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A BRIEF REVIEW OF CFRP-METAL SYSTEMS SUBJECTED TO IMPACT AND BLAST LOADING

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ABSTRACT

Carbon fibre reinforced polymer (CFRP) has great potential for strengthening metallic structures. This paper presents a summary of research into CFRP-metal systems subjected to impact and blast loading caused by man-made hazards such as accidents or terrorist attack. The strain rate effects on the properties of materials (CFRP and adhesives) are presented first, followed by the influence of strain rate on the bond strength between CFRP and steel. The paper also discusses the behaviour of CFRP-strengthened steel sections under impact loading and of CFRP-strengthened aluminium plates subjected to blast loading.

KEYWORDS

CFRP, adhesives, bond strength, impact loading, blast loading, square hollow sections, aluminium plates.

INTRODUCTION

Carbon fibre reinforced polymer (CFRP) has a high strength-to-weight ratio, is resistant to corrosion and environmental degradation and has great potential for strengthening steel structures (Hollaway and Teng 2008). Most of the research on CFRP strengthening of steel structures is related to static, earthquake and fatigue loading (Hollaway and Cadei 2002; Zhao and Zhang 2007; Teng et al. 2012). It is clear that CFRP can improve the performance of steel structures in terms of strength, ductility, energy absorption and fatigue life. However, relatively less work has been carried out in relation to impact and blast loading.

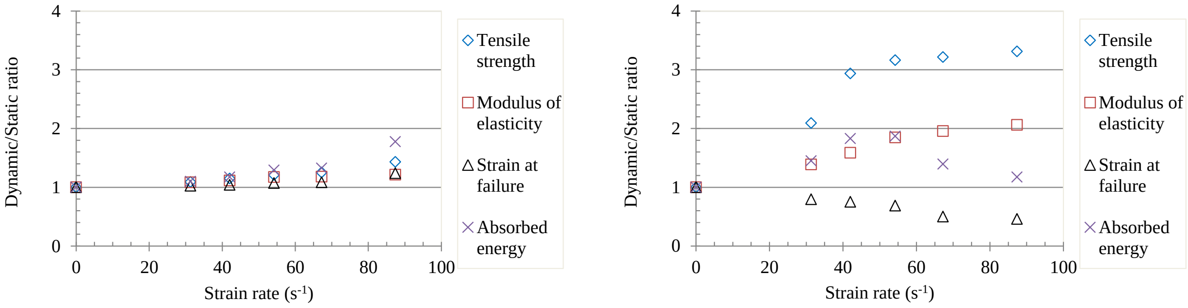
The design of structures against blast, once the preserve of the military, has now become a common design criterion for civilian structures, especially buildings designated as prominent targets or items of critical infrastructure (ASCE 2011; Cormie et al. 2009; Dusenberry 2010). This paper presents a summary of research at Monash University into CFRP-metal systems subjected to impact and blast loading caused by man-made hazards including accidents or terrorist attack. It covers the strain rate effects on the properties of materials (CFRP, adhesives and steel), the influence of strain rate on the bond strength between CFRP and steel, the behaviour of CFRP-strengthened steel sections under impact loading and of CFRP-strengthened aluminium plates subjected to blast loading.

