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BOND CHARACTERISTICS BETWEEN STEEL AND CFRP LAMINATE UNDER IMPACT LOADS

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ABSTRACT

The use of composite materials in strengthening steel structures has been widely performed in the last decades. Steel structures are usually subjected to different types of loadings, and one of the most common is dynamic loading. The effect of impact loading on the bond between CFRP laminates and steel structures is little understood. Although some researchers have studied the effect on the bond between CFRP sheets and steel structures under impact loadings, this effect still needs investigation for CFRP laminates. This paper focuses on the bond characteristics of CFRP-steel double-strap joint specimens under high loading rate. The results show a significant influence on ultimate joint strength and strain under impact loading comparing to that under static loading.

KEYWORDS

Strain distribution, CFRP-steel double-strap joint, CFRP strengthening, dynamic loading.

INTRODUCTION

Many metallic structures were built in the nineteenth and twentieth centuries, most of these structures being for industrial and transportation use, such as bridges, steel buildings and underground tunnels. These structures are deteriorating due to serious issues such as ageing, changes in use, increased loads, and exposure to harsh environments which causes heavy corrosion of metallic structural members. However, they remain in service due to their conservative design. With time, these structures will need to be strengthened to sustain these changes. Carbon fibre reinforced polymer (CFRP) is one of the most common methods of strengthening and has attracted the attention of structural engineers in recent decades. CFRP has superior properties due to its light weight, low density, ease of use and high strength. Impact loading is one of the possible loads to which structures are subjected over a number of years. One of the possible methods of strengthening is using CFRP laminate to enhance the structural capacity. Some researchers have studied the bond properties of CFRP sheets or laminates bonded to steel structures under static and dynamic loadings (Karbhari and Shulley 1995, Bakis et al. 2002, Tavakkolizadeh and Saadatmanesh 2003, Al-Saidy et al. 2004, Fawzia et al. 2006, Al-Zubaidy et al. 2011b). There is a lack of understanding on the effect of impact loading on the bond behaviour of CFRP laminate bonded to steel structures. This paper reports the results of a study of the effect of impact loading on joint strength and longitudinal strain distribution along the bond of CFRP laminates to steel members. A mass of 300 kg was dropped onto the specimens from a specific height to perform the impact loading. Quasi-static loading was also applied to the specimens as a reference loading rate for comparison with the dynamic loading. The loading rates were 201×10^3mm/min for the dynamic loading and 2mm/min for the quasi-static loading.

EXPERIMENTAL PROGRAM

Materials Properties

In order to prepare the CFRP-steel double-strap specimens, a low modulus of CFRP was used to strengthen steel joints by using Araldite 420 epoxy. The tensile strength and modulus of elasticity of the low modulus CFRP and Araldite 420 were 2900MPa and 165GPa, and 32MPa and 1.9GPa respectively.

Preparation of Specimens

In this research, a total of 51 CFRP-steel specimens were prepared for both loading rates. The same procedure was followed for both static and dynamic loading specimens. Two steel plates were bonded together using Araldite 420. The steel plate dimensions were 200mm long, 40mm wide and 16mm thick, and a guide of equal length steel section was used to ensure the two steel plates were in a straight line to avoid any eccentricity in loading. The two steel plates were sandblasted to remove all grease, paint and oil, and then they were cleaned with acetone to remove any dust on the bonding area. Araldite 420 epoxy was then applied along the bond and the CFRP was attached. The CFRP dimensions were 20mm wide, 1.4 mm thick and different lengths, and the CFRP was squeezed to expel any voids in the adhesive layer. The specimens were cured for more than 7 days, as recommended by the manufacturer. 30 specimens were prepared for the quasi-static loading whereas 21 specimens were prepared for the impact loading, and different bond lengths were used from 40 mm to 130mm to find the ultimate bond strength, ultimate strain and the effective bond length.

