Effect of Crack Orientation on Fatigue Behaviour of CFRP-Strengthened Steel Plates

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ABSTRACT: The introduction of carbon fibre reinforced polymer (CFRP) with higher Young's modulus has broadened its application to the strengthening of steel structures, especially under fatigue loading. Most research on CFRP strengthening of steel under fatigue loading has focused on tension fatigue testing, assuming that cracks or crack-like defects propagate in pure tension mode. However, the complex details and welded connections in ageing metallic structures may contain cracks orientated randomly with respect to the loading direction. This paper aims to extend the current knowledge of CFRP strengthening of steel elements in tensile fatigue loading to the case of mixed tension and shear loading. Steel plates were artificially cracked from a central hole at six different angles (10° to 90°) with respect to the loading axis. Each crack angle represents a certain degree of mode mixity. Ultra-high modulus CFRP was used for strengthening in this study. Twelve specimens were strengthened with two CFRP patching configurations. Six unrepaired specimens were tested to act as control specimens. A shifting phenomenon was identified to describe the influence of mixed mode in terms of crack propagation. A mixed mode modification factor was

developed to estimate the fatigue life of CFRP-strengthened steel plates with inclined initial cracks.

KEYWORD: Fatigue; inclined cracks; ultra-high modulus CFRP laminate; CFRP strengthening; steel plate.

NOMENCLATURE

β	Loading angle
θ	Crack propagation angle
a_o	Initial crack length
a_{eq}	Equivalent crack length
Δa	Crack length increment
N	Number of cycles
N_m	Number of cycles under mixed mode (I+II) loading
$N_{(\beta=90^\circ)}$	Number of cycles under mode I loading
$f_{(\beta)}$	Mixed mode modification factor

1 INTRODUCTION

One of the major challenges confronting civil engineering community today is extending the service life of degraded metallic structures, especially ageing road and railway bridges. A considerable number of these structures were built around the world in the last century [1, 2]. However, their design capacity does not comply with current traffic volumes, which has raised concerns regarding the safety of these bridges. The safety of these structures is mainly threatened by the risk of fatigue damage, which is one of the most common reasons for the loss of structure integrity. Some aged metallic bridges have historical value, while others constitute a crucial corridor for the regional economy; therefore, partial or complete replacement is precluded. Furthermore, replacement of degraded bridges is often not feasible, and repairing them using conventional materials is inefficient in terms of the cost, the social and environmental impacts and their durability [3-5]. In this context, an innovative material, carbon fibre reinforced polymer (CFRP), provides a promising solution and a sustainable alternative in civil engineering [6, 7]. However, the absence of comprehensive approved data on CFRP durability in civil engineering applications is an obstacle to the utilization of CFRP on a large scale [8]. There exist a number of design guidelines for the application of fibre composites in the field of civil engineering [9-13]. Complex details and welded connections in old bridges are the most susceptible to fatigue loading, and the probability of fatigue failure is expected to increase significantly with continuous increase of traffic load [14]. Therefore, a considerable number of studies have been carried out on CFRP-strengthened cracked steel plates [15-23]. The research data reveal the exceptional efficiency of CFRP in delaying crack initiation and extending the fatigue life of repaired elements compared with traditional repair techniques such as welded or bolted steel plates. It has been shown that it is possible to prevent fatigue crack initiation in steel elements by strengthening with ultra-high

