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Adhesively bonded CFRP system using recycled MCF enhanced epoxy for strengthening steel structure

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ABSTRACT: This paper investigates the mechanical performance of a structural adhesive epoxy enhanced using milled carbon fibre (MCF) and the bond performance of carbon fibre reinforced polymer (CFRP) and steel adhesively bonded joints using the enhanced epoxy. MCF was recycled from general CFRP products and with an average length of 100 um. The epoxy was enhanced using such MCFs with different weight ratios of 1.5%, 3% and 5%. Tensile experiments were performed on the original and enhanced epoxy specimens according to ASTM D638. More ductile failure process was found for the epoxy after modification and significant improvements of E-modulus and tensile strength were evidenced when the MCF weight ratio is larger than 1.5%. Scanning electron microscopy (SEM) revealed that the failure mechanism of short MCFs pulled out from the epoxy matrix contributed to the enhancement of the mechanical performance of the epoxy. Steel/CFRP double strap joints were prepared using the enhanced epoxy and then tested in tension however no obvious increase in joint stiffness or strength was observed.

1 INTRODUCTION

Steel structures are susceptible to corrosion and fatigue damages and there is an urgent need to repair and retrofit such deteriorated steel structures. The use of adhesively bonded CFRP composites in strengthening of steel structures may be an advantageous solution, because of excellent mechanical properties of CFRP such as high strength to weight ratios (with an E-modulus of 240 GPa and nominal tensile strength of 3800 MPa) and excellent resistance to corrosion and fatigue. In addition, interruption of structural service may be minimized during the strengthening process in this way. The concept of using CFRP in structural rehabilitation was initiated from aerospace engineering in 1970s (Myhre and Beck 1979). Relevant practices of such a concept in civil engineering are increasing rapidly (Hollaway 2010) and recent studies indicated that adhesively bonded FRP and steel can form a reliable load-carrying system and can be utilized in steel structure strengthening in a safe and economic manner (Shaat et al 2004; Zhao and Zhang 2007).

In such strengthened systems, CFRP composites are externally bonded to steel members, therefore the structural adhesive used is of a great importance. Epoxy is a structural adhesive frequently used in strengthening of steel structures and it is reported that failure often occurs through steel and adhesive interface debonding, or adhesive layer failure (cohesive failure) as a result of relatively low strength of epoxy, or delamination of CFRP composites (Zhao and Zhang 2007). There is a need to improve the mechanical performance of adhesive epoxy through enhancement of certain mechanical properties using appropriate additives without significantly decreasing other ones.

Recently studies have focused on the introduction of carbon nanotube (CNT) to modify epoxy. The integration between CNT and resin matrix is of potential to ameliorate the weaknesses of conventional laminated composites including delamination, lack of impact damage resistance, and low transverse mechanical properties (Ashrafi et al. 2011). Compared to neat epoxy, the improvements in flexural strength, glass transition temperature, and decomposition temperature were reported (Zhou et al. 2008). However the demand of high volume and high rate production of CNTs, as well as the associated costs, hinder the applications of CNT-modified epoxy, in large scale particularly in civil infrastructure (Thostenson 2005). And yet, it is a challenge to achieve higher percentage of CNT (especially for single-walled CNT) to a desirable level because of the dispersion problem (Ashrafi et al. 2011).

Recycled milled carbon fibres (MCF), on the other hand, present a promising and more practical way to enhance structural epoxy adhesive. MCF refers to a carbon fibre with a length of 1mm or less and much shorter than chopped carbon fibres, as a result they can be recycled from used carbon materials. The traditional solutions of disposal of such carbon fibre waste are to use land-fill or waste incineration. These solutions represent a waste of natural resources and, considering the fact that carbon fibre does not decompose naturally, environmental issues may be very critical. Several recycling technologies have been developed to reclaim carbon fibres from CFRP materials used in aerospace and military products for other structural applications (Feraboli et al. 2012). Although the exact recycling process to produce milled carbon fibres was patented, it is known that a pyrolysis process is involved (Allen 2008) to burn off the polymer matrix and free the carbon fibres through elevated temperatures.