STRAIN RATE EFFECTS ON THE PROPERTIES OF MATERIALS

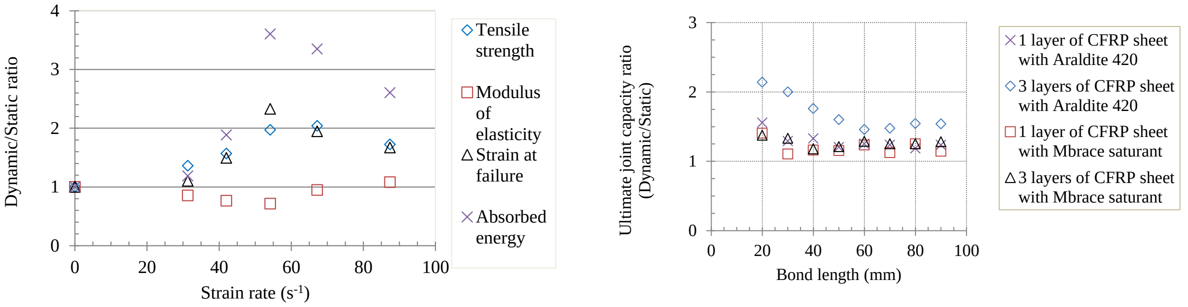
The effect of strain rate on the mechanical properties of fibre reinforced composites and adhesive has been extensively studied by many researchers including Harding and Welsh (1983), Adams and Adams (1990), Gilat et al. (2002), and Shokrieh and Omidi (2009). Al-Zubaidy et al. (2013a) conducted a series of tests to investigate the strain rate effect on the mechanical properties of unidirectional normal modulus CFRP sheet, and Araldite 420 and MBrace saturant adhesives. The materials studied by Al-Zubaidy et al. (2013a) are commonly used to strengthen steel and concrete structures, and differ from those reported in the literature for the aerospace and vehicle industries.

A special rig was designed (Al-Zubaidy et al. 2012) to convert vertical drop weights to tensile force in the specimens. A strain rate up to 87.4 s^{-1} was achieved, which is about 360,000 times that of static tests. Specimens were prepared according to ASTM standards.

The effect of impact loading on the properties of CFRP and adhesives (Araldite 420 and MBrace saturant) is illustrated in Figure 1. For CFRP, the impact load increases its tensile strength, modulus of elasticity, strain at failure and absorbed energy. For Araldite 420, the tensile strength and modulus of elasticity significantly increase, whereas the strain at failure reduces, leading to an insignificant increase in absorbed energy. For MBrace saturant, the modulus of elasticity does not vary much, while a significant increase is observed for tensile strength and strain at failure, leading to a significant increase in absorbed energy.



(a) CFRP (b) Araldite 420



(c) MBrace saturant (d) Bond strength

Figure 1. Effect of impact loading on properties of CFRP, adhesives and bond strength (adapted from Al-Zubaidy et al. 2012a; 2012b; 2013a)

INFLUENCE OF STRAIN RATE ON THE BOND STRENGTH BETWEEN CFRP AND STEEL

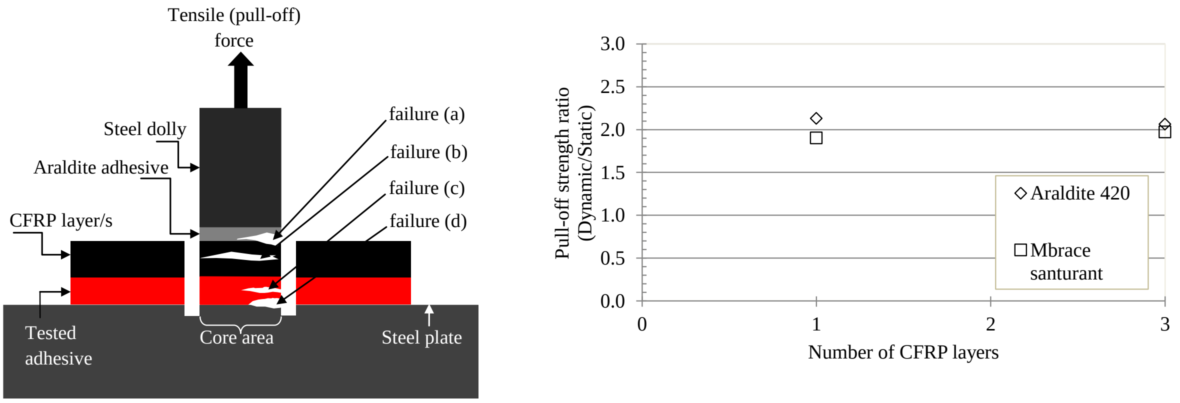
A large number of double-shear pull tests were conducted by Al-Zubaidy et al. (2012a; 2012b) to investigate the influence of impact loads on bond strength between CFRP sheets and steel. The adhesives adopted in the testing program were Araldite 420 and MBrace saturant. Basic parameters of the tests included bond length (varying from 10 to 100 mm), number of CFRP layers (one or three), loading speed (4.26 m/s on average). It was found that the effective bond length is not sensitive to the strain rate, i.e. the effective bond lengths under static and dynamic loading are very close, being around 50 mm in this case. The effect of strain rate on the ultimate joint capacity (or bond strength) is illustrated in Figure 1(d). In general, there is an increase in the bond strength due to the strain rate increase. When the bond length is smaller than the effective bond length, less increase is found for longer bond lengths. When the bond length exceeds the effective bond length the increase becomes almost a constant, i.e. about 25% to 50%.

