# On the Concept of Fatigue Crack Arrest by Bonding a Composite Patch

F. Ellyin
Department of Materials Engineering
The University of British Columbia, Vancouver, Canada V6T 1Z4
E-mail: fernand@composites.ubc.ca

Abstract. Repairs have been made to cracked thin-walled structures by bonding a fibre reinforced polymer composite patch which reduces the crack opening displacement. Here we describe the mechanism of a fatigue crack growth in a composite repaired thick plate. Experimental results of a cracked plate overlaid by a bonded composite patch and cyclically loaded, is presented first. Subsequently, a three dimensional nonlinear finite element study is carried out to determine the required condition for the crack arrest. Both crack bridging by fibres and plasticity-induced crack closure contribute to the arrest. The results of this investigation indicate that the plasticity-induced crack closure phenomenon is beneficial to the repair when the crack tip in the base structure under goes plastic deformation. The effect of the applied patch is most significant at the outer surface, and its influence decreases from the location adjacent to the outer surface through the thickness.

## 1. Introduction

A repair of cracked/corroded structures by fastening a metallic reinforcement to extend their service life has been used in the past. The underlying design concept was to transfer load to the reinforcement at the damaged area and thus, to reduce the driving force at the crack/notch tip. To do so, the stiffness of the reinforcement has to be much greater than the base material onto which the repair is applied. This then creates discontinuity at the local geometry leading to stress concentration, and sites for crack initiation at the boundaries.

Another traditional repair method has been to remove the crack by grinding operations and then welding processes are employed to replace the displaced material. The welding operation, however, has certain disadvantages, e.g. embrittlement of the zone surrounding the weld, making these sites a likely location for crack initiation.

An alternative approach is to bond a fibre reinforced polymer composite patch onto the damaged area. In this manner strong fibres bridge the crack and reduce the crack opening displacement and thus, reduce or arrest the crack growth. This method has been used on the ageing aircraft structures, e.g. see [1]. The substrate onto which the fibre reinforced composite patch is bonded is often thin-walled. There are very limited investigations in the literature that report on the fatigue crack behaviour of a bonded patch on a thick-walled component.

In this paper we describe the mechanism of a fatigue crack growth in a composite repaired thick plate. First, the results of an experimental investigation will be presented in which a fatigue crack is grown from a sharp notch in a thick plate. The behaviour of the crack repaired by a bonded polymer composite patch is then investigated under cyclic loading. Subsequently, a three-dimensional nonlinear finite element study is carried out to demonstrate the required conditions for a crack arrest. Both crack bridging and plasticity-induced crack closure contribute to the arrest of a fatigue crack.

## 2. Experimental Study

The steel adherents were all fabricated from ASTM A-516 Gr 70, low alloy steel. The tensile yield stress was $\sigma_0 =$ 325 MPa, and the elastic modulus, E= 204 GPa. The specimens used to quantify the effect of patching on crack growth behaviour were standard ASTM Compact Tension (CT) fatigue specimens. The CT specimen dimensions are shown in Fig. 1(A). Each specimen was machined from a 25 mm thick plate with the crack oriented along the rolling direction, and the finished thickness of the specimen, b, was 15.9 mm.

2.1 The Composite Patch. The composite material used for this investigation was a pre-impregnated room-temperature cure carbon fibre / epoxy matrix known commercially as REPELARK™. The unidirectional fibre laminate patch was fabricated in-situ by applying a two part epoxy to the steel surface. Next, a carbon fibre pre-impregnated sheet was placed over top of the epoxy. Subsequent layering of the two-part epoxy and carbon fibre sheet was repeated until the carbon fibre patch had been built to the desired thickness. In this study three layers were applied on each surface as shown in Fig. 1(B). The average thickness of each carbon fibre ply was 0.21 mm.

