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Effect of Surface Preparation on the Strength of FRP-to-Mild Steel and FRP-to-Stainless Steel Joints

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ABSTRACT: A detailed understanding of the strength and behaviour of the bond between fibre-reinforced polymer (FRP) composites to metals is an ongoing field of research. The many different geometrical and material parameters make for extensive research demands. This paper in turn reports a series of tests on the shear strength and behaviour of FRP-to metal joints in which the main test parameters, which have received limited attention to date, consists of (i) type of metal (i.e. non-galvanised mild steel and stainless steel), and (ii) surface preparation technique (i.e. different mechanical abrasion methods). All specimens are loaded in displacement control which enables the failure process to be followed and identification of different failure modes to be made. The results enable the effectiveness of different surface preparation techniques upon the bond of FRP to different types of metals to be made.

1 INTRODUCTION

Externally bonded fibre-reinforced polymer (FRP) composites can strengthen metallic members (Hol-laway and Teng 2008). For example, Silvestre et al. (2008) showed the load-carrying capacity of cold-formed steel lipped channel columns strengthened by FRP to be enhanced by up to 20% above control specimens. The effectiveness of the strengthening is, however, largely dependent upon the quality of the bond between the two materials. In particular, understanding the effect of different surface preparation techniques, in addition to the effect of such techniques on different metals, are two important issues which have received limited attention to date.

In adhesively bonded FRP-to-FRP joints, failure has been classified into seven distinct modes (ASTM D5573-99 2005) namely; (i) adhesive failure (ADH), (ii) cohesive failure (COH), (iii) thin-layer cohesive failure (TLC), (iv) fibre-tear failure (FT), (v) light-fibre-tear failure (LFT), (vi) stock-break failure (SB), and (vii) mixed failure (any combination of two or more failure modes). Further subdivision produces *interfacial failure* (i.e. ADH, TLC, FT and LFT), *cohesive failure* (i.e. COH), *adherend failure* (i.e. SB) and *mixed failure*. Such a classification system does not yet exist for FRP-to-metal joints.

A commonly reported FRP-to-metal joint failure mode is *interfacial failure* (e.g. Xia and Teng 2005, Zhao and Zhang 2007). In such joints, the prepara-

tion of the surface of the metal is an important parameter which requires further investigation.

A series of tests is reported in this paper on the shear strength and behaviour of single-lap FRP-to-metal joints. The main test variables are (i) surface preparation, and (ii) type of metal. The results enable the most suitable surface preparation techniques to be determined for two different metals. In addition, the test results will also enable the future development and calibration of analytical models. A much more detailed account of the tests can be found in Kim et al. (2010).

2 EXPERIMENTAL DETAILS

2.1 Test set-up and details of test specimens

The single-lap shear test set-up utilised in this study is shown in Figure 1. In order to minimise bending of the test specimens, the metal plate was stiffened. The flexural rigidity ratio of the stiffened metal plates to FRP was over 13,000 which resulted in minimal bending of the metal plates during testing. The two main test parameters were (i) four different types of surface preparation techniques, and (ii) two different types of metals. The total number of test specimens was twenty-four (i.e. three identical test specimens for each of the eight test permutations). The properties of the two different metals (i.e. mild steel and stainless steel) are fully described in Section 2.2. The four different surface techniques of (i)

solvent wiping, (ii) light sanding, (iii) grinding, and (iv) needling, are described in detail in Section 2.3.

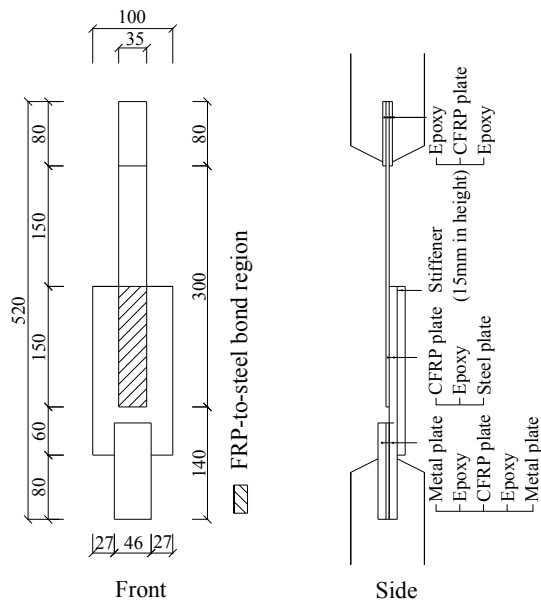


Figure 1. Test set-up.

