with/without GFS are shown in Fig. 11. It can be seen that all specimens exhibited a mixture of CFRP delamination and steel-adhesive interface debonding regardless of the inclusion of GFS. For specimens with GFS, the fragment of GFS can also be observed on the fracture surface (Fig. 11b).

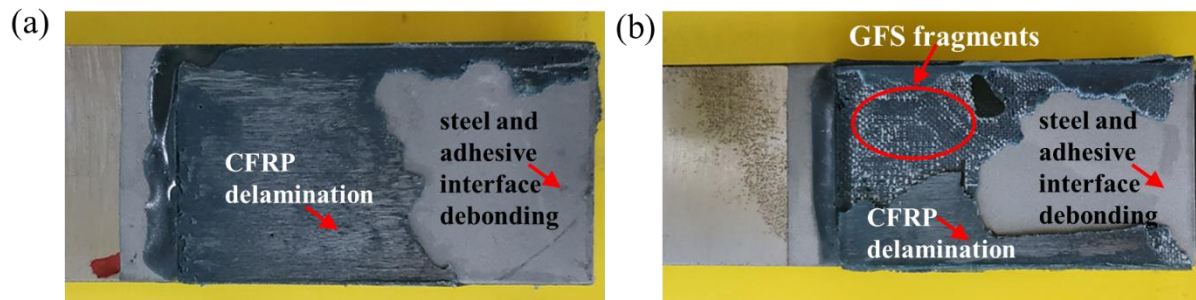


Fig. 11. Typical failure modes of CFRP-steel double strap joints (a) without GFS and (b) with GFS

Table 4 Specimens and residual strength and residual stiffness of double strap joints after fatigue loading

Specimen label	Fatigue load range kN	Fatigue loading cycles	Residual bond strength F_f kN	Stiffness before/after fatigue loading K_{before} / K_{after} kN/mm	Failure mode
C _{ft} -1	3.79-37.90	15000	73.99	117.54/111.83	CFRP delamination & steel-adhesive debonding
C _{ft} -2	3.79-37.90	15000	77.33	137.48/114.13	CFRP delamination & steel-adhesive debonding

G _{ft} -1	4.00-40.02	9000	73.13	144.78/104.44	CFRP delamination & steel-adhesive debonding & GFS fragments
G _{ft} -2	4.00-40.02	9000	76.65	145.99/104.68	CFRP delamination & steel adhesive debonding & GFS fragments

351

352 4.2.2 Residual bond strength after fatigue loading

353 As shown in Table 4, it should be noted that for specimens without GFS, the fatigue tests were
354 continued for 15000 cycles, while for 9000 cycles for specimens with GFS. These number of
355 cycles were selected because they were 60% of the corresponding fatigue lives of those
356 specimens (see Table 3).

357 The residual bond strengths of the specimens after fatigue loading, F_f , are listed in Table
358 4. The bond strength ratio between the residual bond strength (F_f) and the corresponding static
359 bond strength without fatigue loading (F_{ult} , in Table 1), F_f/F_{ult} , can be used to assess the effect
360 of GFS on the residual bond strength of the double strap joints. The bond strength ratios (F_f/F_{ult})
361 are plotted in Fig. 12.

362 It can be seen from Fig. 12 that the fatigue loading has very limited effect on the bond
363 strength of specimens without GFS. The residual bond strength of C_{ft}-2 was even slightly
364 higher than the static bond strength of the same joint without fatigue loading. This negligible
365 effect of fatigue loading on the bond strength was attributed to the limited fatigue damage zone
366 in the bondline. More details regarding the associated mechanism can be found in [21].

On the other hand, more reduction in the residual bond strength was observed for specimens with GFS after being subjected to fatigue loading. The maximum reduction was 8.62%. Since the specimens with GFS were only subjected to 9000 cycles of fatigue loading, it is expected to have more accumulated fatigue damages and consequently more reductions in residual bond strength if they should have been subjected to the same number of cycles of fatigue loading (15000 cycles) as those specimens without GFS.

According to the experimental results, it seems the inclusion of GFS in the adhesive layer has negative effects on the residual bond strength which may decrease when subjected to fatigue loading. Similarly, this is most probably attributed to the interface defects in the bondline introduced by the GFS. As can be seen from the failure mode in Fig. 11b, GFS fragments were observed on the fracture surface. This may be due to the damage propagation from the interface defects between GFS and adhesive.

