Fatigue Tests of Cracked Steel Plates Strengthened with UHM CFRP Plates

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Abstract: Carbon fibre reinforced polymer (CFRP) has shown promise for improving the fatigue performance of steel structures. Previous studies have indicated that increasing the Young’s modulus of CFRP can be beneficial for decreasing the stress intensity factor at the fatigue crack tip. In this project, ultra high modulus (UHM) CFRP plates with Young’s modulus of 460 GPa were adopted to study their fatigue repair effectiveness. A series of fatigue tension tests was carried out on steel plates with an initial crack in the centre. Five strengthening configurations were used and a constant amplitude fatigue loading was applied to all the specimens. The beach marking technique was utilized to record the fatigue crack propagation. The effects of CFRP bond length, bond width and bond locations on the fatigue performance of cracked steel plates were also studied. The experimental results show that UHM CFRP plates can greatly increase the fatigue life of cracked steel plates by a factor ranging from 3.26 to 7.47. When CFRP plates cover the whole crack surface, the fatigue crack of the steel plate is arrested. The strengthening effectiveness of UHM CFRP plates is also compared with those using high Young’s modulus CFRP sheeting and normal Young’s modulus CFRP plates with or without prestressing.

Key words: UHM CFRP plates, fatigue, CFRP strengthening, steel.

1. INTRODUCTION

Carbon Fibre Reinforced Polymer (CFRP) composites have been proven to be excellent alternative materials for retrofitting engineering structures (Hollaway and Head 2001; Zhao and Zhang 2007; Bakis et al. 2002; Hollaway and Teng 2008; Teng et al. 2001). Extensive studies have focused on the static performance of metallic structures with CFRP strengthening (Zhao and Zhang 2007; Cadei et al. 2004; Hollaway and Cadei 2003; Moy 2011; Shaat et al. 2004; Stradford 2008; Wu et al. 2011; Tavakkolizadeh and Saadatmanesh 2003; Roy et al. 2009). However, limited research has been conducted on the fatigue strengthening of steel structures (Fam et al. 2009; Liu et al. 2009a; Miller et al. 2001; Nakamura et al. 2009).

Fundamental research has been conducted by applying CFRP sheets or plates to steel plates with initial centre cracks or edge notches (Liu et al. 2009a; Nakamura et al. 2009; Domazet 1996; Jones and Civjan 2003; Zheng et al. 2006; Tsouvalis et al. 2009; Bocciarelli et al. 2009). The effects of CFRP Young’s modulus (Liu et al. 2009a; Jones and Civjan 2003; Zheng et al. 2006; Tsouvalis et al. 2009), patch geometries (patch length/width) (Liu et al. 2009a), strengthening configurations (single/double-sided repair) (Liu et al. 2009a; Zheng et al. 2006) and adhesive bondline thickness (Mall and Ramamurthy 1989) on the fatigue behaviour of cracked steel plates have been studied. Fatigue testing was performed on tension specimens with either edge notches or a centre...
hole by Jones and Civjan (2003). The fatigue life of CFRP strengthened specimens increased by 115% when 380 mm double layers of Sika Wrap Hex 103C sheets (Young’s modulus 65 GPa) were applied on both sides of the steel plates (specimens N51–52). Similar fatigue loading tests with centre hole steel plates with CFRP strengthening were carried out by Zheng et al. (2006). It was shown that the fatigue lives of strengthened specimens were 155–580% longer than those of un-strengthened specimens. The authors also proposed that longer fatigue life could be achieved by CFRP plates with higher Young’s modulus (320 GPa). Welded web gusset joints are typical details in steel bridges. Fatigue cracks initiated at such joints were repaired with CFRP plates by Nakamura et al. (2009). Different repair methods were attempted and the testing results confirmed great improvement in fatigue performance with CFRP plates (Young’s modulus 188 GPa) covering the whole fatigue crack area. The repair of centre cracked steel plates with both normal Young’s modulus and high Young’s modulus CFRP sheets was studied by Liu et al. (2009a). Four repair configurations were investigated with single/double sided CFRP strengthening. The experimental results showed that fatigue life can be extended by up to 7.9 times over un-reinforced steel plates. It was also shown that more improvement can be achieved by bonding high Young’s modulus CFRP sheets on both sides of the cracked steel plates. Similar single-sided CFRP repair was also studied by Tsouvalis et al. (2009). A factor of up to 2 was achieved in terms of the extension of fatigue life of centre-cracked steel plates.