modulus [24] or pre-stressed CFRP laminates [25]. Based on these results, a pre-stressed unbonded retrofit (PUR) system has been developed [26, 27] and used for fatigue strengthening of a 120-year-old metallic bridge [28, 29]. The efficiency of the CFRP strengthening achieved relates to the mechanical properties and the axial tensile stiffness [15, 30] of the composite, and the damage level of the components to be strengthened [19, 31, 32]. Introducing CFRP with Young's modulus up to almost three times that of the steel has broadened FRP applications further, as the composite material participates in sustaining the applied load before the steel plate yields [2]. Strengthening damaged metallic elements with high modulus CFRP sheets or UHM-CFRP laminates has shown great improvement in fatigue performance, especially when the whole crack area is covered [15, 18, 22, 23, 30, 33, 34]. Liu *et al.* [15] reported that the fatigue life of centrally cracked steel plates strengthened by 5 layers of high modulus CFRP sheets ($E=640\text{GPa}$, $t_{\text{one-layer}}=0.19\text{mm}$) increased by almost 8 times, whereas a study carried by Wu *et al.* [33] showed that only one layer of UHM-CFRP ($E=460\text{GPa}$, $t=1.4\text{mm}$) was sufficient to halt crack growth. Similarly, an investigation of the elastic behaviour of steel beams strengthened with normal, high and ultra-high modulus CFRP laminates revealed the superiority of UHM-CFRP plates in reducing tensile (mode-I) stresses at the crack tips through the greater increase of the in-plane stiffness of the CFRP-strengthened system [35]. High modulus CFRP also presents an effective solution for strengthening steel beams with increased load-carrying capacity and stiffness [36]. It has been shown that for a steel element with an existing crack, mode-I fatigue cracking can be arrested if pre-stressed CFRP laminate is used for strengthening [37]. Ghafoori *et al.* [38, 39] have presented a method to calculate the minimum CFRP pre-stress level by which mode-I fatigue crack growth in steel is arrested.

Nearly all the existing studies on fatigue strengthening of steel elements have focused on mode-I fatigue strengthening. However, many structural components, especially complex

details in old bridges such as connections and welded joints, are subjected to multi-axial fatigue loading. Such multi-axial loading can result in fatigue crack initiation and propagation governed by mixed-mode fracture mechanics. From the mid 1970s, extensive research has been conducted on bare steel plates, to investigate the fracture mechanism under mixed-mode loading. The scope of these efforts covered the areas of crack initiation and crack propagation in steel plates under mixed mode conditions (I+II, I+II+III), [40-42], where modes I, II and III refer to tension, shear and torsion mode, respectively.

The current knowledge of FRP applications on steel structures (e.g. Shaat *et al.* [43], Teng *et al.* [44], Kamruzzaman *et al.* [45]) reveals a lack of research on FRP strengthening of cracked members subjected to shear and tensile stresses. Therefore, it is not clear whether the CFRP repair method can achieve the same performance under the combined action of tensile and shear stresses. A preliminary study on the fatigue performance of centrally inclined cracked steel plates strengthened by CFRP laminates was conducted by the authors of the current paper [46]. This paper extends the work to cover a wider range of loading angles. Steel plates, with different crack orientations with respect to the loading axis, were retrofitted with two patching configurations of UHM-CFRP plates. A “shifting phenomenon” was introduced to explain the crack propagation behaviour in steel plates subjected to mixed-mode fatigue loading. A mixed-mode modification factor (MMMF) was developed to estimate the fatigue life of CFRP-strengthened steel plates with inclined initial cracks. The research presented in this paper forms part of a large research program on the CFRP strengthening of metallic bridges under combined actions at Monash University in collaboration with Swinburne University of Technology, and the Swiss Federal Laboratories for Materials Science and Technology (Empa), which is sponsored by the Australian Research Council, VicRoads and S&P Clever Reinforcement Company AG.

2 EXPERIMENTAL PROGRAM

In this study, twelve CFRP-strengthened centrally cracked steel plates were designed and tested under fatigue tensile loading. Two CFRP strengthening configurations were adopted to investigate the effect on fatigue performance. All steel plates were artificially notched from a 5 mm central hole with different crack inclination angles to investigate the effect of the combined action of stresses on the crack tip on the fatigue life and CFRP strengthening performance. For each crack-inclined specimen, two repairing configurations were applied. Six un-strengthened crack-inclined steel plates were prepared as control specimens.