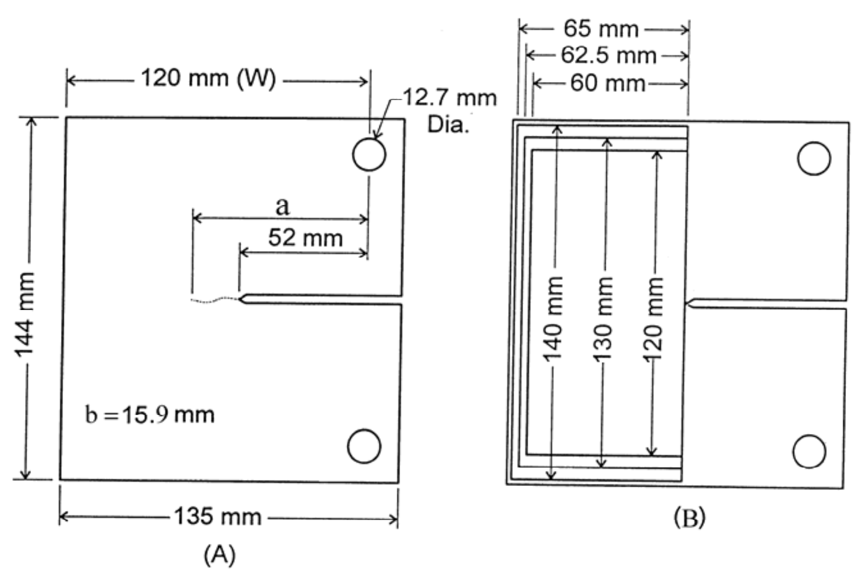



Figure 1. (A) geometry of a compact tension (CT) specimen with a propagated fatigue crack and (B) patch geometry overlaid on the cracked portion.

The cure temperature has a considerable effect on the strength of the reinforced layer. It was found that an optimum cure temperature cycle was to cure for 3 days at the ambient temperature (22° C) and then further two hours at 93° C. This resulted in an ultimate strength increase of over 50 times when compared to ambient temperature curing for seven days. An interest reader is encouraged to consult ref. [2] for further details. The uniaxial tensile strength of thus prepared composite laminate was 292 KN/m/ply, tensile strain to failure was 1.15% and tensile stiffness was 25.3 MN/m/ply. This unit of strength and stiffness was used because the thickness of the applied intra-laminate epoxy resin may vary depending on the specimen preparation.

2.2 Measuring Crack Growth. Carbon fibre patches consisting of three layers were placed on both sides of the cracked CT specimens in order to keep loading symmetrical. Because composite patches cover the crack, the crack growth cannot be determined by visual monitoring on either side of the specimen. A potential drop system was employed.

## 3. Experimental Results

After the pre-cracking procedure was completed, the CT specimens were loaded with a mean tensile load of + 2.63 KN with a superimposed cyclic load amplitude of 2.38 KN or $P_{max} = 5.0$ KN with $R = P_{min} / P_{max} = 0.05$. Using a data acquisition system, the potential drop readings were recorded every 5000 cycles. Through a calibration curve, the potential drop recordings were converted to a crack length ratio, a/W, and plotted as a function of the number of cycles. Figure 2 shows the crack length ratio, a/W, of the specimens as a function of the number of applied cycles. At 5,345,000 cycles, the crack length ratio of the unpatched (control) specimen (CTS1) was approximately 0.82, and the loading was stopped.