Al-Zubaidy et al. (2013b) also performed FE modelling of the double-shear pull scenario and obtained reasonable predictions in terms of bond strength, effective bond length, failure patterns and strain distribution along the bond length.

EFFECT OF IMPACT LOAD ON ADHESION BOND STRENGTH

The adhesion pull-off test is commonly employed to evaluate the adhesion bond strength of adhesive. Al-Zubaidy et al. (2013c) carried out a series of pull-off tests on CFRP sheet and steel under impact load (up to 5 m/s). The test set-up is shown in Figure 2(a). A steel dolly is glued to CFRP which is bonded to a steel plate. It is the adhesive between the CFRP and steel plate (shown as “tested adhesive” in Figure 2(a)) that is under investigation. Two types of adhesives were adopted, i.e. Araldite 420 and MBrace saturant. The number of CFRP layers varied from one to three.

The failure modes are defined in Figure 2(a), namely (a) interface epoxy failure (failure in the adhesive layer between the steel dolly and the CFRP layer); (b) cohesive failure of the CFRP layer (failure within the CFRP layer by separation of some fibres from the resin matrix); (c) cohesive failure of adhesive (adhesive layer failure); (d) steel and adhesive interface failure (bond interface failure between bonding adhesive and steel plate). When one layer of CFRP is applied with Araldite 420, the failure mode is a combination of modes (a) and (b). When one layer of CFRP is applied with MBrace saturant, the failure mode becomes a combination of failure modes (c) and (d). This is mainly attributed to the brittle behaviour of MBrace saturant adhesive, which is less ductile than Araldite 420 adhesive. The brittle nature of the MBrace adhesive affects its sensitivity to loading velocity. When three layers of CFRP are applied, the failure mode is dominated by failure mode (b). The effect of loading speed (4.26 m/s on average) on pull-off strength is shown in Figure 2(b), where the vertical axis is the ratio of the pull-off strength from dynamic loading to that from static loading. The increase in pull-off strength is about 100% for all cases.



(a) Failure modes (b) Pull-off strength

Figure 2. Effect of loading speed on pull-off strength (adapted from Al-Zubaidy et al. 2013c)