2.1 Material Properties

The test program was conducted on CFRP-bonded centrally cracked steel plates. The steel plates were 300Plus Grade with a nominal thickness of 10 mm. The mechanical properties of the steel plates were obtained in this study through tensile coupon tests according to AS1391 [47], as shown in Table 1. For strengthening purposes, unidirectional pre-cured MBRACE laminates 460/1500 were used. The laminates had a width of 50 mm, and a measured thickness of about 1.5 mm. Based on the manufacturer's data sheet, the CFRP laminates have a nominal modulus of 460 GPa, a nominal ultimate tensile strength of 1500 MPa, an inter-laminate shear strength of 50 MPa and an elongation at break of 0.3-0.4%. Araldite 420 was used for bonding the composite system components. The measured mechanical properties of the CFRP laminates and Araldite 420 are also listed in Table 1, which were determined in [33, 48].

2.2 Preparation of Specimens

The centrally cracked steel plates were designed and prepared in a similar way to the work reported in (33). The geometries and the dimensions for the test specimens were identical, as illustrated in Figure 1(a). To simulate the mixed mode loading (I+II) at the crack tip, all steel plates were notched with the same damage level (slit length) but with different inclination angles (10° - 90°) with respect to the loading axis, as shown in Figure 1(b). The cracked steel plates were repaired on a single side using two CFRP strengthening configurations, to produce fully- and partially-strengthened specimens, as shown in Figure 2. The tensile stiffness of the CFRP laminates of the fully-repaired specimens was just above twice that of the partially-repaired specimens.

The load-carrying capacity of the CFRP adhesively bonded steel components is mainly related to the efficiency of the chemical links achieved between the adhered surfaces during the surface treatment process [49]. Therefore, most of the recommendations reported in the literature [44, 50, 51] to obtain sufficient bonding strength by achieving free, clean, and chemically-active surfaces of the adherends, were taken into account during the composite system fabrication process. The bonded steel surface was abraded by sand-blasting to increase its roughness for better bonding and interlocking with CFRP laminates [52, 53]. The effectiveness of the surface treatment was visibly evaluated during the process of sand-blasting. The abraded-surface was then cleaned using Acetone solvent. Within two hours of sand-blasting the steel plate surfaces, the two components of Araldite 420 were mixed according to the manufacturer's instructions. Next, a uniform adhesive layer was applied immediately on both substrates of CFRP and steel plates using a brush. Two pieces of CFRP laminate were placed together on the cracked area or away from the central hole, based on the required configurations. Excess adhesive coming from the edges of the laminate was

chamfered to a fillet of approximately 45° . A heavy steel block was put on the top of strengthened specimens to bleed excess adhesive and air voids. The CFRP laminates were supported from both sides of the specimens until sufficiently cured. As the adhesive bond-line thickness affects the fatigue resistance of CFRP-repaired specimens, the adhesive thickness was controlled for (0.5 mm), using the procedure reported in [33].

2.3 Experimental Set-up and Testing Procedures

The influence of six loading angles on the fatigue life was investigated in both un-strengthened and strengthened specimens under tension fatigue testing. The tests were carried out in an Instron 8802 servo-hydraulic testing machine with a load cell capacity of 250 kN, as shown in Figure 3. The machine gripping force was calibrated based on the maximum test loading, according to the guidelines for the use of the Instron machine. All the specimens were subjected to sinusoidal loading with a maximum stress level around 46% of the steel tensile yield stress. This load constitutes 30% of the ultimate static failure stress.

The test loading was applied within the frequency of 20Hz and at a loading ratio of 0.1. It should be noted that the stress ratio of 0.1 is commonly used in fatigue testing of CFRP strengthening of steel plates [e.g. 15, 18, 19] with similar configuration. This paper focuses on the comparative performance of un-strengthened and strengthened specimens. The same stress ratio of 0.1 was adopted for easy comparison purpose. Another reason for choosing a stress ratio of 0.1 is because bridge structural members are often subjected to stress ratio about 0.1 due to the effect of dead load. However, for specimens that did not fail at the designed stress range, the maximum cyclic stress was increased to around 60% of the steel tensile yield stress. The well-known beach marking technique [e.g. 15, 18, 19, 54] was used for crack length measurement. This technique involves the generation of marks on the fracture section by reducing the applied stress range for a short number of cycles. The