Photogrammetry Technique and Foil Strain Gauges

In this test program, capturing the strain during the test was done using two methods, depending on the loading rate. The two methods were foil strain gauges and photogrammetry. These two methods were both used in the static testing, whereas only the foil strain gauges were used for the dynamic test, due to the low number of readings per second in the photogrammetry VIC-3D camera. For the static tests, strain gauges were attached along the bond length of one side of the specimen at distances of 15 mm. The other side of each specimen was prepared for the VIC-3D camera technique by being painted with white colour and then randomly dotted with black colour, according to the manufacturer's guidelines. For the dynamic loading specimens, a line of strain gauges was attached on one side of the specimen with gaps of 15mm. Figure 1 shows a specimen under loading with both methods of capturing strain.

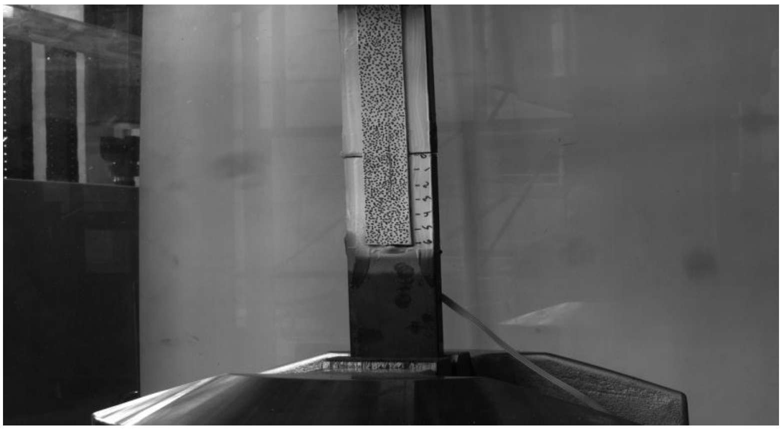

Figure 1. CFRP-steel double-strap specimen under static loading showing the face with VIC-3D camera strain capture

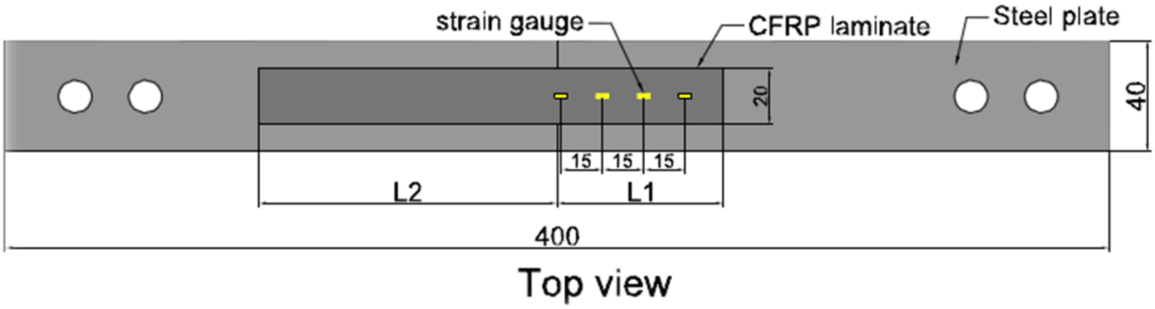

Figure 2. Schematic of strain gauge locations along CFRP-steel specimens

Testing Program

As mentioned above, this paper focuses on the longitudinal strain distribution along the bond between CFRP laminate and steel plates under static and dynamic loadings. The static testing was carried out using the MTS 250kN machine at Swinburne University of Technology with a strain rate of 2mm/min. The dynamic tests were carried out using the drop mass rig designed by John in 1978 (John, 1978) and then modified for tension tests in 2011 at Monash University (Al-Zubaidy et al. 2011b). 201×10^3mm/min was the load rate used in this program. This velocity was calculated as follows:

$$v = \sqrt{2gh} \tag{1}$$

where:
v: Velocity (m/sec)
g: The gravity (m/sec^2)
h: is the height of dropping mass (m)
Therefore, for the height of 0.575m the generated velocity is 201×10^3mm/min.