Taking advantage of the material properties of CFRP, and in order to achieve greater improvement in fatigue strengthening effectiveness, a number of researchers in Europe have attempted CFRP prestressing techniques (Bassetti et al. 2000; Colombi et al. 2003a; Täljsten et al. 2009; Ye et al. 2010). Prestressed up to 41.2 kN (corresponding to a prestress of 690 MPa in the CFRP cross section), CFRP plates of Sika CarboDur M614 (E = 210 GPa, t = 1.4 mm), were adhesively attached on centre cracked steel plates. The fatigue lives of strengthened specimens were increased by a factor of about twenty (Bassetti et al. 2000; Colombi et al. 2003a). In another study (Täljsten et al. 2009), both prestressed and non-prestressed CFRP plates were utilised for strengthening steel plates with an initial crack in the centre. It was shown that non-prestressed test specimens could have their fatigue life prolonged by 2.45–3.74 times, compared to un-strengthened steel plates. Furthermore, prestressed laminates with a Young’s modulus of 70 GPa were shown to stop crack propagation. In a similar study (Colombi et al. 2003a), the effects of the applied stress range, CFRP Young’s modulus, and prestressing level on the crack growth behaviour of edge-notched steel plates were investigated. CFRP (Young’s modulus 205 GPa) plates with the highest prestressing level were found to perform the best, prolonging the fatigue life by as much as four times over the un-strengthened steel plates. Although CFRP prestressing has shown great success in fatigue strengthening, more work is needed before this technique can be widely applied in the field (Täljsten et al. 2009). For example, elegant design of the prestressing rig is necessary to hold the prestress in CFRP during the curing of the adhesive. Another major issue is the effective transfer of the prestress from the CFRP to the adherent steel.

It is evident (Liu et al. 2009a; Zheng et al. 2006) that increasing the Young’s modulus of non-prestressed CFRP plates can be an alternative solution to the CFRP prestressing technique, in terms of the fatigue life extension of steel structures. However, there are only few studies conducted to investigate fatigue strengthening of steel structures by using CFRP plates with Young’s modulus higher than 200 GPa (Dawood et al. 2007). A high modulus unidirectional carbon fibre product, Mitsubishi K 13710, with a Young’s modulus of 640 GPa was adopted for reinforcing cast iron struts in Moy and Lillistone (2006) as well as steel bridge in Moy and Bloodworth (2007). The CFRP plate was made by prepreg method with a fibre content of 60%. Similar carbon fibre sheets with Young’s modulus of 640 GPa were also used in Fawzia (2007), and it was shown that the prepreg CFRP made from this carbon fibre sheet achieved a reduced Young’s modulus of 552 GPa. In this paper, a pultruded CFRP plate with a Young’s modulus of 460 GPa (fibre content 71%) is adopted to investigate the effectiveness of fatigue strengthening using fatigue tension tests. Compared with previous CFRP Young’s modulus reported in the literature, this CFRP plate is called ultra high modulus (UHM) CFRP in this paper. UHM CFRP plates were attached on both sides of steel plates, which have a hole and two slots in the centre. Five different repair configurations were investigated. The effects of CFRP bond length, bond width and bond locations on the fatigue performance of strengthened specimens were also studied. Constant fatigue loading was applied on each specimen and the crack propagation was recorded using the “beach marking” technique. Finally, the experimental results of this paper are compared with findings on different CFRP systems, including high Young’s modulus CFRP sheeting, normal Young’s modulus CFRP plates and CFRP prestressing.
2. MATERIALS AND SPECIMENS

The experimental studies were performed at the Smart Structures Laboratory at Swinburne University of Technology in Melbourne, Australia. In this testing program, 11 fatigue tension specimens were designed, of which 8 specimens were strengthened on both sides with one layer of UHM CFRP plates. Three steel plates without CFRP strengthening were also tested as control specimens. Five different strengthening configurations were investigated.

2.1. Material Properties

The steel plates were 10 mm 300+ grade steel. The nominal yield stress is 335 MPa and the nominal ultimate tensile strength is 530 MPa. The mechanical properties of the steel plates were measured using tensile coupon tests according to ASTM E8 (2008) and the results are listed in Table 1.

UHM CFRP plates, MBRACE® Laminate 460/1500, are provided in strips of 1000 mm long and 50 mm wide with a measured thickness of 1.4 mm. Based on the technical data provided by the manufacturer, CFRP plates have a nominal axial Young’s modulus of 460 GPa, a nominal ultimate tensile strength of 1500 MPa and nominal 0.3˜0.4% elongation at break. The material properties of CFRP plates were obtained by coupon tests according to ASTM D3039 (2008). Aradite 420, was used as bonding adhesive. Its reported material properties (2007) are also presented in Table 1. The materials used in the experiments are shown in Figure 1.

2.2. Specimen Preparation

The specimens were made of UHM CFRP plates bonded on both sides of cracked steel plates by epoxy adhesive, as shown in Figure 2(a). The dimensions of the geometry of the specimens are shown in Figures 2(b) and 2(c). Both ends of the specimen were gradually narrowed to fit in the gripping jaws. All steel plates were machined with a centre hole of 5 mm in diameter together with two initial slots made by wire cutting. The slots were 1 mm long and 0.3 mm wide, as shown in Figure 2(d). The cracked plates were prepared according to ASTM E-647 (2001) with minor modifications as explained in Liu et al. (2009a).

The bonding areas of the steel surface were first sand-blasted. The surfaces were then cleaned with acetone immediately before the adhesive application to remove grease and dust and to expose a fresh chemically-active surface to ensure better mechanical interlocking (Liu et al. 2009a) The adhesive was then applied uniformly using a brush. UHM CFRP plates were then laid onto the adhesively-coated steel plates. Finally, a steel block was placed on top of the CFRP plates to apply uniform pressure until extra adhesive and air pockets were forced to bleed out. The specimens were cured for two weeks before the adhesive achieved full strength.