required number of marks could be induced by manipulating the stress intensity factor (SIF) at the crack tip for a certain number of cycles, as illustrated in Figure 4. In this study, the number of cycles adopted for beach marking was half that of the normal designed load. The reduction in the stress range changes the stress intensity factor at crack tips. Consequently, the rate of crack propagation is modified and visible marks are left on the crack surfaces. This enables the observation of crack size and shape after fatigue failure of the test specimens [15]. The beach marking is working properly no matter what the crack angle is.

2.4 Measurement of Crack Length

All the test specimens had two inclined cracks, as shown in Figure 1(b). The length of crack growth on one side (half crack length) was used in the crack propagation curves. This length represents the distance from the hole centre to the position of the beach mark on the strengthened surface of steel plates for each crack increment. The crack propagation lengths (e.g. a_1 , a_2 , and a_i) on the fracture surface were first measured from the crack tip of the initial crack length to the beach mark on the CFRP patched surface, as illustrated in Figure 5 (a). The crack length measurement was done by using a steel ruler. Then, the kinked crack (initial inclined crack and the measured crack increment length components) was represented by an equivalent straight line (see Figure 5 (b)). The equivalent crack lengths (e.g. $\bar{a}_1$, $\bar{a}_2$ and $\bar{a}_i$) were then calculated, and the results used with the recorded number of cycles to plot the crack growth curves. More details of this procedure can be found in Sih and Barthelemy [55] and Jeong [56].

3 EXPERIMENTAL RESULTS

3.1 Fatigue Life

The experimental program and the test results are summarized in Table 2. The table shows the fatigue lives and fatigue life extension ratios of unrepaired and CFRP-repaired specimens. The fatigue life represents the number of stress cycles that the specimens sustained before cracks propagated along the plate width, whereas the fatigue life extension ratio represents the ratio of the fatigue lives of the CFRP-repaired specimens to that of the corresponding unrepaired specimens. The specimens were identified in terms of the strengthening status, crack angle, and patching configurations. The symbol 'US' refers to the un-strengthened specimens, which served as test control specimens. Similarly, the symbol 'SHA' refers to the single-sided repaired specimens fully covered with UHM-CFRP plates, whereas 'SHD' stands for the single-sided repaired specimens partially covered with two patches placed away from the central crack, as shown in Figures 1(a) and 1(b). The number after the hyphen indicates the loading angle.

For steel plates with loading angles less than 30° the test ran out. The test was repeated with a fatigue loading level increased to 60% of the yield tensile strength of steel plates. This load was high enough for specimens with 30° inclined cracks to fail, whereas it was not high enough for specimens with 10° inclined cracks to fail. For cracked specimens with the highest S-SIF, ($\beta=10^\circ$), the fatigue test ran out, even when higher fatigue stress level was applied on the un-strengthened specimens.

3.2 Crack Propagation

Fatigue loading test results are commonly expressed through the relationship of the cyclic stress and the number of cycles using ($S-N$) curves [57], or the relationship between the crack

length and the number of cycles in crack propagation curves ($a-N$) [58]. In this study, the crack propagation curves were adopted to investigate the behaviour of the CFRP-strengthened steel plates under mixed-mode loading. The relationships between the measured crack length and the number of cycles of unrepaired, partially-repaired and fully-repaired specimens are illustrated in Figures 6-8 respectively. The ratio of the S-SIF to the tensile stress intensity factor (T-SIF) reaches higher values for loading angles less than 30° . Therefore, the un-strengthened specimens with this loading angle ran out at 10 million cycles under the applied loading level (0.46 fy). However, the same test was repeated with a higher load (0.6 fy). The fatigue test (on US-30) was repeated for an adequate number of beach marks, and the average value of the fatigue lives of the two tests was adopted for the crack propagation curves in Figure 9. Specimens US- 30° , SHA- 30° , and SHD- 30° failed at loading level of 0.6 fy, as shown in Table 2, whereas specimen US- 10° was still a “run out” even at loading level of 0.6 fy.