RESULTS AND DISCUSSION

A total of 51 CFRP-steel double-strap specimens were tested under low velocity of 2mm/min and high velocity of 201×10^3 mm/min to perform the static and dynamic loading respectively. The results focused on the maximum joint capacity, maximum strain of the specimens with different bond lengths, and then those results, the effective bond length can be observed. Each bond length has been tested three times and the average load is shown. All specimens were failed within the shorter side of the joint (L1), see figure 2.

Effect of Impact Loading on Ultimate Strength

A significant increase in bond strength was shown in dynamic testing comparing to that in quasi-static; the load carrying capacity was increased by up to 50% for the short bond lengths whereas this percentage becomes less as the bond length increases and reaches close to the effective bond length. This significant increase can be attributed as the shear capacity of the adhesive has a significant influence under high strain rates (Al-Zubaidy et al. 2011a, Yokoyama and Shimizu 1998). Figures 3 & 4 are showing the maximum failure mode for each bond length under the two velocities.

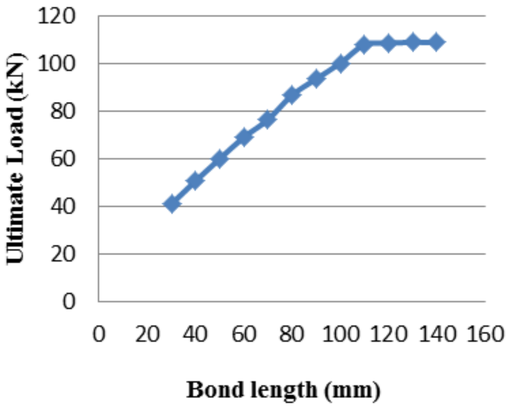

Figure 3. Ultimate vs. bond length for specimens with load rate of 2mm/min

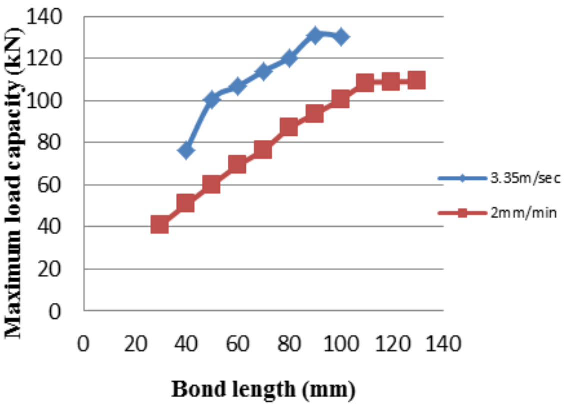

Figure 4. Ultimate load vs. bond length for specimens with load rate of 201 $\times 10^3$mm/min

As can be seen in the two plots above in Figures 3 and 4, the ultimate load increases approximately linearly with bond length until at a certain bond length (known as the effective bond length) the joint strength reaches a maximum. After this point, further increasing the bond length has virtually no effect on joint strength. With the quasi-static loading case in Figure 3, the effective bond length is 110mm. Figure 4 shows the dynamic loading case where the effective bond length is 90mm.

Effect of Impact Loading on the Strain Distribution along the Bond Length

As mentioned above, for static testing two methods were used to capture the strain along the bond length, the results showed a significant agreement between the two methods; Figure 5 is showing the ultimate strain at the joint for both methods of capturing strain, therefore it was decided to use the strain readings from the photogrammetry technique as it gives more data along the bond length.