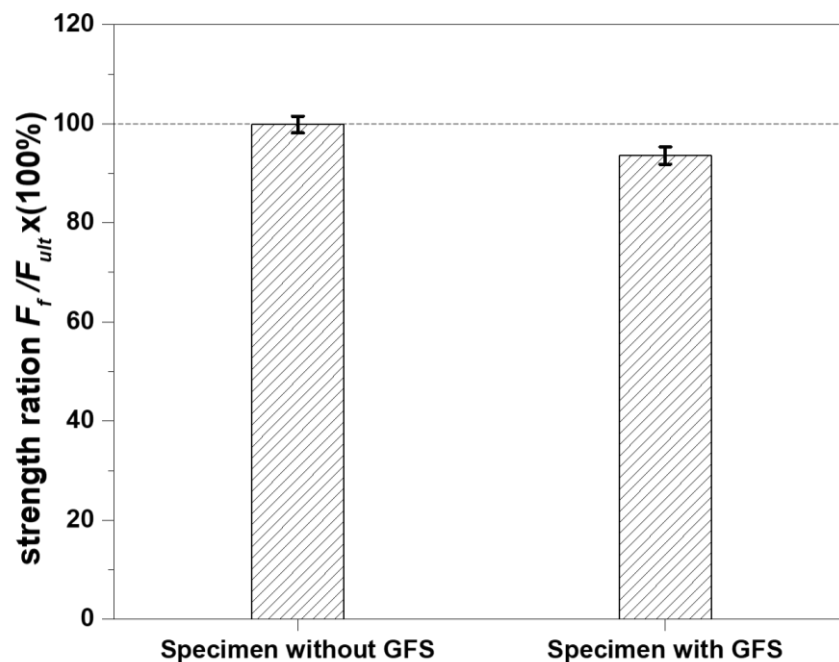


Fig. 12. Effect of GFS on the residual bond strength of double strap joints

4.2.3 Residual stiffness after fatigue loading

The stiffness is defined as the slope of the load-displacement curve of the double strap joint under tension. Comparing the joint stiffness before and after fatigue loading provides another angle for understanding the effect of GFS on the bond behaviour between CFRP and steel. The ratios of the stiffness after and before the fatigue loading are compared in Fig. 13. It can be seen from Fig. 13 that the average stiffness reduction of specimen without GFS is 10.92%. On the other hand, more reductions in joint stiffness was observed for specimen with GFS (28.08% in average). It seems that the inclusion of GFS in the adhesive also has negative effect on the stiffness of the CFRP-steel double strap joint. The reason is the same as that for residual bond strength of the joint, which is due to the defects in the bond introduced by the GFS.

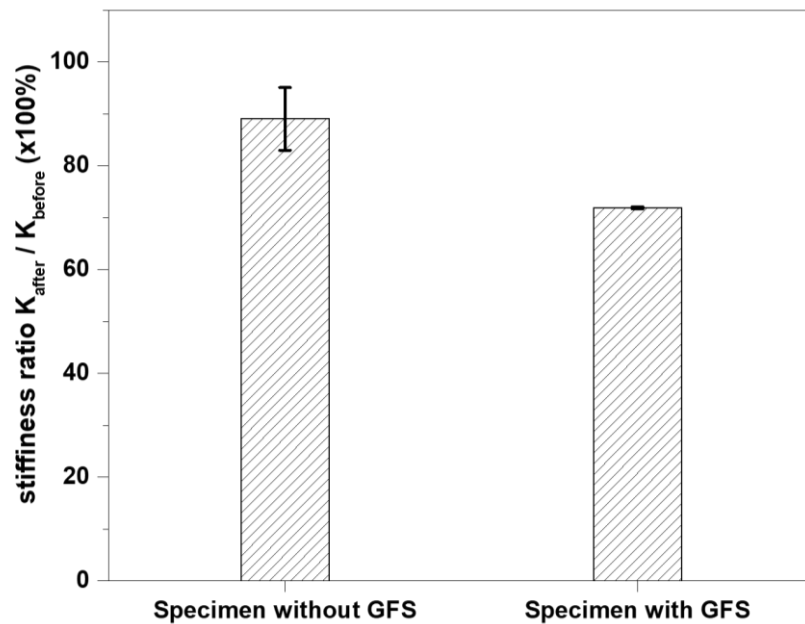


Fig. 13. Effect of fatigue loading on the residue stiffness of CFRP-steel double strap joint

5. Conclusions

The effect of GFS on the galvanic corrosion and bond behaviours of CFRP-steel bonded system is investigated in this paper. Three types of experimental testing were conducted including accelerated corrosion test, static tension test and fatigue test with CFRP-steel double strap joints with/without GFS in the adhesive. Based on the experimental results and observations in this paper, the following conclusions can be drawn:

- a. The adhesive layer alone can be effective to suppress the potential galvanic corrosion of CFRP-steel bonded system. Embedding GFS in the adhesive can provide one additional protection to reduce the galvanic corrosion hazard. However, this conclusion is only valid when the quality of bonding process of CFRP to steel is strictly controlled and no contact between carbon fiber and steel exists. If the bonding quality is not well controlled, neither the adhesive nor GFS can be effective and the galvanic corrosion is inevitable;
- b. Under either static or fatigue loading, GFS has little effect on the failure modes of CFRP-steel double strap joints, except that GFS fragments can be observed on the fracture surface of specimens with GFS;
- c. The inclusion of GFS in the adhesive can be useful to slightly increase the effective bond length and bond strength of CFRP-steel double strap joints under static loading;
- d. On the other hand, the inclusion of GFS may reduce the fatigue life of CFRP-steel double strap joints under fatigue loading; and more reductions in residual bond strength and residual stiffness of the joints after being subjected to fatigue loading were observed when GFS was embedded in the bond line.

e. The negative effect of the GFS on the fatigue behaviour of the bond between CFRP and steel can be attributed to the defects which were introduced by the GFS in the adhesive.

The experimental results indicate that the inclusion of GFS can only slightly increase the bond strength and effective bond length under static loading, but will negatively affect the bond behaviour under fatigue loading. Considering the adhesive alone can be effective to suppress potential galvanic corrosion of CFRP-steel bonded system provided good quality control of the bonding process, it seems not necessary to use GFS for the protection of the galvanic corrosion. Therefore, for engineering practice, it is recommended to strictly control the quality of the bonding process. If the project budget allows, GFS can be embedded in the adhesive to provide additional protection in projects which are not sensitive to fatigue loading.

Acknowledgments

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Data Availability Statement

The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

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