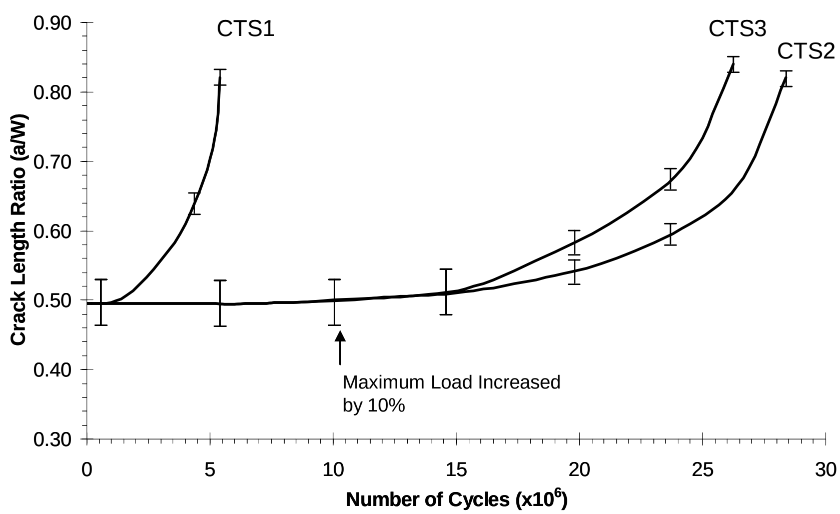



Figure 2. The crack length ratio, a/W as a function of the applied cycles.

For the patched specimens (CTS2 and 3) the crack did not propagate under the above loading conditions. To propagate the crack the cyclic loading amplitude was increased by 10% to 2.61 KN, and the mean load was also increased by 10% to + 2.89 KN resulting in a maximum load of $P_{max}$ = 5.5 KN and R=0.05, and the specimens were cycled further. Under these increased loading conditions, the crack in the patched specimens began to propagate. A parameter of interest in the fatigue crack propagation is the rate at which the crack grows da/dN. From the relationship of the crack length ratio, a/W, versus the number of applied cycles, the crack growth rate, da/dN, can be determined. Figure 3 shows the crack growth rate, da/dN, as a function of the stress intensity factor range, ΔK. Note that ΔK value for the patched specimens are based on the unpatched CT specimen geometry and is used, in this paper, for comparison purposes only. Because the ΔK value incorporates both the far field applied load and the crack length into formulation, it is a practical measure to compare the growth rates of the different specimens. For the unpatched specimen (CTS1) the threshold stress intensity factor range, $\Delta K_{th}$ = 8.0 MPa $(m)^{1/2}$ . The crack growth rate in the intermediate regime does not strictly follow a linear relationship when plotted against ΔK value on a log-log scale. However, the crack growth values are in general agreement with the values published by Craig et al. [3] and Ellyin and Li [4]. The apparent threshold stress intensity factor range for the patched specimens (CTS2 and 3) are greater than that of the unpatched one. In comparing these values with the unpatched configuration, it is observed that the apparent threshold stress intensity, $\Delta K_{th}$ , under which a crack will not grow, is increased by about 20% with the addition of a very thin patch (0.6 mm). It was also observed that in the 'Paris' regime, a crack in the patched configuration will grow slower under the same applied ΔK value. For this configuration, the patch reduces the damage produced at the crack tip and extends the life of the cracked structure considerably.