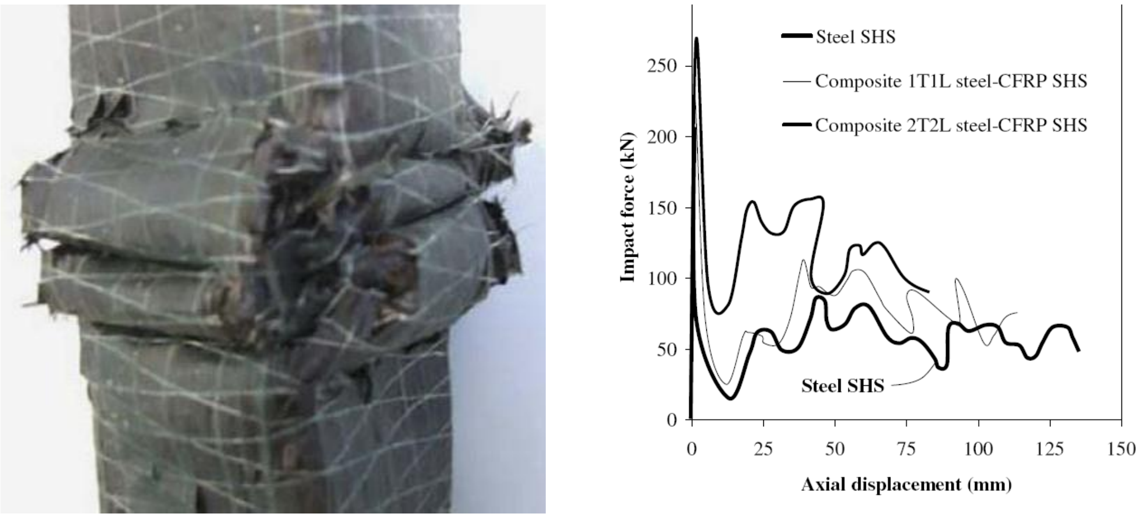
CFRP-STRENGTHENED STEEL SECTIONS UNDER IMPACT LOADING

CFRP-Strengthened SHS under Axial Impact Loading

Bambach et al. (2009) conducted a series of tests on CFRP-strengthened SHS under axial impact loading. Four different steel SHS geometries were selected to achieve section slendernesses from 30 to 66. Normal modulus (230 GPa) CFRP sheet and Araldite 420 epoxy were adopted in the testing program. Two different fibre layouts were investigated: one layer laid transversely (i.e. around the SHS perpendicular to the direction of axial load) with one layer longitudinally (i.e. in the direction of axial load), hereafter termed 1T1L, and two layers transversely with two layers longitudinally, termed 2T2L. The combination of transverse and longitudinal fibres has been found to be efficient in strengthening steel tubular columns and beams under static loading, as reported by Shaat and Fam (2006) and Haedir et al. (2009).

The typical failure mode for CFRP-strengthened SHS, as shown in Figure 3(a), is generally an axi-symmetric ductile, stable plastic collapse mode. The failure mode is similar to CFRP strengthened SHS under quasi-static loading reported in Bambach and Elchalakani (2007). A comparison of typical impact force versus axial deformation curves (e.g. for SHS 50×50×2) is given in Figure 3(b). It can be seen that strengthening scheme 1T1L does not significantly improve the behaviour, whereas strengthening scheme 2T2L does. More research is needed to investigate the effect of the number of CFRP layers. The dynamic mean crushing load of steel SHS can be increased by about 80% due to CFRP strengthening, while the specific energy absorption can increase by about 50%.

A theoretical method was derived (Bambach and Elchalakani 2007) to calculate the mean crushing load for CFRP-strengthened SHS under quasi-static axial load. The theory took into account the contributions to the total collapse energy of the face folding mechanism, the yielding of the corners and the corner folding restraint. This theory was modified (Bambach et al. 2009) to calculate the dynamic mean crushing load of CFRP-strengthened SHS by considering the strain rate effect on material properties. Since CFRP-strengthened SHS deforms under plastic collapse, the strains in the yield lines of the steel folds will be much larger than the strains at which first yield occurs, and would correspond to stresses closer to the ultimate stress of the material rather than the yield stress. The formula for the strain rate effect on yield stress presented in Abramowicz and Jones (1984) was used, except that the yield stress was replaced by ultimate tensile strength. The predicted mean crushing load was reasonably close (within 5% on average) to that obtained experimentally.