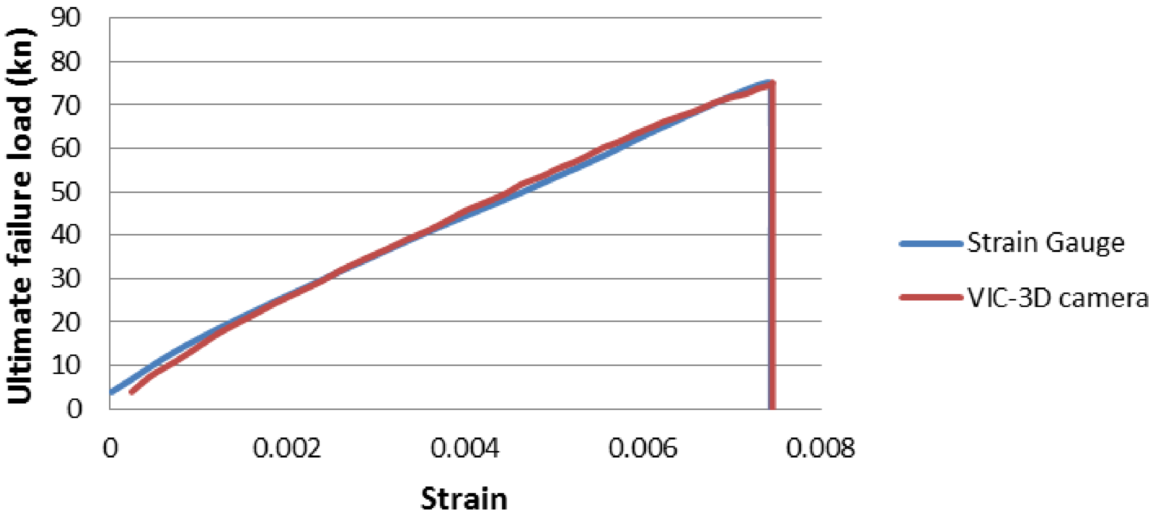

Figure 5. Load vs Strain curve for strain gauge method and the photogrammetry method

The two loading rates were used in this testing program using both the MTS machine and the drop mass rig for static and dynamic testing respectively. Different bond lengths were used, and each bond length was tested three times to obtain the average results for each bond length. Based on the strain captured from foil strain gauges and the photogrammetry camera, the strain distribution was shown to slightly increase as the load rate increased. Figure 6 and 7 show the strain along one of the bond lengths (70mm) under different load levels. All bond lengths showed the same trend of the strain distribution curve.

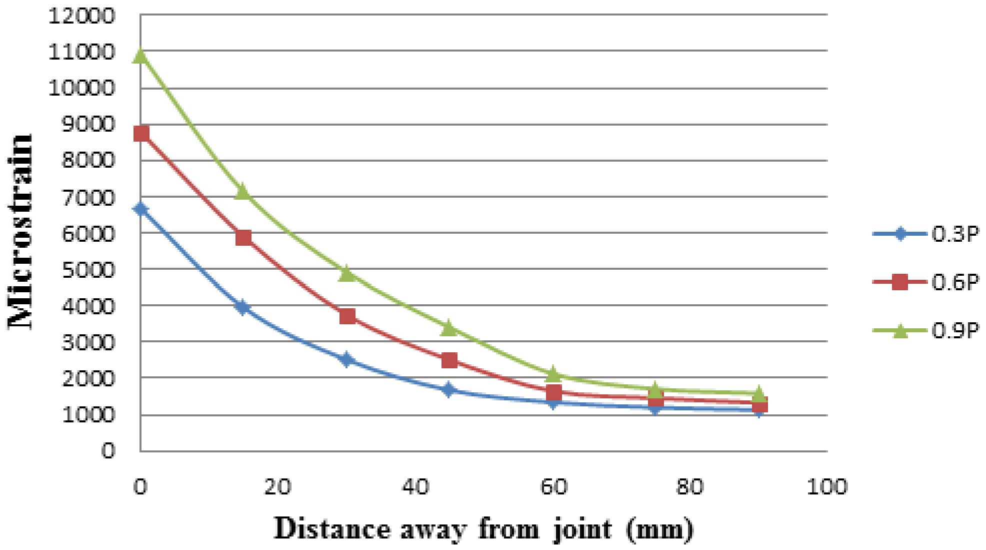

Figure 6. Strain distribution along the 70mm bond length for load rate of 201×10^3 mm/min