Although investigations on enhancement of epoxy using chopped carbon fibres indicated an improvement of its crashworthiness up to a fibre volume fraction of 36% (Jacob et al. 2006), studies on the mechanical performance of modified epoxy using MCFs are limited. In this paper, MCFs were used to enhance an epoxy and the resulting epoxy was used to prepare a steel/CFRP adhesively-bonded system in a form of double strap joints. Different percentages of weight ratio of MCFs were investigated in the epoxy specimens and joint specimens. Both specimens were tested in tension to examine the mechanical properties such as stress-strain response, E-modulus and ultimate load. Failure modes were identified and discussed with respect to the effects introduced by the addition of MCFs. In addition, SEM was used to understand the changes of mechanical performance after introducing MCFs to the epoxy and steel/CFRP adhesively-bonded joints.

2 EXPERIMENTAL INVESTIGATIONS

2.1 Materials and specimens

Araldite420 epoxy was used for MCF addition and also used as the adhesive to prepare the joint specimens. Previous experiments indicated a nominal tensile strength of 32 MPa, tensile modulus of 1.9 GPa and tensile ultimate strain of 2.4% for the epoxy (Fawzia 2007). The milled carbon fibre (MF100) used to modify epoxy was recycled and supplied by ELG Carbon Fibre Ltd. It is with an average particle diameter of 7.5 um and length of 100 um. The fibre density was reported as 1800 kg/m^3 and the tensile strength and tensile modulus were 3150 MPa and 200 GPa respectively. The carbon fibre sheet used to prepare steel/CFRP double strap joints was CF130 (supplied by BASF) with a nominal elastic modulus of 240 GPa and nominal tensile strength of 3800 MPa. The steel elastic modulus was measured as 200 GPa and the yield stress and ultimate stress were measured as 359 MPa and 430 MPa respectively.

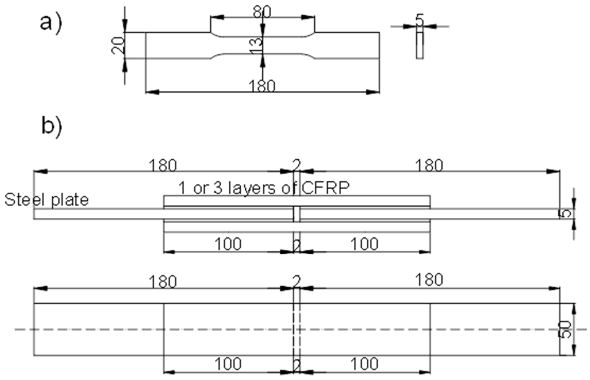
2.2 *Specimens and scenarios*

Two scenarios were examined as summarized in Table 1. Scenario EP investigated the mechanical properties of the epoxy after MCF modification. Dog-bone specimens were prepared with different weight ratios of milled carbon fibres to epoxy (see Table 1). It was suggested that Araldite 420A and 420B should be mixed with ratio by weight of 100:40 to form the epoxy matrix before application. To achieve a sufficient time for mixing and vacuum in order to minimise the amount of bubble in the epoxy, Araldite 420A was first mixed with the milled carbon fibres and placed in the vacuum pump for two days before the addition of hardener 420B. After that, the 420B hardener was mixed into the mixture. This was a gentle process otherwise bubble would be produced and make the vacuum pumping process useless. Once this process was completed, the MCF enhanced epoxy was poured into the mould to form the dog-bone epoxy specimens as shown in Fig. 1a, according to the geometry specified in ASTM D638. The pouring process was as slowly as possible to minimise the formation of air bubble. The MCF enhanced epoxy was left in the mould to cure in the room temperature for 10 days according to the manufacturer's instructions. The specimens without MCF were deep green and became dark after the MCF addition. Totally, twelve specimens were prepared in this scenario, and therefore three identical specimens (named as EPx-y, where x represents the weight ratio and y is from 1 to 3 as the specimen number) were repeated for each MCF weight ratio.