A constant adhesive thickness was maintained by adhering small plastic prisms of equal size to the metal substrate prior to bonding of the FRP. Post-test measurements revealed an average adhesive thickness of 1.3 mm and standard deviation of 0.1 mm. A long bond length of FRP (i.e. 150 mm) and slow loading rate (0.2 mm/min) was utilised in order to capture the full failure process of the joints.

2.2 Materials

All metal plates were nominally 9 mm thick. Three coupons were averaged to produce yield strengths of 322 MPa and 426 MPa and elastic moduli of 212 GPa and 178 GPa for the mild and stainless steels, respectively. Five FRP coupons (nominal thickness of 1.4 mm) were tested and averaged to produce an elongation at rupture of 1.47 %, tensile strength of 3,367 MPa and elastic modulus of 230 GPa. Five dog-bone shaped epoxy adhesive samples were tested and averaged to produce an elongation at rupture of 0.36 %, tensile strength of 27 MPa and elastic modulus of 8,886 MPa.

2.3 Surface preparation

The four different surface preparation techniques considered in this study were (i) no treatment (denoted as NT), (ii) sanding of the metal surface with fine sandpaper attached to an electric sander (i.e. 220 grit sandpaper comprising an average particle diameter of 68 μm) (denoted as SF), (iii) grinding of the metal surface with a 11000 rpm 840w electric angle grinder fitted with a metal grinding wheel (denoted as GR) and (iv) needling of the metal surface

with a pneumatically powered needle scaler containing 26 \times 2.8 mm diameter needles (denoted as NS). Prior to application of the FRP to all prepared surface, the surfaces were cleaned by wiping with a solvent (i.e. an aromatic and oxygenated solvent). The time which elapsed from the beginning of the surface preparation treatment to the application of the FRP was limited to 3 hours. Such limitation of time was primarily on account of minimising the oxidised layer that formed on the surface of the mild steel. Note that the stainless steel did not contain any form of protective coating.

For preparation by sanding (i.e. SF), the electric sander was applied for 3 minutes with new sandpaper used for each specimen. Of the three minutes, one minute was devoted to sanding parallel to the longitudinal axis of the plate and then one minute for $\pm 45^\circ$ to the longitudinal axis. The grinding and needling techniques were also applied for 3 minutes for each specimen although in no specific manner. In the case of grinding, an optimal surface preparation was achieved when the base metal was exposed. Optimal needling occurred when the complete bond surface was affected. In the case of sanding (i.e. SF), a very small portion of the mild steel oxide layer was removed (Figure 2b). In the case of grinding, the bare steel was exposed (Figure 2c) for the mild steel although the surface texture was the same for both mild steel and stainless steel. The needling left minor impressions on the surface for both mild steel and stainless steel and partially removed the oxide layer from the mild steel (Figure 2d).

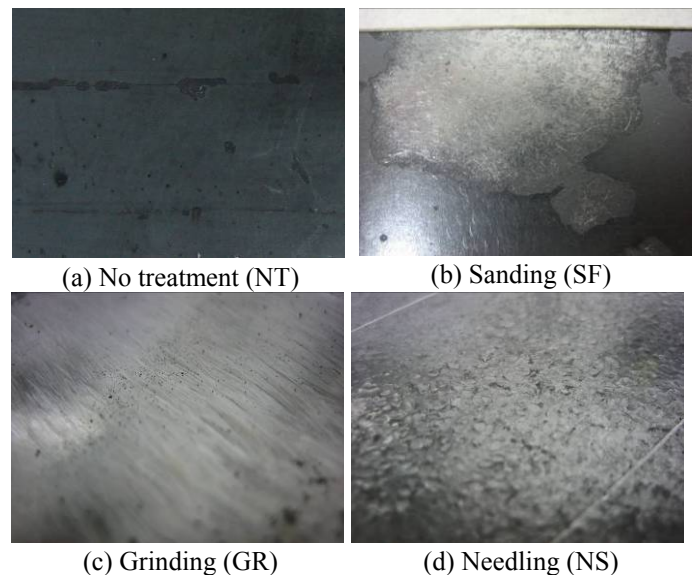


Figure 2. Surface preparation techniques.