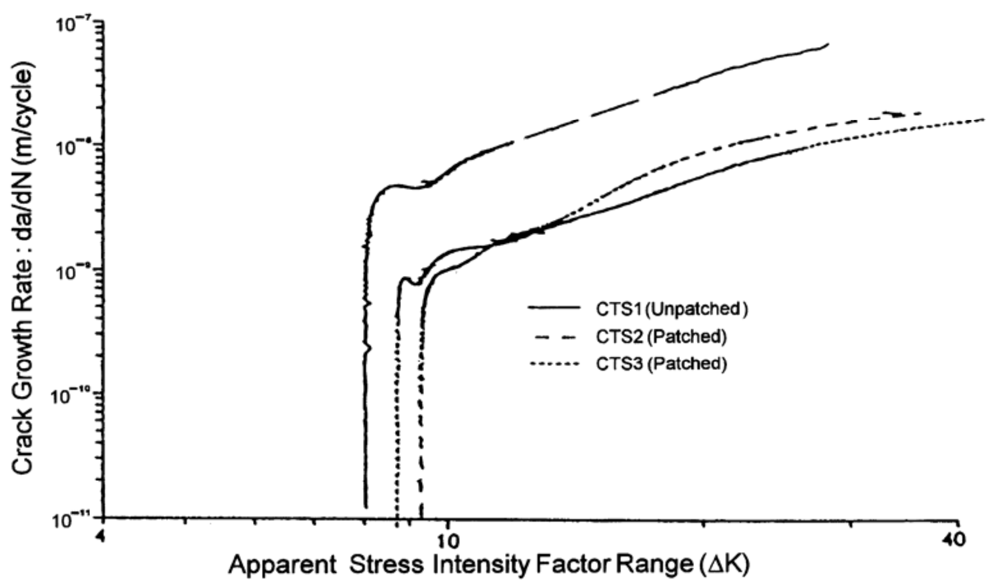



Figure 3. The crack growth rates, da/dN plotted as a function of the stress intensity factor range, ΔK.

## 4. Finite Element Analysis

To investigate the effectiveness of a bonded patch repair researchers have used numerical techniques, mainly the finite element method. The majority of these investigations have utilized two dimensional (2-D) elements or Mindlin plate elements to model a cracked plate, e.g. see refs. [5, 6] among others. The 2-D or pseudo 3-D models cannot capture the crack front shape which has been shown to influence the stress intensity factor variation through the thickness of the plate [7, 8]. A full 3-D model allows for a better understanding of the crack front and through thickness stress and strain distribution.

In addition, for a thick plate and thin patch an analysis based on the linear elastic fracture mechanics, which has been used in the previous investigations, is not adequate. An elastic-plastic analysis of the base-plate will capture the inelastic deformation around the crack front.

### 4.1 Geometry of the Model

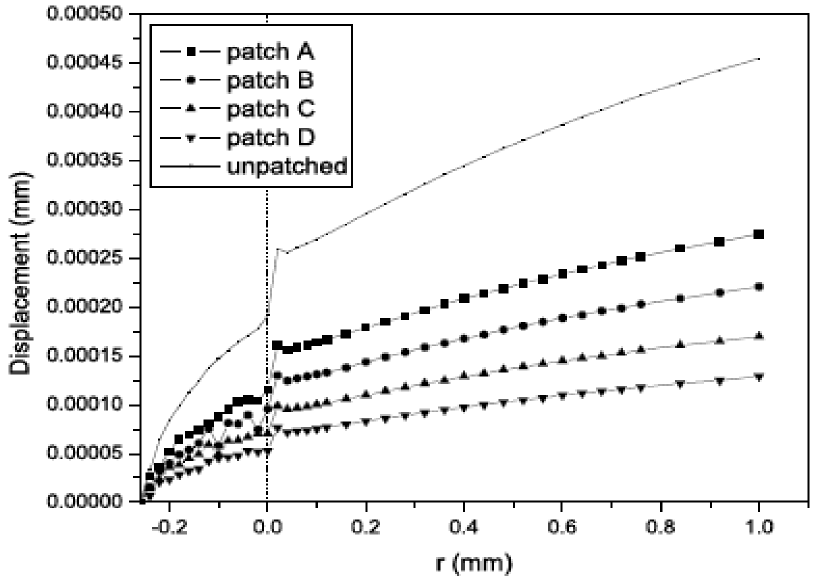
A through thickness centre-cracked plate with the crack length 2a=8 mm, is considered here. A double sided graphite / epoxy composite patch is bonded to the base-plate by an adhesive layer. For the purpose of effective patch design four patch thicknesses were considered: Patch A with $t_p$ =0.5 mm, B: 1 mm, C: 2 mm and D: 4 mm. Due to the three planes of symmetry, this geometry allows for only one eighth of the plate to be analyzed. The base-plate material is the same steel as described in Section 2, experimental study. The patch and adhesive properties and their geometry are specified in ref. [9]. All three parts, i.e. base-plate, adhesive and patch were meshed with 3-D elements. The Ellyin-Xia constitutive material model for cyclic plasticity [10] was used in this analysis.