The thickness of adhesive layer has considerable effects on bond behaviour and fatigue performance (Mall and Ramamurthy 1989; Fawzia 2007; Lam et al. 2007). In order to achieve consistent bond behaviour, the adhesive thickness was controlled during the specimen preparation procedures (Figure 3). The adhesive thickness can be expressed as

<table>
<thead>
<tr>
<th>Table 1. Measured material properties of steel, CFRP and adhesive</th>
</tr>
</thead>
<tbody>
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<td>Materials</td>
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<tr>
<td>----------------</td>
</tr>
<tr>
<td>Steel</td>
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<tr>
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</tr>
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<td></td>
</tr>
<tr>
<td>Adhesive</td>
</tr>
</tbody>
</table>
where $t_a$, $t_{steel}$, $t_{CFRP}$, and $t_{total}$ are the thicknesses of adhesive layer, steel plate, CFRP plate, and the strengthened specimen, respectively. When four “Teflon blocks” (“thickness controlling blocks” in Figure 3) of constant thickness are used, a constant adhesive thickness can be achieved, provided that the steel plates and CFRP plates have constant thicknesses.

2.3. Strengthening Configurations
The specimens with five CFRP strengthening configurations were fabricated and tested (Figure 4). Configuration “a” is the steel plate fully covered by CFRP plates. It is assumed to compare with configuration “b” in terms of the effect of CFRP bond width (total width of CFRP) on the strengthening effectiveness. Configuration “c” was similar to “b” with a shorter bond length, so that the effect of bond length could be studied. Configurations “d” and “e” had the same bond width and bond length as “b”. However, the CFRP plates were split into halves and straddled the centre hole to different distances. By comparing configurations “b”, “d” and “e”, the effects of CFRP bond locations on the fatigue performance of cracked steel plates could be investigated.

3. FATIGUE TESTING
The tests were carried out on an MTS fatigue hydraulic frame at the Smart Structures Laboratory at Swinburne University of Technology in Melbourne, Australia. The testing set-up is shown in Figure 5. This photograph was taken after the failure of an unstrengthened steel plate.
3.1. Fatigue Loading
All the specimens were subjected to constant amplitude fatigue loading with a frequency of 10 Hz and a stress ratio of 0.1 until the steel plates fractured. The stress ratio is defined as the ratio of the minimum stress to the maximum stress applied. The same fatigue loading as that used by Liu et al. (2009a) is adopted in this paper for comparison purposes. Therefore the minimum stress in the fatigue loading spectrum is 15 MPa and the maximum stress is 150 MPa.

3.2. Measurement of Fatigue Crack Propagation
In any fatigue test, the relationship of crack propagation and fatigue cycles is a key indicator. The technique of “beach marking” is adopted in this paper, in consideration of its applicability and availability compared with other crack detection methods (Liu et al. 2009a; Liu 2008). Clear beach marking can be generated on the fracture surface by reducing the applied stress range for a short number of cycles. The reduction in the stress range changes the stress intensity factor range at the crack tip. Consequently, the rate of crack propagation is modified and visible marks are left on the crack surfaces (Liu et al. 2009a). The observation of crack size and shape after fatigue failure of the test specimens is made possible.

In the current study, after a sufficient number of cycles with a stress range of 15-150 MPa (long waves), the stress range was changed to 82.5-150 MPa (short waves, Figure 6) for a certain number of cycles. According to the operating mechanism of the hydraulic loading system, a higher frequency of 20 Hz was assigned to the short wave cycles to ensure that the transfer between long waves and short waves was smooth, so that the impact effect from the hydraulic system could be minimized.
4. EXPERIMENTAL RESULTS

The specimens and corresponding parameters, i.e. bond length, bond width and adhesive thickness and fatigue lives, are presented in Table 2. Specimen $B_i$ refers to the $i$th steel plates without CFRP strengthening. They act as control specimens. Specimen $D_n$ stands for double-sided CFRP strengthening with the $n$th strengthening configuration (from “a” to “e”). Because fatigue behaviour can be affected by a number of factors, the fatigue testing results can scatter. Therefore, two identical specimens were prepared and tested for most of the strengthening configurations, with the specimen labelled “$-1/-2$”. As mentioned in Subsection 2.2, adhesive thickness was controlled during the specimen preparation. It can be seen from Table 2 that the adhesive thickness ranged from approximately 0.5 mm to 0.85 mm with an average adhesive thickness of 0.65 mm. The bond behaviour was expected to be very much the same for adhesives within this thickness range.

4.1. Failure Modes

For adhesively-bonded CFRP-steel specimens, there can be six different failure modes, as summarized by Zhao and Zhang (2007). The failure modes of specimens with different strengthening configurations are shown in Figure 7. For specimens with shorter bond length, i.e. $Dc-1$ and $Dc-2$, CFRP delamination (separation of some carbon fibres from the resin matrix) dominated the failure mode [Figure 7(c)], whereas for all the other specimens with longer bond length, CFRP fracture became the dominant failure mode compared with CFRP delamination and CFRP-adhesive interface failure.