Table 1. Experimental scenarios and key parameters

Scenarios	Materials	Specimens	Weight ratio of Milled carbon fibre	Carbon fibre sheet layers
EP	Milled carbon fibre, epoxy	Dog-bone coupons	0%, 1.5%, 3% and 5%	NA
DJ	Milled carbon fibre, epoxy, CFRP sheet, steel plate	Double strap joints	0%, 1.5%, 3% and 5%	1 and 3

The joint specimens were prepared using modified epoxy adhesives (with different weights ratios of milled carbon fibre, see Table 1), steel plates and CFRP sheets. Two steel plates with a dimension of 5 mm × 50 mm × 180 mm were used to fabricate the double strap joint, after surface preparation (cleaning and sand-blasting). Then the prepared epoxy was applied on each surface of the steel plate, and one layer of CFRP sheet were placed and again the same epoxy was applied on its surface or between CFRP layers to form the polymer matrices of the CFRP composite. The resulting specimens are illustrated in Fig. 1b where a bond length of 100 mm was used for all the specimens. This bond length was greater than the effective bond length 40 mm of the one-layer CFRP joints and 50 mm for the three-layers CFRP joints with identical geometry prepared using original epoxy (Nguyen et al. 2011). The specimens were designated as DJx-y-z, where x represents the weight ratio of milled carbon fibre, y is the number of CFRP sheets (1 or 3) and z is the specimen number (1 or 2) in each specified condition.



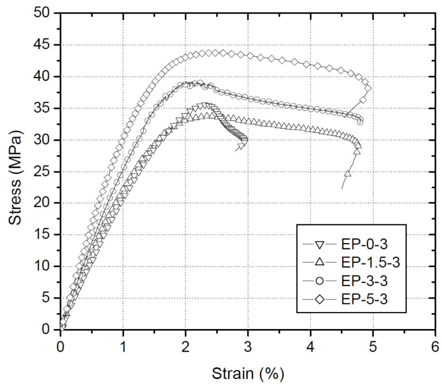


Fig. 1 Configurations for a) EP and b) DJ specimens   Fig. 2 Stress-strain curves of typical EP specimens

2.3 Experimental setup

For the EP specimen, the tensile test was performed using an INSTRON machine with a load capacity of 5 kN. The strain gages with the resistance of 120.0±0.3% and gage factor of 2.095±0.5% at room temperature was installed at the middle of the specimens to measure the load-strain developments. The specimens were loaded in tension at displacement control rate of 1 mm/min.

A Shimadzu Universal Hydraulic Testing Machine was used to test the DJ specimens in tension to failure. This testing was carried out at a constant rate of 2 mm/min. Two string potentiometers, LX-PA2 manufactured by Unimeasure, with accuracy of 1.25 × 10-3 mm, were used to measure the elongation of a joint region of 205 mm, which was then averaged by the readings from the two string potentiometers.

2.4 Scanning electron microscopy

SEM was used to observe the microstructure of the epoxy after MCF addition with different weight ratios. The samples used in SEM were cut from the damaged EP specimens after testing and the observation target was the failure surface.

The samples were examined at the Monash Centre for Electron Microscopy, using an accelerating voltage of 10 kV. Different magnifications ranging from 100 to 2500 were adopted for each specimen with different weight ratios (0%, 1.5%, 3% and 5%), in order to identify any differences among them.

