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Experimental investigation on the CFRP strengthening efficiency of steel plates with inclined cracks under fatigue loading

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ABSTRACT

Employing advanced material such as carbon-fibre-reinforced-polymer (CFRP) in tension fatigue strengthening of aged roads and railway bridges have shown a great capability of arresting or delaying crack initiation and/or propagation in steel structures. However, it is not clear whether the fatigue behaviour and the CFRP strengthening efficiency is the same when the cracked-steel elements exhibit a state of complex loading. The aim of this paper is to investigate the fatigue behaviour of the CFRP strengthening of steel plates with central initial inclined cracks with a focus on the effect of the CFRP properties. The initial slit-like cracks were oriented to introduce a state of combined action of tension (mode-I) and shear (mode II) stresses at the crack tips. The key parameters in this study are the mixed-mode (shear to tension stresses) ratio, the crack-starter length ratio (initial crack length to the plate width), patching configurations, and mechanical properties of the composite material. All the test specimens were artificially notched with central cracks of different damage levels. This study covered the fatigue performance of steel plates strengthened with two configurations of composite materials of different tensile stiffness (high modulus CFRP sheets, and normal modulus CFRP plates). Furthermore, the efficiency of strengthening systems of different fibre orientation relative to the initial crack angle was investigated. The outcomes of this study are extending the current knowledge of the CFRP strengthening to its applications on metal plates contain defects subjected to mixed-mode fatigue loading.

1. Introduction

Failure of steel components due to fatigue loading is a well-known problem. There are several variables that affect the fatigue behaviour of a structure and therefore different scenarios can be adopted for designing against fatigue failure. The nature of the fatigue loading and the fatigue strength of the loaded elements obviously have a direct effect on shortening or extending their fatigue life. Based on the loading conditions fatigue cracks can be initiated either in tension (mode-I), or shear (mode-II). The initiated cracks may propagate under pure tension (mode-I), or combined tension-shear (mixed-mode I + II) loading. Experimental researches that conducted on steel components showed a distinguished difference in the crack growth mode under different degree of the mode-mixity for different materials and load levels [1,2]. Therefore, when repairing or strengthening a structural element it is always necessary to evaluate the load conditions that govern its performance. Regarding fatigue strengthening, composite materials such as carbon-fibre-reinforced-polymer (CFRP) have shown a great capability to reduce the stress intensity and enhance the fatigue performance of the damaged metallic structures [3–12]. Consequently, the composite material was utilized successfully in different strengthening techniques, i.e.; the adhesively bonded CFRP system [12–16], and the prestressed CFRP system [17–19]. It is obvious that the mechanical properties of the composite material, the strengthening schemes (CFRP location relative to the defect area) and the strengthening method (double-sided repair vs. single-sided repair) are key factors in determining the effectiveness of the strengthening system in delaying or arresting the crack growth. The use of the CFRP has been traditionally focused on strengthening metallic plates [20,21] and members [22-24] with tension cracks (mode-I) where the unidirectional composite fully contributes to bridging the crack faces. However, fatigue failures in steel components subjected to service loads, often occur from cracks initiating and/or growing under the combined action of tensile and shear stresses (mixed-mode I + II). Therefore, it is essential to evaluate the