To analyze the test results for different loading levels, the fatigue lives of specimens which failed under higher fatigue loading (178MPa) were converted to the equivalent number of cycles under the lower fatigue level (135MPa). A design fatigue curve ($S-N$), with a slope of 3, was employed for this purpose, as detailed in [59]. The test results for all specimens are shown in Figures 9-11. It should be noted that for specimens which failed under higher S-SIF ($\beta < 30^\circ$), the crack propagated steadily only on one side of the central hole, while it did not on the other side. The average measured crack length of both sides was adopted in the crack growth curves. Single-sided repaired specimens are subjected to out-of-plan bending. This effect was more noticeable under higher load in terms of asymmetric crack growth, as shown in Figure 12. The crack propagation path on the fracture surface showed that the effect of mode mixity was always within the crack tip area before the tensile mode dominates the

crack growth. Figure 13 illustrates a typical crack propagation route of partially-strengthened steel plates subjected to mixed-mode loading ($\beta=45^\circ$).

4 EFFECT OF CRACK INCLINATION ON FATIGUE LIFE

4.1 Un-strengthened Steel Plates

The fatigue lives of un-strengthened steel plates with central inclined cracks are significantly influenced by the degree of crack inclination or the loading angle (β). The T-SIF at the crack tip of the centrally cracked specimens with flat cracks ($\beta=90^\circ$) is the maximum of the tested specimens. As β decreases, the S-SIF increases, while T-SIF at the crack tip decreases. In the mixed-mode FCG, the tension component of the SIF is dominant. Therefore, when T-SIF is decreased, the fatigue life of the specimen is increased. In other words, the fatigue life is extended due to the decrease in the crack driving force. Figure 6 shows a noticeable increase in the fatigue life of each inclined cracked specimen. This increase is inversely proportional to the loading angle or the crack inclination degree, which is the reason why the fatigue life of US-45° is nearly twice that of US-90°. For specimens with angles larger than 45°, the crack driving force is mainly dominated by the T-SIF effect, and the crack propagation curves are therefore almost identical for these specimens. In contrast, for specimens which have loading angles smaller than 45°, the crack driving force is mainly dominated by the S-SIF effect, at least until the crack initiates and before it starts to propagate in mode I. Once the crack begins to propagate in mode I, the T-SIF becomes dominant in the fracture mechanism. The phase dominated by S-SIF or the combined action of T-SIF and S-SIF usually happens first and it takes part of the fatigue life before the crack initiates. This part reached almost infinity for specimen US-30° under the designed stress range (135MPa). For a better illustration of the mode-mixity effect among a wider range of crack angles, it was

necessary to obtain the test results for specimens with high shear stress components by increasing the stress ranges. Figure 9 presents the converted crack propagation curves of unrepaired plates under higher test loadings. The fatigue behaviour of the tested samples can be divided into four groups: (1) specimens with cracked angles larger than 45° which are almost merged into one curve, (2) specimen US-45, a little shifted to the right, (3) specimen US- 30° , which stands out with a higher fatigue life, and (4) specimen US- 10° , which ran out. It is necessary to note that the crack propagation curves of specimens with inclined cracks were turned to pure mode I (almost the same as specimens with flat cracks) after propagating under mixed-mode conditions.