3 RESULTS AND DISCUSSION

3.1 Results from EP specimens

All the EP specimens failed in a similar way as the breakage at the middle region of the dog-bone shape. The stress and strain curves of typical EP specimens with different weight ratios of MCFs are summarized in Fig. 2, where the stress values were calculated using the measured loads divided by the sectional area at the failure position. It can be identified that the slope of curves at the elastic region (linear part), i.e. the E-modulus, is improved with the increase of the MCF weight ratio, as well as the ultimate stress at failure (i.e. the tensile strength).

The detailed values of E-modulus and tensile strength of all the specimens (average values and standard derivations) are summarized in Table 2. The E-modulus of the original epoxy showed an average E-modulus of 2.06 GPa and very similar to the value (1.9GPa) reported by the manufacturer. The improvement of E-modulus was not obvious (only 6.8%) at the weight ratio of 1.5% of MCFs while such an improvement became significant (31.1%) when the weight ratio increased to 3%, and became 50.5% when only 5% by weight of MCFs were used to modify the epoxy. More than 5% by weight of MCFs made the specimen preparation very difficult because of the loss of mobility of the epoxy resin. Surfactant may be necessary to prepare the epoxy specimens modified using MCFs with a weight ratio more than 5%.

The tensile strength of enhanced epoxy specimens demonstrated similar variation as that of E-Modulus. No improvement was found for the specimens with a weight ratio of 1.5% MCFs but a slight decrease (see Table 2). It was believed that the slight decrease of strength for specimens EP1.5-x in comparison to EP0-x in Table 2 was because of data scattering rather than any physical mechanism. Considerable tensile strength enhancement (15.2%) was identified for the specimens EP5-x with a weight ratio 5% of MCFs.

Table 2. Elastic modulus, strength and ultimate stain of modified epoxy with different weight ratios of milled carbon fibre (values were averages of three identical specimens)

Specimen	Weight ratio	E-modulus (MPa)	Strength (MPa)
EP0-x	0%	2.06±0.06 (100%)	34.8±1.1 (100%)
EP1.5-x	1.5%	2.20±0.10 (106.8%)	32.8±1.4 (94.3%)
EP3-x	3%	2.70±0.17 (131.1%)	37.3±1.7 (107.2%)
EP5-x	5%	3.10±0.37 (150.5%)	40.1±3.3 (115.2%)

The strain at ultimate load of specimens EP0-x was found to be 2.37±0.03% and this value is in consistence with that (2.4%) reported previously (Fawzia 2007). Similar but slight smaller strain values at the ultimate loads were found for the other specimens (EP1.5-x, EP3-x and EP5-x) in a range from 2.15% to 2.37% with larger derivations. After the ultimate loads were reached, the strains kept increasing without significant loss of applied stress for the epoxy after MCF addition and this behaviour demonstrated a “yielding” stage in their stress-strain curves, implying that a ductile performance was introduced to the epoxy after MCF addition. As a result, the strains at the final breakage failure were largely improved to be in a range from 3.5% to 4.7% for the MCF enhanced epoxy specimens, in comparison to that (3.0%) for the original epoxy, as also evidenced in Fig. 2.

3.2 SEM results

Fig. 3a shows the failure location of the sample from the original epoxy without MCF addition at a magnification of 250. The rough surface was a result of fracture in tension, and a number of small pieces of epoxy were evidenced also in Fig. 3a, as a result of relatively brittle failure of the specimen.

The microscopic images were shown in Fig. 3b for the sample from the epoxy with an MCF weight ratio of 1.5 (EP1.5) and in Fig. 3c for EP3. It was found from in Fig. 3b that a number of carbon fibres were partially embedded into the damage surfaces and more fibres were evidenced in Fig. 3c corresponding to a denser distribution, because of a larger MCF weight ratio in specimens EP3. The carbon fibres were randomly dispersed in the matrix during specimen preparation and therefore different orientations to the damage surface were noticed. In addition to these fibres, a number of holes with very similar diameters to the fibres were also identified from Figs. 3b and 3c – they were produced because the corresponding fibres were pulled out from the matrix and left (still embedded) in the other damage surface. The bond failure between milled carbon fibres and epoxy matrix contributed to the improvement of E-modulus and strength of the modified epoxy specimens. Furthermore, this additional failure mechanism and associated energy dissipation also explains a more ductile failure process for the MCF enhanced epoxy than the original one, overall resulting a smoother damage surface in Figs. 3b and 3c than the fracture surface shown in Fig. 3a.