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Nomenclature

β	crack angle
a_o	initial crack length
$2a_o/W$	initial crack length/plate width = crack length ratio = the damage level
a_i	the distance from the initial crack-starter tip to the propagated crack tip on the fracture surface of the steel plates
fy	tensile yield stress of the steel plates
UHM-CFRP	plate composite with ultra-high-modulus (E = 478 GPa, t = 1.5 mm)
NM-CFRP	plate composite with normal-modulus (E = 205 GPa, t = 1.4 mm)
HM-CFRP	sheet composite with high-modulus (E = 640 G MPa, t = 0.1 9 mm)
US	un-strengthened steel plates
SHA	single-sided strengthened specimens with configuration A (fully covered as defined in Fig. 1)
SHD	single-sided strengthened specimens with configuration D (partially covered as defined in Fig. 1)
DHA	double-sided strengthened specimens with configuration A
DHD	double-sided strengthened specimens with configuration D
N_m, $N_{m\ (I+II)}$	number of cycles in mixed mode (I + II) loading phase
$N_{m\text{-}I}$, $N_{(\beta=90^\circ)}$	number of cycles in mode (I) loading phase
$N_{m\ (I+II)c}$, $N_{m\ (I+II)p}$	number of cycles in mixed mode (I + II) loading in strengthened, and un-strengthened plates, respectively
$N_{(m\text{-}I)c}$, $N_{(m\text{-}I)p}$	number of cycles in mode-I loading in strengthened, and un-strengthened plates, respectively
N, N_T	total fatigue life of the CFRP-strengthened specimens
$f_{(\beta)}$, MMMF	mixed mode modification factor
N_{US}	fatigue life of un-strengthened steel plates
N_{SHA}	fatigue life of single-sided strengthened specimens with configuration A
N_{SHD}	fatigue life of single-sided strengthened specimens with configuration D
N_i	number of cycles counted for initial crack to propagate from crack length ratio ($2a_o/W$) of 2% to 30%
STDEV	standard deviation of a sample

fatigue performance and understand the fatigue behaviour of the current strengthening systems under such loading conditions. Limited studies have been conducted on such a case and mostly were on thin metallic members in aerospace applications.

Bouiadjra et al. [25] conducted a finite element analysis and using linear elastic fracture mechanic (LEFM) approach to investigate the behaviour of the bonded patching system considering both mode-I and mixed-mode loading. In this study, the suggested model consisted of a thin aluminium plate with straight and inclined fatigue cracks patched with graphite/epoxy composite. The tensile stiffness of the composite material was nearly 20% larger than the repaired plates. The authors have been concluded that while there was a significant reduction in the tensile stress intensity factor (SIF), the drop in the shear stress intensity factor was almost marginal. Chung et al. [26] investigated the fatigue behaviour of single notched aluminium plates with initial fatigue crack and different loading angles to simulate the mixed-mode condition at the crack tip. They have then reported that the fatigue behaviour varied over the range of the introduced loading angles. In civil engineering applications the metal components are thicker and have higher tensile stiffness and therefore, the strengthening ratio (i.e., the tensile stiffness of the composite patch to that of the repaired metal) for the same composite material is much less than that in the aerospace applications.

The authors of the present study have already conducted an experimental investigation on thick steel plates (t = 10 mm) artificially notched with initial inclined cracks strengthened by ultra-high-modulus (UHM) CFRP plates (with a Young's modulus of 478 GPa, and a thickness of 1.5 mm) [27]. Mixed-mode loading (I + II) conditions were introduced at the tips of the slit cracks by manipulating the initial crack angle relative to the loading axis. Crack angles between (90°-10°) were introduced in the test specimens covering a range of the mode-mixity (shear to tensile stresses), whereas the crack length was fixed to 0.9 mm for all specimens (i.e., the crack length to the steel plate width ratio = 2%). Test results showed that the fatigue life increased proportionally to the mixed-mode ratio which represents the ratio of the

Table 1
The Experimental program of the current work.

			w/o-CFRP	CFRP material												No. of Specimens
				NM-CFRP						HM-CFRP						
Strengthening method	Strengthening scheme	Damage level →	5%	2%	10%	5%	20%	30%	40%	2%	10%	5%	20%	30%	40%	
		Initial crack angle ↓														
Un-strengthened		90°	✓													1
		60°														
		45°														
		30°	✓													1
Single sided	Partial	90°		✓				✓		✓		✓		✓		5
		60°		✓				✓		✓				✓		4
		45°		✓				✓		✓				✓		4
		30°		✓				✓		✓		✓		✓		5
	Full	90°		✓				✓		✓		✓		✓		5
		60°		✓				✓		✓				✓		4
		45°		✓	✓		✓	✓	✓	✓[a]	✓		✓	✓	✓	18
		30°		✓				✓		✓		✓		✓		5
Double sided																
	Partial	90°		✓				✓								2
		45°		✓				✓								2
	Full	90°		✓				✓								2
		45°		✓				✓								2
Total																60

[a] Eight specimens were added to the experimental program to study the effect of the fiber orientation of the composite patches.