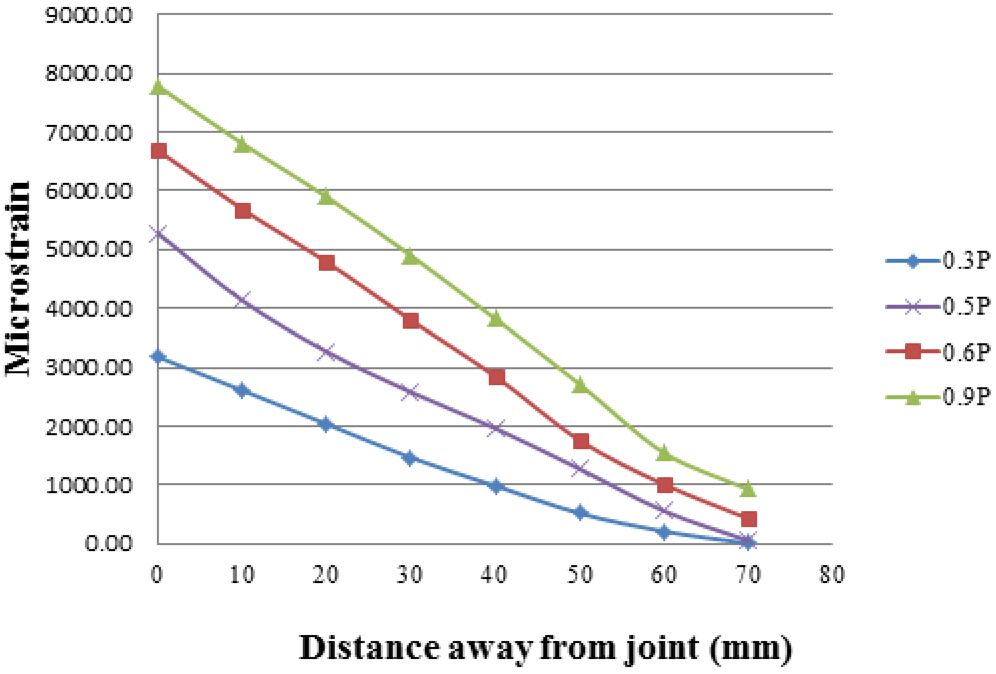

Figure 7. Strain distribution along 70mm bond length for load rate of 2mm/min

It is obvious from both figures above (Figure 6 and 7) that the trend of strain curve has a maximum value at the centre of the joint, and then it decreases away from the joint to reach a constant strain value at a specific distance for all load levels. The failure strain was shown to be constant beyond a specific bond length; this specific bond length was 110mm for static loading and 90mm for the dynamic loading which is another method to confirm the effective bond length rather than the ultimate strength.

Comparing these results with the strain distribution along the bond length of CFRP sheet and steel plate that studied by other researchers (Al-Zubaidy et al. 2012), there is a significant increase in the strain on the bond length of CFRP laminate to that in CFRP sheet.

CONCLUSION

This paper has studied the effect of impact loading on the bond characteristics between CFRP and steel in the double-strap joint specimens. The strain reaches a maximum value at the centre of the joint specimen and the strain distribution decreases away from the joint for both loading rates. The strain curve tends to be linear for low load rates, and a non-linear curve for high load rates. A slight strain difference was observed between static and dynamic loading and the higher the loading rate the higher the failure strain. The results also show a significant increase in the load carrying capacity of the joints under impact loading, this increase is up to 50% comparing to that in quasi-static loading. The effective bond length was observed from both strain and ultimate strength plots. There is also little effect on the effective bond length, which is 110mm for static testing and 90mm for dynamic testing.

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