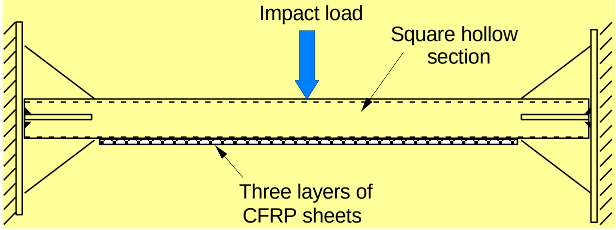
(a) Deformed specimen (b) Impact force versus axial deformation

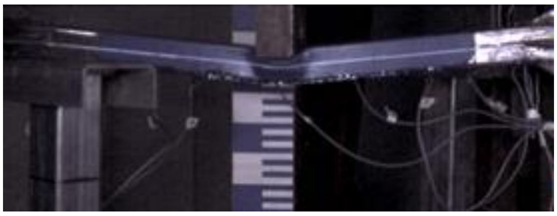
Figure 3. CFRP-strengthened SHS under axial impact load (adapted from Bambach et al. 2009)

CFRP Strengthened SHS under Lateral Impact Loading

Beams subjected to impact loads to produce large inelastic deformation have been studied by many researchers, including Liu and Jones (1987) and Shen and Jones (1992), who concentrated on tubular and solid beams under lateral impact. Others like Zeinoddini et al. (2002) investigated pre-loaded steel tubes, while Chen and Yu (1999) studied clamped beams under impact loads and included the effect of cracks at the supports. Jama et al. (2006) extended the existing work to investigate the effect of CFRP on the load-carrying capacity of steel SHS fixed at both ends.

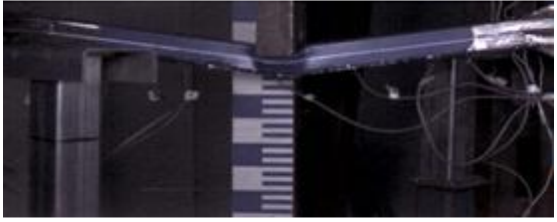
Three layers of normal modulus (230 GPa) CFRP sheet were applied to the tension side of the SHS as shown in Figure 4(a). Araldite 420 was the adhesive used in the testing program. Three different width-to-thickness ratios were tested to create different compactnesses of SHS. The impact velocity was about 7 m/s achieved from a drop rig (see Figure 4(b)).



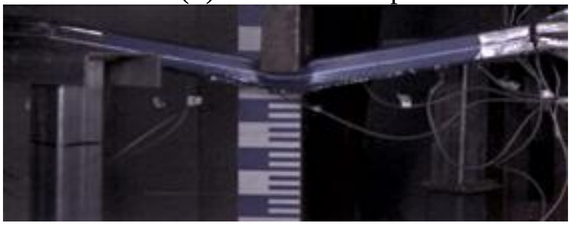


(a) Specimen layout

(i) 8ms after impact



(ii) 12ms after impact



(iii) 14.5ms after impact

(b) Specimen in impact drop rig

(c) Specimen after impact

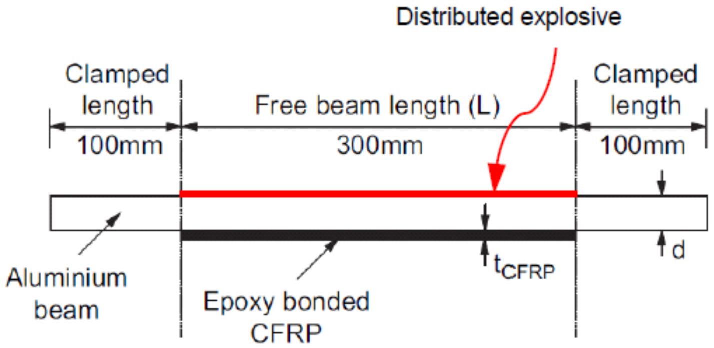
Figure 4. CFRP-strengthened SHS under side impact force (courtesy of Dr. H. Jama)

It was found that fixed-ended, CFRP-strengthened SHS behaves differently, depending on the section slenderness when loaded statically and by impact. Only a 15% increase in ultimate load was observed. Fibre-tear failure mode was observed on all the CFRP on the beams tested by impact. The above observation relates to CFRP strengthening on only one of the beam surfaces. It is also important to remember that the fixed-ended beams developed three plastic hinges and the CFRP system only strengthened the plastic hinge at the middle of the beam. More research is needed to investigate the influence of a wider range of parameters on strengthening efficiency.