3 TEST RESULTS

A summary of the measured adhesive thickness and FRP plate dimensions in addition to the failure loads and failure modes are provided in Table 1.

3.1 Failure modes

All specimens failed by debonding which generally occurred in a sudden manner. The failure sequence involved initial cracking between the FRP and metal at the loaded plate end (Figure 3a) which then propagated toward the plate end (Figure 3b). The modes of failure can be categorised into two main categories (i.e. *Modes 1* and 2) as per the following. One of the failure modes is further sub-divided.

Mode 1: Adherend failure in oxidised layer

Mode 2A: Thin-layer cohesive failure in metal-to-adhesive interface

Mode 2B: Thin-layer cohesive failure in FRP-to-adhesive interface

Mode 2C: Mixed thin-layer cohesive failure

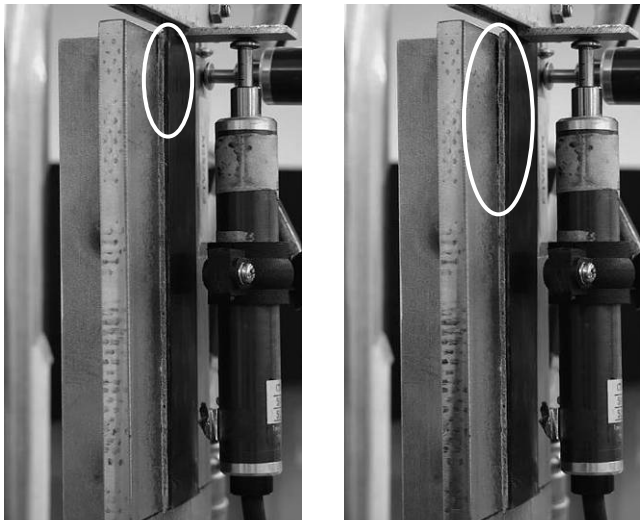


Figure 3. Debonding crack (SS-NS-2).

Table 1 Test results

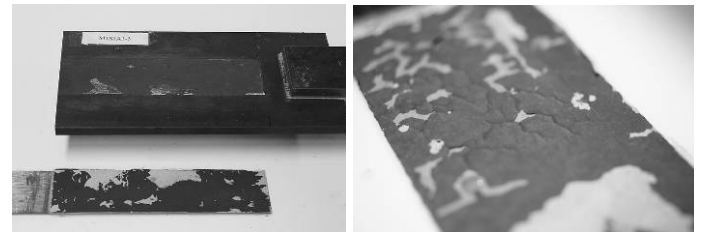
Specimen*	Adhesive Thickness# (mm)	FRP		P _u (kN)	Failure Mode
		Width# (mm)	Length# (mm)		
MS-NT-1	1.5	36.0	150.7	28.0	Mode 1
MS-NT-2	1.4	36.0	150.3	22.9	Mode 1
MS-NT-3	1.3	36.0	150.6	30.4	Mode 1
MS-SF-1	1.3	35.7	150.3	32.5	Mode 1
MS-SF-2	1.4	35.4	152.3	31.5	Mode 1
MS-SF-3	1.4	36.3	150.7	35.9	Mode 1
MS-GR-1	1.2	35.1	152.0	33.0	Mode 2B
MS-GR-2	1.5	35.7	151.0	34.5	Mode 2B
MS-GR-3	1.3	35.2	150.2	33.8	Mode 2B
MS-NS-1	1.2	35.4	151.2	31.7	Mode 2B
MS-NS-2	1.4	36.1	151.4	31.7	Mode 2B
MS-NS-3	1.3	34.8	153.6	36.2	Mode 2B
SS-NT-1	1.3	35.1	151.4	35.5	Mode 2A
SS-NT-2	1.5	35.6	151.6	33.4	Mode 2A
SS-NT-3	1.3	36.2	152.1	37.5	Mode 2A
SS-SF-1	1.4	35.9	150.9	35.8	Mode 2B
SS-SF-2	1.3	35.8	150.5	41.3	Mode 2B
SS-SF-3	1.4	34.9	150.6	37.4	Mode 2B
SS-GR-1	1.5	34.7	149.8	34.8	Mode 2C
SS-GR-2	1.4	35.9	151.6	37.0	Mode 2C
SS-GR-3	1.4	35.4	151.3	35.0	Mode 2C
SS-NS-1	1.2	36.2	150.3	32.2	Mode 2A
SS-NS-2	1.3	36.1	150.7	31.0	Mode 2A