The different failure modes can be explained by the elliptical debonding/delamination area around the crack and the effective bond length concept in the Hart-Smith model (Hart 1973). Due to the stress concentration at the fatigue crack tip, an elliptical debonding/delamination area around the fatigue crack tip under fatigue loading has been discovered by Colombi et al. (2003b, c). According to the Hart-Smith model, an effective bond length of about 110 mm for UHM CFRP plates bonded on steel plates with Araldite 420 was reported by Wu et al. (2010). As shown in Fig. 8, an elliptical debonding/delamination area can be generated surrounding the fatigue crack during the fatigue loading. The failure modes are most probably dependent on the remaining bond length of the CFRP plates when the steel plate fractures. According to the results for double strap joints (Wu et al. 2010), if half of the remaining bond length is shorter than the effective bond length, CFRP delamination failure will appear [Specimens $Dc-1$ and $Dc-2$ in Figure 7(c)]. However, if the remaining bond length on one side is longer than the effective bond length, CFRP plates will rupture along the outline of the elliptical delamination area. Therefore, the specimens will show delamination failure at the elliptical delamination area, together with CFRP rupture across the outline of the elliptical delamination area. In some cases in Figure 7, CFRP delamination failure also appeared within the remaining bond length for specimens with longer bond length. This observation can be attributed to the damage of the adhesive bondline within this area during the fatigue loading. More critical studies on the elliptical delamination area around the fatigue crack tip and damage of the adhesive bondline under fatigue loading should be conducted in the future.

4.2. Crack Surfaces with Beach Markings

Figure 9 shows typical fracture surfaces of the unstrengthened steel plate as well as specimens with all the strengthening configurations. Two different regions have been generated on the fracture surfaces. The smooth region results from the fatigue crack propagation process. Under fatigue loading, the crack is

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Table 2. Experimental results with UHM CFRP plates

<table>
<thead>
<tr>
<th>Specimens</th>
<th>Strengthening configurations</th>
<th>Bond length (mm)</th>
<th>Bond width (mm)</th>
<th>Adhesive thickness (mm)</th>
<th>Fatigue life</th>
<th>Fatigue life extension ratio $R_{UHM CFRP}$ plate</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>Without CFRP</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>234033</td>
<td>N/A</td>
</tr>
<tr>
<td>B2</td>
<td>Without CFRP</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>266820</td>
<td>N/A</td>
</tr>
<tr>
<td>B3</td>
<td>Without CFRP</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>289312</td>
<td>N/A</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>263389</td>
<td>N/A</td>
</tr>
<tr>
<td>Da-1</td>
<td>a</td>
<td>250</td>
<td>90</td>
<td>0.46</td>
<td>more than $10^8$</td>
<td>Run-out ($\geq 380$)</td>
</tr>
<tr>
<td>Da-2</td>
<td>a</td>
<td>250</td>
<td>90</td>
<td>0.61</td>
<td>more than $10^8$</td>
<td>7.47</td>
</tr>
<tr>
<td>Db-1</td>
<td>b</td>
<td>250</td>
<td>50</td>
<td>0.77</td>
<td>1829410</td>
<td>5.21</td>
</tr>
<tr>
<td>Db-2</td>
<td>b</td>
<td>250</td>
<td>50</td>
<td>0.62</td>
<td>2107272</td>
<td>5.21</td>
</tr>
<tr>
<td>Dc-1</td>
<td>c</td>
<td>100</td>
<td>50</td>
<td>0.85</td>
<td>1493001</td>
<td>5.21</td>
</tr>
<tr>
<td>Dc-2</td>
<td>c</td>
<td>100</td>
<td>50</td>
<td>0.63</td>
<td>1251356</td>
<td>5.21</td>
</tr>
<tr>
<td>Dd-1</td>
<td>d</td>
<td>250</td>
<td>25+25</td>
<td>0.58</td>
<td>858486</td>
<td>3.26</td>
</tr>
<tr>
<td>De-1</td>
<td>e</td>
<td>250</td>
<td>25+25</td>
<td>0.67</td>
<td>1532384</td>
<td>5.82</td>
</tr>
</tbody>
</table>
developed gradually until the stress intensity factor at the crack tip exceeds the fracture toughness of the base material. Final fracture then happens, and a rough fracture region is left on the fracture surface. The length of the smooth region is defined as the fatigue crack propagation length \(2a\), measured from the centre of the steel plates, including the dimension of the centre hole and slots.

In the smooth region of the fracture surfaces, the crack propagation has been clearly recorded by beach markings. Two typical observations can be made. The first observation is that, almost all the beach markings are symmetrical in both directions of thickness and width of the specimens, with almost the same number of markings on either side of the centre hole. This observation indicates that the strengthening effects from both sides of the CFRP are nearly identical. It is also observed that, more striations are generated in CFRP strengthened specimens compared with the un-strengthened steel plates. This observation means that the crack propagation rate is decreased and a longer fatigue life has been achieved by CFRP strengthening.

Figure 7. Typical failure modes: (a) bare steel plates; (b) specimen Db; (c) specimen Dc; (d) specimen Dd; (e) specimen De
4.3. Fatigue Life

The fatigue lives of all the specimens and the corresponding fatigue life extension ratios are listed in Table 2. The fatigue life is the number of fatigue cycles counted until complete fracture of the specimen. The fatigue life extension ratio, $R$, is defined as the fatigue life of each CFRP-strengthened specimen ($N_{\text{steel with CFRP strengthening}}$) divided by the average fatigue life of the unstrengthened steel plates ($N_{\text{steel without CFRP strengthening}}$) as follows:

$$ R = \frac{N_{\text{steel with CFRP strengthening}}}{N_{\text{steel without CFRP strengthening}}} \quad (2) $$

It can be seen from Table 2 that the fatigue lives of CFRP strengthened specimens are increased by at least 3.26 times over un-strengthened steel plates. It is of interest that both specimens Da-1 and Da-2 did not fail even after the fatigue tests ran more than $10^8$ cycles before testing was stopped and considered as a run-out.
According to the results in Table 2, it is promising that the fatigue cracks can be retarded or even arrested by UHM CFRP plates under fatigue loading in the current tests.