Fig. 3d shows the microscopic image of the damage surface for the epoxy with 5% MCF addition (EP5) at a higher magnification of 1000, where the top left corner of this image is of further interests. It can be found from there a fibre nearly parallel to the damage surface was pulled out and the bond surface between the fibre and matrix were revealed. A few cracking traces were initiated from the bond surface and along the fibre direction – they evidenced the stress transfer from the fibre to the surrounding matrix through the bonding in between. Both matrix and fibre surfaces after de-bonding remained smooth, implying that the failure might occur at the interface. In this figure, the diameter of carbon fibres was measured as 7.22 um and close to the value (7.5 um) reported by the manufacturer.

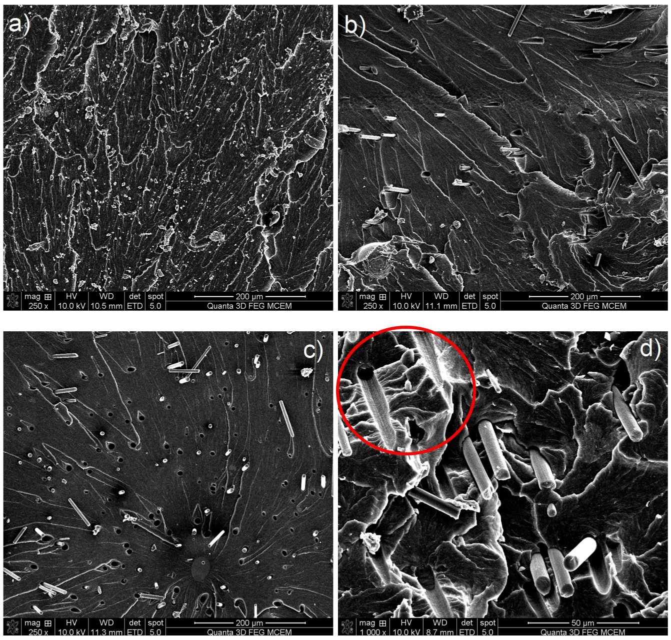


Fig. 3 Typical SEM images of epoxy specimens with dfferent weight ratios of MCFs a) 0%, b) 1.5%, c) 3% and d) 5%

3.3 Results from DJ specimens

The specimens of steel/CFRP double strap joints with one layer of carbon fibre sheet failed through the delamination of the carbon fibre sheet at the middle of the joints, regardless of different MCF weight ratios used in the epoxy adhesive. Only a part of carbon fibres was pulled out from the full bond length of 100mm and the steel surface in the joint region was still covered by most of the carbon fibre sheet. No adhesive interface debonding or cohesive failure was identified and this result suggested that the bonding provided by the epoxy between the carbon fibre sheet and steel surface was almost intact. Again, the failure modes of steel/CFRP double strap joints with three layers of carbon fibre sheets failed mostly through delamination with the layers of carbon fibre sheets, independent of the MCF weight ratios. It was found that the steel surface in the joint region was largely covered by carbon fibre sheets. Such a failure mode may imply that the joint load-carrying capacity is dominated by the interlaminar shear strength of the carbon fibre sheets, rather than the epoxy strength of the adhesive layer.