4.2 CFRP-Strengthened Steel Plates

The positive effect of utilizing UHM-CFRP laminates appears clear by extending the fatigue lives of specimens with crack angles $\beta < 45^\circ$. The fatigue lives of partially-repaired specimens increased by around 1.6 compared to about 2.2 for fully-repaired specimens, as illustrated in Figures 10 and 11. In contrast, the CFRP efficiency was not pronounced for strengthened specimens with the higher S-SIF ($\beta = 30^\circ$), where the benefit gained from UHM-CFRP was less than 30%. Similar fatigue behaviour was observed for both patching configurations (SHA- 30° and SHD- 30°). Having almost the same material properties and test conditions, the fatigue life of double-sided repaired specimens (SHD- 90°) improved by 3.26 and 3, as reported in [33] and [19] respectively, compared to only 1.6 for the single-sided repaired plates in the present work. The influence of the inclination angle on the behaviour of crack propagation for strengthened specimens appears similar to that for un-strengthened specimens by comparing Figures 6-8 and Figures 9-11. The four behaviour groups identified in Section 4.1 for un-strengthened specimens also apply to the strengthened specimens.

5 “SHIFTING PHENOMENON” UNDER MIXED MODE CONDITIONS

The positive effect of the crack inclination degree on the fatigue life has been demonstrated on both un-strengthened and CFRP-strengthened elements. The smaller the inclination angle, the greater the increase in fatigue life. Based on Figures 6 to 11, it appears that the mixed mode (I+II) crack growth curves ($\beta < 90^\circ$) can be approximated by the same crack growth curve of mode I ($\beta = 90^\circ$) with a shift to the right. The amount of shift depends on the inclination angle. Interestingly, the same concept of the shifting of $a-N$ curves was observed for the specimens under different configuration effects, as shown in Figures 14-18. A schematic view of the “shifting phenomenon” is illustrated in Figure 19. The explanation for the shifting phenomenon is that when the crack is subjected to near-threshold mixed-mode loading, it starts to grow in mixed-mode condition and later kinks to tensile mode (mode I fracture). The duration of the first phase (i.e., mode II fracture) is dependent on the ratio of S-SIF to T-SIF.

6 FATIGUE LIFE ESTIMATION USING MIXED-MODE MODIFICATION FACTOR

The process of crack propagation in mixed-mode problems can be simplified by separating the fatigue life into two regions: (i) the crack propagates under mixed-mode phase, and, then (ii) the crack propagates in tensile mode phase. When the loading angle decreases, the T-SIF decreases while the S-SIF increases. Therefore, angled cracks propagate under mixed mode conditions before kinking to pure mode I. Therefore, identification of the fatigue life under the mixed mode (I+II) phase makes it more possible to estimate the total fatigue life of CFRP-strengthened specimens. Furthermore, it was found that the crack propagation did not change but delayed starting after the number of cycles increased directly to mode mixity.

This conclusion can be used to derive a modification factor for mode-I crack growth curve to include the mixed mode (I+II) phase. This can be done by employing the shifting concept illustrated in Figure 19. The derived mixed-mode modification factor (MMMF, $f(\beta)$) is the ratio of the number of cycles under mixed mode condition (N_m) to that under mode I ($N_{\beta=90^\circ}$), and it is a function of the loading angle (β). It also represents the extension ratio in the fatigue life due to crack orientations. Consequently, by using MMMF, the total fatigue life (N_T) of structural elements with different crack orientations can be estimated using the following two equations:

$$f_{(\beta)} = \frac{N_m}{N_{\beta=90}} \quad (1)$$

$$N_T = N_{\beta=90} \times (1 + f_{(\beta)}) \quad (2)$$

The values of Eq. (1) based on test data are summarized in Table 3. Using non-linear fitting for the test results in terms of MMMF (Eq. (1)), an accurate but complicated formula can be derived (see Eq. (3)) for loading angles ranging from 30° to 90° .

$$f_{(\beta)} = 0.0394 + \frac{711}{\left(1 + \exp\left(\frac{\beta + 0.1424}{6.943}\right)\right)} \quad (3)$$

Figure 2- presents the experimental MMMF values for different crack inclination angles together with Eq. (3). The expression of $f(\beta)$ can be simplified into three linear equations (see Eq. (4)) over three regions, i.e. from 30° to 45° , from 45° to 60° and from 60° to 90° . The average values listed in Table 3 are utilized to derive the equations. For the inclination angle of 30° , the average value of 9.33 is replaced by 9 as an approximation.