The fatigue propagation against the fatigue cycle number was extracted from the beach markings on the fracture surfaces and the results are plotted in Figure 10. The peak point of each curve in Figure 10 represents the fatigue life of the specimen and its corresponding fatigue crack propagation length (2a: length of the smooth region in Figure 9). It is interesting to find that the fatigue crack propagation length increases with the fatigue life of the specimen. This is most likely because CFRP strengthening delays the final fracture of the specimen by effectively decreasing the crack propagation rate. In Figure 10, the crack propagation curves of un-strengthened steel plates are very close to each other. Specimens with the same CFRP strengthening configurations, such as Db-1/-2 and Dc-1/-2, also show some consistency. The scattering can be attributed to faults in the CFRP application process, i.e. misalignment of CFRP in both longitudinal and transverse directions and adhesive thickness. Another possible reason may be the misalignment of the specimen in the fatigue machine. Despite this scattering, the fatigue crack propagation curves in Figure 10 clearly show the distinct strengthening effectiveness of different strengthening configurations.

The influence of the CFRP bond width on the fatigue performance of cracked steel plates was investigated by comparing the results of specimens Da and Db. Table 2 shows that when the CFRP bond width was 50 mm (Db), an average fatigue life of 1.97 million cycles was achieved. For specimens Da-1/2 with CFRP covering the whole width of the cracked steel plates, no failure was observed after $10^6$ fatigue cycles. These observations indicate that more strengthening effectiveness can be achieved by increasing the CFRP bond width, probably because more fatigue loading can be shared by CFRP with a larger cross section area, reducing the stress intensity factor range at the steel crack tip. Similar conclusions regarding the CFRP bond width effects on the fatigue lives of cracked steel plates were also drawn for CFRP sheeting systems in (Liu et al. 2009a).

The effect of CFRP bond length on fatigue crack propagation behaviour was found by comparing results of specimens Db and Dc. The bond lengths were 250 mm and 100 mm for Db and Dc respectively. The experimental curves in Figure 10 show that the crack growth rate was much greater for specimen Dc, arriving at a shorter fatigue life of 1.49 million cycles for Dc-1 and 1.25 million cycles for Dc-2. An average fatigue life of 1.97 million cycles was achieved by specimen Db, with a fatigue life extension ratio of 7.47. This large difference in strengthening effectiveness due to the CFRP bond length can be attributed to the load transfer mechanism of adhesively-bonded joints. According to the Hart-Smith model (Hart 1973), sufficient bond length (effective bond length) is required so that more loading can be transferred from the steel plates to the CFRP composites through the adhesive layer. Therefore, under fatigue loading, specimens with longer CFRP strengthening can ensure the load transfer mechanism between the adherents, and thus effectively decrease the stress intensity factor range at the crack tip of the steel plates. The effect of CFRP bond length on the fatigue behaviour of cracked steel plates was not evident in CFRP sheeting systems (Liu et al. 2009a).

Finally, the CFRP strengthening locations had considerable influence on the fatigue behaviour of cracked steel plates. Configurations “b”, “d” and “e” had the same bond width, 50 mm, whereas the CFRP plates were split into halves and bonded to a distance from the centre hole for configurations “d” and “e”. Figure 10 shows that specimens Db yielded longer fatigue lives (on average 1.97 million cycles) with slower crack propagation rates. The fatigue lives for specimens Dd-1 and De-1 were 0.86 million and 1.53 million cycles, respectively. It can be concluded that CFRP plates should cover the crack or at least be bonded as close as possible to the crack tip to achieve the best strengthening benefits. This is because the stress intensity factor at the crack tip increases with the crack size. It is always better to repair the crack as early as possible before it becomes too long. For example, the CFRP strengthening could not effectively reduce the stress concentration at the crack tip when strengthening configuration “d” was adopted. When the crack propagates to the CFRP strengthened area, the crack size is already too big, resulting in a higher crack propagation rate, which cannot be reduced as effectively as strengthening configuration “e”. This bond location...
effect on the crack propagation behaviour of steel plates was not clearly identified for the CFRP sheeting system (Liu et al. 2009a).

5. COMPARISON WITH HIGH YOUNG’S MODULUS CFRP SHEETING SYSTEMS

Previous researchers in the authors’ research group have completed extensive studies of the fatigue strengthening of cracked steel plates with CFRP sheeting systems (Liu et al. 2009a, b, c). However, specimen preparation was tedious due to the need to attach multiple layers (e.g. 5 layers) of CFRP sheets to achieve sound repair benefits. The resulting properties of such CFRP composites may not be as consistent as those of commercially manufactured CFRP plates. The experimental results of the UHM CFRP plates in this paper were therefore compared with those from CFRP sheeting systems, to show the advantages of using UHM CFRP plates to improve the fatigue performance of cracked steel plates.