CFRP- STRENGTHENED ALUMINIUM PLATES SUBJECT TO BLAST LOADING

The dimensions of the aluminium beams are shown in Figure 5(a). Three different beam depths of 6 mm, 10 mm and 12 mm were selected. Normal modulus CFRP (1, 3 or 5 layers) and Araldite 420 were used. The experimental method was to fix a 13 mm thick polystyrene buffer to the specimen surface in order to provide a small stand-off, attenuate the blast load to produce a uniform distribution of impulse and to prevent surface spalling. The explosive was applied as a cord of nominal diameter 5 mm of Pentaerythritol tetranitrate 'PETN', and distributed as evenly as possible on the beam (see Figure 5(b)).

Typical failure modes are shown in Figure 5(b) and 5(c). In general, more reduction in deformation is found for specimens with more CFRP layers and thinner plates, as shown in Figure 6. The major failure modes are fibre rupture and interlaminar debonding. The experimental results show that although a significant amount of energy may be absorbed by the layer of carbon fibres bonded directly to the metal, subsequent carbon fibre layers suffer from interlaminar debonding mechanisms as a result of shock spalling that reduces their efficiency. A theoretical method has been developed whereby the energy absorbed by the carbon fibres may be determined, and the remaining explosive energy is absorbed by the plastic deformation of the metal. Fibre efficiency factors for multiple fibre layers and dynamic effects have been introduced and are shown to produce reasonable agreement with the test results.



(a) Specimen layout

(b) 10mm thick plate with low explosive impulse

(c) 10mm thick plate with high explosive impulse

Figure 5. CFRP strengthened aluminium plates under blast loading (courtesy of Dr. M. Bambach)

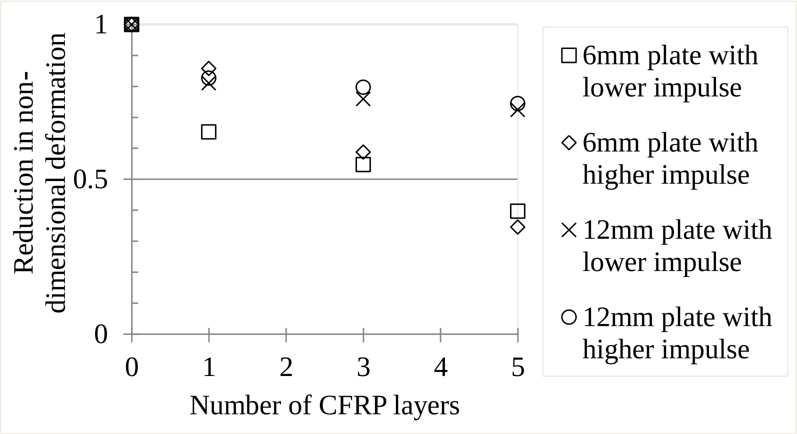


Figure 6. Reduction in non-dimensional deformation due to CFRP strengthening with epoxy ratio of 1:3 (adapted from Bambach et al. 2010)

CONCLUSIONS

This paper provides a summary of research conducted at Monash University into CFRP-metal systems subjected to impact and blast loading, in terms of material properties, bond strength between CFRP and steel, the behaviour of CFRP-strengthened steel sections under impact loading and of CFRP-strengthened aluminium plates subjected to blast loading.

More work is needed to understand the influence of a wider range of strain rates on bond strength between FRP and metal since there is potential to use FRP to strengthen metallic structures subject to impact and blast loading. The phenomenon of interlaminar debonding due to shock spalling requires more investigation. Both experimental testing and theoretical analysis are necessary to understand the behaviour of other CFRP-strengthened metallic elements (e.g. beams, columns) and connections under impact and blast loading. More tests are needed of much wider parameters in terms of bond length, CFRP modulus, types of adhesives, structural geometries and boundary conditions.

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