SS-NS-3	1.3	35.0	151.3	33.0	Mode 2A
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* MS (Mild steel)/SS (Stainless steel), NT (No treatment)/SF (Sanding)/GR(Grinding)/NS (Needling) # Measured dimension

Mode 1

All six mild steel specimens with sanded surfaces or surfaces with no preparation failed in a Mode 1 manner (Figure 4). Figure 4a shows the failure interface to be located either purely in the oxidised layer-to-base metal interface or in combination with the adhesive-to-oxidised layer (Figure 4b).



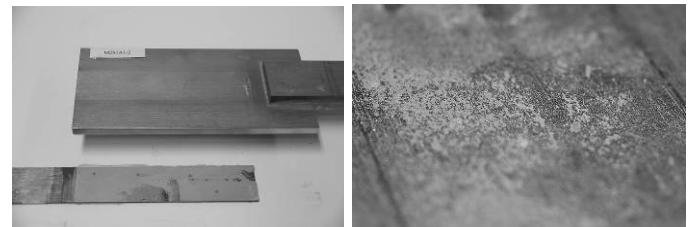
(a) MS-NT-3

(b) Peeled off oxidised layer on metal surface

Figure 4. Mode 1 failure.

Mode 2A

Mode 2A failure occurred in all six stainless steel specimens prepared by needling or with no treatment. For these specimens, the epoxy was completely removed (Figure 5a) with a very thin layer adhesive (herein referred to as a *light-dusting*) remaining attached to the metal surface (Figure 5b).



(a) SS-NT-1

(b) Light-dusting of adhesive on stainless steel

Figure 5. Mode 2A failure.

Mode 2B

All mild steel specimens prepared with grinding or needling failed in a Mode 2B manner while the stainless steel specimens prepared with sanding also failed in the same manner. Similar to Mode 2A failures, all specimens exhibited near complete delamination (> 90 % of the bond region) of the FRP plate from the adhesive (Figure 6a) with a light-dusting of adhesive remaining attached to the FRP surface (Figure 6b). A very small portion of adhesive (< 10 %) remained attached to the metal in the stainless steel specimens; in such cases the adhesive detached from the metal substrate (Figure 6b). In some cases, splitting of the FRP plates along the fibre direction was observed post-debonding failure.

Mode 2C

This failure mode was observed in all three stainless steel specimens prepared by grinding. The failure interfaces were located in both the metal- and FRP-to-adhesive layers (Figure 7). A light-dusting of adhesive was observed on the failure surfaces.