$$f(\beta) = 9 - \frac{8}{15}(\beta - 30) \text{ for } 30^\circ \leq \beta < 45^\circ$$

$$f(\beta) = 1 - \frac{0.8}{15}(\beta - 45) \text{ for } 45^\circ \leq \beta < 60^\circ \quad (4)$$

$$f(\beta) = 0.2 - \frac{0.1}{15}(\beta - 60) \text{ for } 60^\circ \leq \beta < 90^\circ$$

Interestingly, the MMMF was almost the same for both un-strengthened and strengthened specimens for the two configurations, as illustrated in Figure 20. However, the formulas presented in Eq. (4) were derived based on the test results for inclined cracked plates reinforced with UHM CFRP on one side, and work is ongoing to investigate the effect of using different Young's modulus CFRP on the fatigue behaviour of steel plates with central inclined cracks. The shifting concept is expected to be noticed even with different mechanical properties of the composite material or under different load range.

It should be pointed out that this paper focuses on the experimental aspect of CFRP strengthening of steel plates in mixed tension and shear fatigue loading. It is the first stage of a large research program which will include analytical derivation using fracture mechanics and numerical simulation.

The theory in Anderson's fracture mechanics book [60] for pure steel plates will be extended to include CFRP strengthened steel plates. The stress intensity factors (T-SIF and S-SIF) can be expressed in terms of stress intensity factor when $\beta = 90^\circ$ and β defined in Figure 1 of this paper.

$$\text{T-SIF} = \text{SIF}_{\beta=90} \sin^2 \beta \quad (5a)$$

$$\text{S-SIF} = \text{SIF}_{\beta=90} \sin \beta \cos \beta \quad (5b)$$

The influence of CFRP strengthening on this relationship will be studied in the future.

The initial crack angle (β) was fixed at the beginning of the test. The loading was applied vertically all the time. During the tests, the crack propagates initially in mixed mode, then eventually in mode I (tension mode), as illustrated by the “shifting phenomenon”. The mixed mode gradually transfers to mode I after certain number of cycles, i.e. the shift shown in Figure 18. It is difficult to capture this transition of angles during the experimental testing. Future research is being carried out by the authors on numerical simulation (e.g. boundary element method incorporating fracture mechanics as reported in [61, 62, 63]) to capture this transition of angles.

7 CONCLUSIONS

Experimental tests were carried out on CFRP-strengthened steel plates with inclined initial cracks under fatigue loading. The steel plates were artificially cracked from a central hole at six different angles (10° to 90°) in relation to the loading axis to represent different degrees of mixed-mode (I+II) loading. A shifting phenomenon was identified to describe the influence of mixed mode. The following observations and conclusions are made, based on limited experimental data.

- a) The fatigue performance of fully-strengthened specimens (SHA) is about twice that of un-strengthened specimens, whereas the performance is about 1.6 times for partially-strengthened cases. The fatigue performance of single-sided repaired plates, with partial coverage of UHM-CFRP (SHD- 90°) is almost 50% of that of double-sided repaired plates reported in the literature.
- b) For cracked specimens with the highest S-SIF ($\beta=10^\circ$), the tensile stresses at the crack tips were always beneath the endurance limit, even when a higher fatigue stress level was

applied. For specimens with an inclination angle larger than 60° , tensile mode I is dominant. The interaction of mode II and mode I was observed for specimens with inclination angles between 30° and 60° .

- c) The test results in terms of crack growth curves revealed a 'shifting phenomena', i.e. the mixed-mode (I+II) crack growth curves ($\beta < 90^\circ$) can be approximated by the same crack growth curve of mode I ($\beta = 90^\circ$) with a shift to the right. The smaller the inclination angle, the larger the amount of shift.
- d) A mixed-mode modification factor was derived to taken into account the shifting phenomenon, which has been used to estimate the fatigue life of CFRP-strengthened steel plates with inclined cracks.