All the joint specimens with one or three layers of carbon fibre sheets showed a linear load-displacement development until the final failure. Although the epoxy demonstrated a ductile failure process after MCF addition, such behaviour was not observed for the joints with different MCF weight ratios. This may be attributed to the failure mode of delamination, rather than the cohesive failure. The change of joint stiffness with the weight ratio of MCF is shown in Fig. 4a and that of joint ultimate load is shown in Fig. 4b. No obvious improvement of joint stiffness or joint ultimate load was observed after the MCF addition to the specimens with one and three layers of carbon fibre sheets, again as a result of the delamination failure mode of the carbon fibre sheet. The slight variation of results in Figs. 4a and 4b is because of data scattering rather than any solid physical mechanisms.

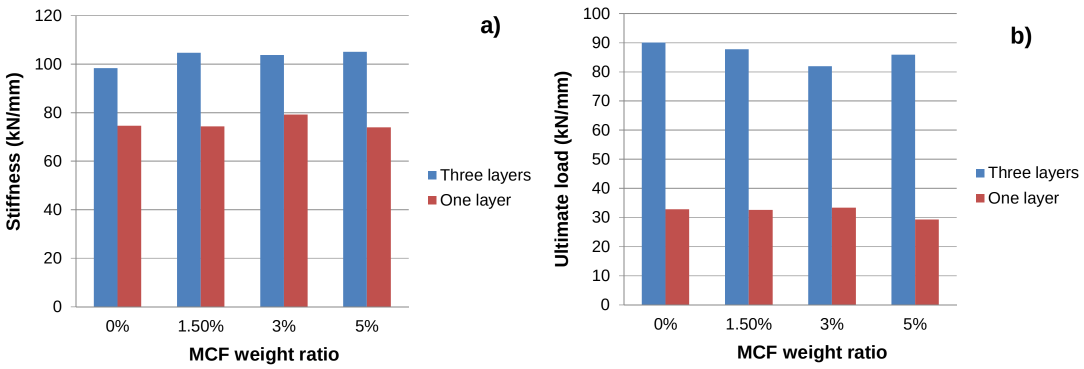


Fig. 4 Comparison of a) stiffness and b) ultimate load of DJ specimens with different MCF weight ratios

4 CONCLUSIONS

In this study, recycled MCF was used to enhance an epoxy adhesive in order to improve its mechanical performance. Original and enhanced epoxy specimens were tested in tension and the mechanism of the improved mechanical properties was revealed by SEM. Double strap steel/CFRP joints adhesively bonded using the enhanced epoxy were further examined. From this work, the following conclusions can be drawn:

1) Addition of MCFs to the epoxy adhesive considerably enhanced its E-modulus and tensile strength when the MCF weight ratio is greater than 1.5%. The improvement of tensile strength was 7.2% for a weight ratio of 3% and 15.2% for a weight ratio of 5%, and that of E-modulus was 30.1% for a MCF weight ratio of 3% and 50.5% for a weight ratio of 5%. It was also found that the failure process of the MCF enhanced epoxy specimens became more ductile, resulting in a much larger ultimate strain at the final breakage in tension.

2) SEM indicated that the MCFs were randomly dispersed in the matrix with various orientations to the damage surface. Those short fibres were pulled out from the fracture surfaces during the tensile failure of the enhanced epoxy specimens. This bond failure between MCFs and epoxy matrix, in addition to the tensile fracture of the pure epoxy, contributed to the improvement of E-modulus and tensile strength of the modified epoxy. The associated energy dissipation during the de-bonding of MCFs and epoxy explains a more ductile failure process.

3) Although a considerable improvement of stiffness and strength was observed for the MCF enhanced epoxy, steel/CFRP double strap joints adhesively-bonded using the epoxy did not show corresponding increases in joint stiffness and ultimate load. This is because of the failure occurred at the carbon fibre sheet through delamination, rather than in the adhesive layer where the mechanical properties of epoxy are more dominant. Further experimental study is going to investigate the mechanical performance of double strap joints of steel and CFRP laminates bonded using epoxy. For such an adhesively-bonded system, cohesive failure was reported as a major failure mode where adhesive layer played a more important role than that in the delamination failure.

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