Liu et al. (2009a) carried out fatigue testing with both high and normal Young’s modulus CFRP sheeting systems. The specimens and the experimental results are listed in Table 3. The first letter “D” in the label of specimen in Table 3 means “double-side-reinforced”; the second letter “H” or “N” refers to “high Young’s modulus CFRP sheet” or “normal Young’s modulus CFRP sheet”, respectively; the number “3” or “5” specifies the specimen has “3 layers” or “5 layers” CFRP sheets; the fourth letter denotes that which strengthening configuration is adopted by the specimen; the last number is the total bond length of CFRP reinforcement. It should be noted that the ID (B, C or D in the label) for the strengthening configuration is different from the ID (a, b, c, d and e in Figure 4) in this paper. They have the following relationships (Table 4):

<table>
<thead>
<tr>
<th>Specimens</th>
<th>Equivalent to configurations of this paper</th>
<th>Layer number</th>
<th>Bond length (mm)</th>
<th>Bond width (mm)</th>
<th>Fatigue life</th>
<th>Fatigue life extension ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>Without CFRP</td>
<td>N/A</td>
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<td>N/A</td>
<td>244950</td>
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<td>N/A</td>
<td>241642</td>
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<td>542353</td>
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<td>250</td>
<td>60</td>
<td>1135592</td>
<td>4.70</td>
</tr>
<tr>
<td>DH5C250</td>
<td>e</td>
<td>5</td>
<td>250</td>
<td>30 + 30</td>
<td>1219451</td>
<td>5.05</td>
</tr>
<tr>
<td>DH3B250</td>
<td>a</td>
<td>3</td>
<td>250</td>
<td>60</td>
<td>1604008</td>
<td>6.64</td>
</tr>
<tr>
<td>DH5B100</td>
<td>a</td>
<td>5</td>
<td>100</td>
<td>60</td>
<td>1872900</td>
<td>7.75</td>
</tr>
<tr>
<td>DH5B250</td>
<td>a</td>
<td>5</td>
<td>250</td>
<td>60</td>
<td>1920000</td>
<td>7.95</td>
</tr>
</tbody>
</table>

Table 4. The relationship between the strengthening configurations in Liu et al. (2009a) and those in this paper

| Strengthening configuration in Liu et al. (2009a) | B   | C   | D   |
| Corresponding configuration in this paper        | a   | e   | b   |

It can be seen that the fatigue lives of un-strengthened steel plates in these two studies are quite close (see Table 2 and Table 3). The crack propagation curves are also compared in Figure 11(a). A reasonable correlation has been achieved, indicating the consistency in terms of steel plates selected and fatigue test methods adopted in these two studies.

For CFRP strengthened specimens, those with the same equivalent strengthening configurations (i.e. DH5B250 vs. Da, DH5D250 vs. Db and DH5C250 vs. De) were selected for comparison in terms of fatigue life extension ratio and the results are shown in Figure 12. It can be seen that cracked steel plates benefit more from UHM CFRP plates than 5-layer high Young’s modulus CFRP sheets. When 5 layers of high Young’s modulus CFRP sheets were applied covering the whole width of the cracked steel plate (DH5B250), a fatigue life of 1.92 million cycles was achieved. However, when UHM CFRP plates were applied with the same configuration (Da), the crack was arrested with more than 10^8 cycles of fatigue loading. The fatigue life extension ratios of configuration “b” and “e” were 159% and 115% higher than those with high Young’s modulus CFRP sheets, respectively.

The fatigue crack propagation curves of DH5B250 and DH5C250 are also compared with those of specimens Db and De respectively in Figures 11(b) and 11(c). The
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Chao Wu, Xiao-Ling Zhao, Riadh Al-Mahaidi, Mohammad R. Emdad and Wenhui Duan

Run-out

5 layers high modulus CFRP sheet
1 layer UHM CFRP plate

Strengthening configuration

(a) Results of bare steel plates

(b) Results of strengthening configuration "b"

(c) Results of strengthening configuration "e"

Figure 11. Comparison between UHM CFRP plate and high modulus CFRP sheeting systems (Liu et al. 2009) in terms of fatigue crack propagation behaviour

Figure 12. Comparison between UHM CFRP and high modulus CFRP sheeting (Liu et al. 2009) for different strengthening configurations

factor range at the crack tip by the application of UHM CFRP plates. Furthermore, these curves demonstrate again the conclusion drawn in Subsection 4.3 that a longer fatigue crack propagation length can be developed when the specimen has longer fatigue life.

Another interesting finding is that, for the high Young’s modulus CFRP sheeting system in Table 3, CFRP bond length (DH5B100 vs. DH5B250) and bond locations (DH5C250 vs. DH5D250) exhibited minor effects on the fatigue performance of cracked steel plates (Liu et al. 2009a). However, those effects were clearly shown by the UHM CFRP plates.

6. COMPARISON WITH NORMAL YOUNG’S MODULUS CFRP PLATE

Comparison with previous normal Young’s modulus CFRP plate results is important to show the extent to which the fatigue performance of cracked steel plates can benefit from UHM CFRP plate strengthening. Existing fatigue studies with similar specimens and experimental set-up were selected, and their experimental results are presented in Table 5. Parameters including CFRP Young’s modulus and thickness, CFRP bond length, bond width and fatigue life extension ratios are also provided, together with the equivalent strengthening configurations defined according to Figure 4.