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Figures

(a)

(b)

Figure 1. Specimen details: (a) geometry and dimensions, (b) notch details, (in mm, not to scale)

Figure 2. CFRP configurations of the strengthened steel plates: (a) fully repaired specimen (SHA), (b) partially repaired specimen, (SHD), (in mm, not to scale)

Figure 3. Experimental set up

Figure 4. Fatigue loading range for the adopted beach marking technique

Figure 5. Schematic view of the measurement of the crack length: (a) cross section of the fracture surface, with measured crack length (a_1 , a_2 , and a_3), and (b) the calculated crack length, $\bar{a}_1$, $\bar{a}_2$, and $\bar{a}_3$

Figure 6. Crack length vs. no. of cycles of unrepaired specimens under maximum loading of (0.46fy)

Figure 7. Crack length vs. no. of cycles of partially repaired specimens under maximum loading of (0.46fy)

Figure 8. Crack length vs. no. of cycles of fully repaired specimens under maximum loading of (0.46fy)

Figure 9. Crack length vs. no. of cycles of unrepaired specimens under maximum loading of (0.6fy)

Figure 10. Crack length vs. no. of cycles of partially repaired specimens under maximum loading of (0.6fy)

Figure 11. Crack length vs. no. of cycles of fully repaired specimens under maximum loading of (0.6fy)

(a)

(b)

(c)

Figure 12. Typical crack propagation for specimens with $\beta=30^\circ$, (a) unrepaired specimen US, (b) partially repaired specimen SHD, and (c) fully repaired specimen SHA

(a)

(b)

Figure 13. Typical crack propagation path of partially strengthened specimens ($\beta=45^\circ$): (a) free surface, and (b) strengthened surface

Figure 14. Crack length vs. no. of cycles for loading angle (90°)

Figure 15. Crack length vs. no. of cycles for loading angle (80°)

Figure 16. Crack length vs. no. of cycles for loading angle (60°)

Figure 17. Crack length vs. no. of cycles for loading angle (45°)

Figure 18. Crack length vs. no. of cycles for loading angle (30°)

Figure 19. Schematic view of the shifting phenomenon in mixed mode fatigue crack growth curves

Figure 20. Eq. (3) and Eq. (4) for loading angles (90° - 30°)

Tables

Table 1. Material properties of tested specimens

	Steel	CFRP Laminates [27]	Araldite 420 [39]
Tensile strength (MPa)	500	1603	28.6
Yield strength (MPa)	329	-	-
Young’s modulus (GPa)	204	478	1.9
Thickness (mm)	10	1.46	

Table 2. Experimental program and results

Specimen Symbol	Fatigue loading level	P _{max} (kN)	P _{min} (kN)	Fatigue life	Fatigue life extension ratio
US-90°	0.46 fy	135	13.5	202,784	-
US-80°				210,860	-
US-60°				251,221	-
US-45°				402,436	-
US-30°				> 10 ⁷	-
US-10°				> 10 ⁷	-
US-30°	0.6 fy	178	17.8	1,139,899	-
US-30°				1,253,736	-
US-10°				>10 ⁷	-
SHD-90°	0.46 fy	135	13.5	319,724	1.6
SHD-80°				334,738	1.6
SHD-60°				388,030	1.5
SHD-45°				669,035	1.7
SHD-30°	0.6 fy	178	17.8	1,418,742	1.2
SHD-10°				>10 ⁷	Run Out
SHA-90°	0.46 fy	135	13.5	460,684	2.3
SHA-80°				486,592	2.3
SHA-60°				529,940	2.1
SHA-45°				881,792	2.2
SHA-30°	0.6 fy	178	17.8	1,463,308	1.3
SHA-10°				>10 ⁷	Run Out

Table 3. Values of the ratio ($N_m/N_{\beta=90}$)

Specimen Type	Inclination angle			
	30°	45°	60°	90°
US	12.53	0.98	0.24	0.00
SHD	9.17	1.09	0.21	0.00
SHA	6.28	0.91	0.15	0.00
Average	9.33	1.00	0.20	0.00