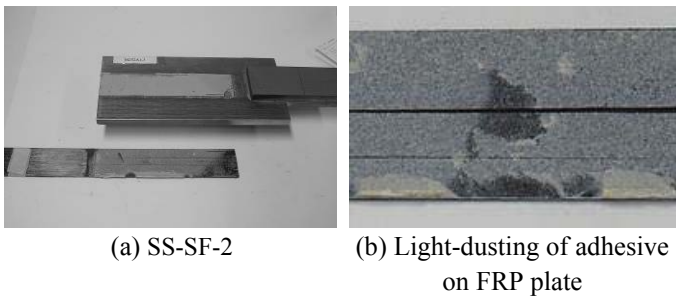


Figure 6. Mode 2B failure

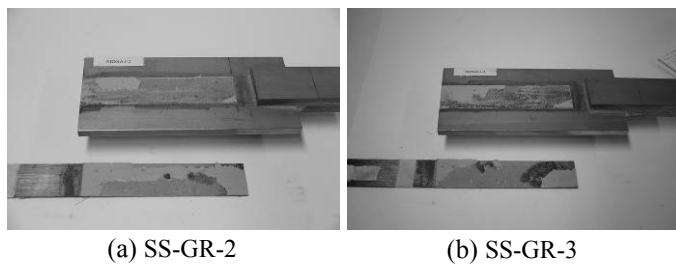


Figure 7. Mode 2C failure.

3.2 Effect of surface preparation techniques

The effect of the different methods of surface preparation upon the stainless steel joints was much more obvious than the mild steel joints (Figure 8). The weak oxidised layer inherent in mild steel was the important contributing factor making the results less sensitive to the surface preparation method. Grinding was marginally the most optimal on average.

As the rate of oxidisation of stainless steel is well below that of mild steel, the former did not suffer from the same fate as the latter. As a result, Figure 8 reveals the optimal method of preparation for stainless steel is via sanding although there is a deal of scatter in the results. It would appear that the surface damage caused by the needle gun severely affects the strength of the bond for FRP-to-stainless steel. The strength of FRP-to-mild steel joints was superior to FRP-to-stainless steel joints.

3.3 Load-displacement response

Figure 9 shows typical load-displacement responses for both mild steel and stainless steel specimens. Typical responses for each of the four different surface preparation techniques for mild steel yielded slightly different behaviours, while all stainless steel specimens yielded approximately the same behaviour. Stainless steel exhibited a peak load plateau.

4 CONCLUSIONS

The fundamental behaviour and strength of FRP-to-metallic joint assemblies, in which different metals have been prepared with different surface preparation techniques, have been reported. The most suitable preparation methods for mild-steel and stainless steel was grinding and sanding respectively. In addition, four distinct failure modes were observed. In the case of mild-steel, it is important to minimise the time allowed for oxidation to occur.

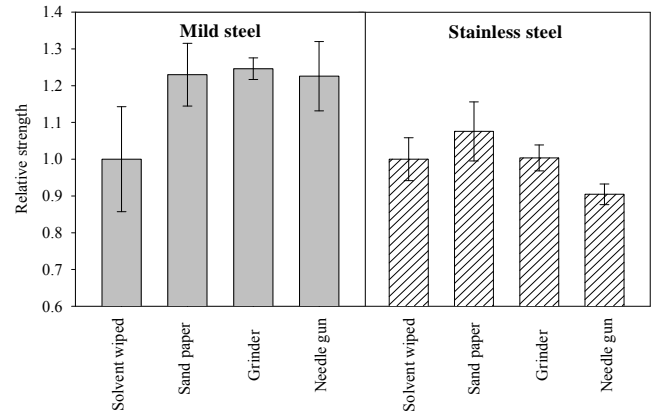


Figure 8. Relative strength enhancements (relative to solvent wiped specimens)

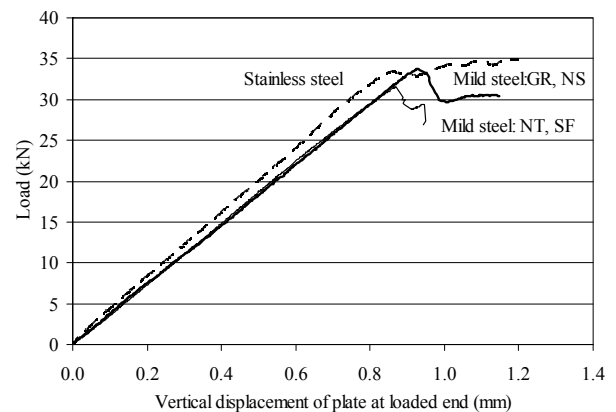


Figure 9. Load-displacement response.

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