CFRP plates with the highest Young’s modulus for fatigue strengthening were adopted by Zheng et al. (2006). In their study, cracked steel plates with a centre hole and two slots were covered along the whole width by CFRP plates on both sides. A stress range of 90 MPa with a maximum fatigue loading of 150 kN was applied. Specimen D90 obtained a fatigue life of 3.3 million cycles, which was 6.8 times more than those of

...
un-strengthened steel plates. Compared with the other studies in Table 5, they achieved the best strengthening efficiencies with only 1 layer of CFRP plate.

In Figure 13, the fatigue life extension ratios of specimens with UHM CFRP plates and normal Young’s modulus CFRP plates in Table 5 are compared for strengthening configurations “a”, “b” and “e”. For strengthening configuration “a”, UHM CFRP plates produce a fatigue life extension ratio of approximately 55 and 125 times over CFRP plates with a Young’s modulus of 320 GPa and 144 GPa, respectively. For specimens with strengthening configurations “b” and “e”, UHM CFRP plates also yield much higher fatigue life extension ratios than those with normal Young’s modulus CFRP plates, i.e. about 70% to 400% higher for configuration “b” and about 50% to 300% higher for configuration “e”.

### 7. COMPARISON WITH CFRP PRESTRESSING

Limited results have been reported regarding fatigue strengthening with CFRP prestressing (Colombi et al. 2003a; Täljsten et al. 2009; Ye et al. 2010). Three fundamental experimental studies and their results are listed in Table 6, including the level of prestress applied. It should be noted that all three studies adopted only one layer of CFRP plates bonded on both sides of the steel plates. All the CFRP plates had the same thickness of 1.4 mm.

Colombi et al. (2003a) carried out fatigue tests with cracked steel plates with a centre hole and two slots. The steel plates were reinforced with CFRP plates (500 × 50 × 1.4 mm) bonded on both sides with configuration “e” as defined in Figure 4. Both prestressed and non-prestressed CFRP plates were applied. The CFRP plates of two different Young’s modulus (174/216 GPa) were compared. All specimens were fatigue loaded to failure under a stress range of 80 MPa and a stress ratio of 0.4. They found that the fatigue life was increased by a factor of five if CFRP plates were prestressed to 632 MPa before attachment to the steel plates. Under the same prestressing level, longer fatigue life was achieved by CFRP plates with higher Young’s modulus (216 GPa).

In another fatigue study by Täljsten et al. (2009), the fatigue performance of old metallic structures with both prestressed and non-prestressed CFRP plates was

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### Table 5. Fatigue studies with normal modulus CFRP plate strengthening (one layer CFRP in all cases)

<table>
<thead>
<tr>
<th>CFRP modulus (GPa)</th>
<th>CFRP thickness (mm)</th>
<th>Equivalent to configurations of this paper</th>
<th>Bond length (mm)</th>
<th>Bond width (mm)</th>
<th>Average fatigue life extension ratio</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>320</td>
<td>1.4</td>
<td>a</td>
<td>300</td>
<td>100</td>
<td>6.8</td>
<td>Zheng et al. (2006)</td>
</tr>
<tr>
<td>144</td>
<td>1.27</td>
<td>a, fully covered the bottom flange with side notches (single side repair)</td>
<td>300</td>
<td>76</td>
<td>≈3</td>
<td>Tavakkolizadeh and Saadatmanesh (2003)</td>
</tr>
<tr>
<td>188</td>
<td>1.2</td>
<td>b</td>
<td>200</td>
<td>50</td>
<td>4.33</td>
<td>Nakamura et al. (2009)</td>
</tr>
<tr>
<td>65</td>
<td>1.0</td>
<td>b, fully covered 255</td>
<td>76</td>
<td>50</td>
<td>1.54</td>
<td>Jones and Civjan (2003)</td>
</tr>
<tr>
<td>174</td>
<td>1.2</td>
<td>e</td>
<td>500</td>
<td>50 + 50</td>
<td>≈3</td>
<td>Colombi et al. (2003)</td>
</tr>
<tr>
<td>155</td>
<td>1.4</td>
<td>e, with side notches on base plate</td>
<td>400</td>
<td>50 + 50</td>
<td>2.86</td>
<td>Täljsten et al. (2009)</td>
</tr>
<tr>
<td>260</td>
<td>1.4</td>
<td>e</td>
<td>800</td>
<td>50</td>
<td>1.47</td>
<td>Ye et al. (2010)</td>
</tr>
<tr>
<td>205</td>
<td>1.4</td>
<td>e, with side notches on base plate</td>
<td>800</td>
<td>50</td>
<td>1.47</td>
<td>Ye et al. (2010)</td>
</tr>
</tbody>
</table>

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![Figure 13. Comparison between UHM CFRP and normal modulus CFRP plates for different strengthening configurations](image-url)
investigated. Testing variables include CFRP Young’s modulus (155/260 GPa), adhesive properties, adhesive thickness and prestressing force in CFRP plates. All specimens were loaded under the same stress range of 97.5 MPa. The experimental results indicated the fatigue strengthening efficiencies using prestressed CFRP plates. When CFRP plates with a Young’s modulus of 260 GPa were prestressed to 12 kN (171 MPa according to CFRP cross section area), the specimen endured more than $16 \times 10^6$ cycles before the test was stopped and considered a run-out, showing a total crack stopping behaviour. Similar fatigue testing was conducted (Ye et al. 2010) with steel plates having edge notches. 50 mm wide CFRP plates were prestressed to different stress levels and attached on both sides of the notched steel plates. All specimens were tested under constant amplitude fatigue loading with 15 Hz using different fatigue stress ranges but the same stress ratio of 0.4. It was found that higher Young’s modulus CFRP with higher prestress decreased the crack growth rate and increased the fatigue life effectively. When 1200 MPa prestress was applied, the fatigue life of specimen E2 (CFRP Young’s modulus 205 GPa) was increased to 4.2 times over un-strengthened specimens.

In this paper, UHM CFRP plates with a Young’s modulus of 460 GPa were bonded to cracked steel plates with a centre hole and two initial slots. Constant fatigue loading was applied to all specimens with a frequency of 10 Hz, a load ratio of 0.1 and a stress range of 135 MPa. Specimens with strengthening configuration “e” achieved an average fatigue life extension ratio of 5.82, indicating a comparable strengthening efficiency against those achieved by prestressed CFRP plates. It should be pointed out that in most cases the bond length and bond width of specimens De-1 and De-2 were only half of those with prestressing. Furthermore, it is promising to find that when UHM CFRP plates cover the whole width of the cracked surface, fatigue crack propagation can be arrested under fatigue loading.

### 8. CONCLUSIONS

This paper has reported an experimental study on the improved fatigue performance of cracked steel plates strengthened with UHM CFRP plates. A constant amplitude fatigue loading was applied to all specimens. Compared to the un-strengthened steel plates, the crack propagation rates of CFRP strengthened specimens were effectively decreased, resulting in extended fatigue lives. The experimental results of UHM CFRP plates were then compared with previous studies with high Young’s modulus CFRP sheeting systems and normal Young’s modulus CFRP plates with or without prestressing. The following observations and conclusions are made based on the limited test data.

- The fatigue life of steel plates with UHM CFRP strengthening is increased by a factor ranging from 3.26 to 7.47 over un-strengthened steel plates, depending on the strengthening configurations. The crack propagation is arrested by covering the whole crack surface with UHM CFRP plates.
- The experimental results show that the CFRP bond length, bond width and bond location have considerable influence on the fatigue behaviour of the strengthened steel plates. Generally, it is better to cover the whole cracked surface with CFRP. If it is impossible in some situations, CFRP should be bonded next to the crack tip as close as possible.
- In comparison with the previous studies using CFRP sheeting systems and normal Young’s modulus CFRP plates, the experimental results with UHM CFRP plates show great advantages for improving the fatigue behaviour of cracked steel plates.
- In comparing with existing research conducted using CFRP prestressing techniques, UHM CFRP plates exhibit comparable strengthening effectiveness, even when the bond length and bond width are only half of those with prestressing.

### Table 6. Fatigue studies with CFRP prestressing (one layer CFRP in all cases)

<table>
<thead>
<tr>
<th>CFRP modulus (GPa)</th>
<th>CFRP thickness (mm)</th>
<th>Equivalent to configurations of this paper</th>
<th>Bond length (mm)</th>
<th>Bond width (mm)</th>
<th>Prestress (MPa)</th>
<th>Fatigue life extension ratio $R_{\text{CFRP prestressing}}$</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>174</td>
<td>1.4</td>
<td>e</td>
<td>500</td>
<td>50 + 50</td>
<td>632</td>
<td>5</td>
<td>Colombi et al. (2003)</td>
</tr>
<tr>
<td>216</td>
<td>1.4</td>
<td>e</td>
<td>400</td>
<td>50 + 50</td>
<td>214/171</td>
<td>10.5</td>
<td>Täljsten et al. (2009)</td>
</tr>
<tr>
<td>155</td>
<td>1.4</td>
<td>e, with side notches on base plate</td>
<td>800</td>
<td>50</td>
<td>1200</td>
<td>&gt;&gt; 34 (run out)</td>
<td>Ye et al. (2010)</td>
</tr>
<tr>
<td>260</td>
<td>1.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4.2</td>
<td></td>
</tr>
<tr>
<td>205</td>
<td>1.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5.82</td>
<td>This paper</td>
</tr>
<tr>
<td>460</td>
<td>1.4</td>
<td>e</td>
<td>250</td>
<td>25 + 25</td>
<td>0</td>
<td>5.82</td>
<td></td>
</tr>
</tbody>
</table>
Theoretical work is being conducted by the authors to predict the stress intensity factors (SIFs) and fatigue life of UHM CFRP plate strengthened steel plates. Preliminary results can be found in (Wu et al. 2012).

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REFERENCES


NOTATION

- $2a$: fatigue crack propagation length
- $E_{CFRP}$: CFRP Young’s modulus
- $N$: fatigue life
- $R$: fatigue life extension ratio by CFRP strengthening
- $I_a$: adhesive thickness
- $I_{CFRP}$: CFRP plate thickness
- $I_{steel}$: steel plate thickness
- $I_{total}$: total thickness of CFRP strengthened specimen