### 4.2 Loading Condition and Determination of Crack Opening Values

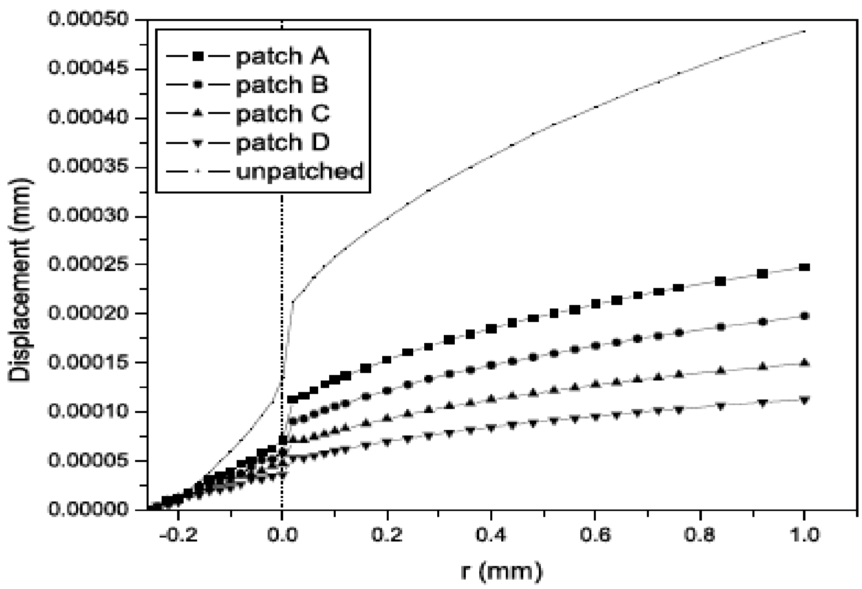
The model was subjected to 20 cycles of triangular wave form with $\sigma_{max}$ =0.3 $\sigma_0$ and $\sigma_{min}$ = 0. The loading was applied with small incremental steps to allow for accurate determination of the crack opening values through the thickness of the base-plate. At the crack front nodes the reaction forces were monitored and when they became tensile, it was indicative of a fully open crack at that node [11]. When the crack was fully open through the entire thickness, the crack front was advanced by one element, $\Delta a$ =0.02 mm, at the maximum cyclic load. During the unloading part of the cycle the displacement values of the crack surface nodes were monitored and when they became negative, the nodes were constrained in the crack surface plane. At the minimum load before reloading the constraints were removed prior to reloading. It was found that after 14$^{th}$ load cycle, the crack opening levels stabilized.

4.3 Displacement Profiles

Figures 4(a) and (b) show the crack displacement profile at crack front when the crack just becomes fully opened at the mid-plane of the base-plate and the base-plate surface bonded to the patch, respectively. The result show that as the




(a)




(b)

Figure 4. (a) Crack displacement profile for the mid-plane , and (b) the surface adhesively bonded to the patch at the load corresponding to fully opened crack.

thickness of the patch increases, the displacement profile of the base-plate decreases through the thickness. The effect of plastic deformation at the crack front can be seen through a sudden change in the crack profile at the point corresponding to the initial crack tip., i.e. r=0 [11]. These jumps in the displacement profiles can be attributed to the built-up of compressive residual stresses due to plastic deformation at and behind the initial crack tip, i.e. $r \leq 0$. This then promotes plasticity induced closure as the crack propagates.

## 5. Conclusions

Using standard CT specimens, the effect of a carbon fibre composite patch on crack propagation in a thick-walled steel plate was investigated. It was found that a very thin patch increased the threshold stress intensity factor range and reduced the crack propagation rate in the intermediate range of crack growth.

An elastic-plastic three dimensional finite element analysis was undertaken to study the effect of crack tip plasticity on an adhesively bonded composite patch repair of a cracked plate. It was found that the plasticity induced crack closure is beneficial to the repair when the base plate undergoes plastic deformation around the crack tip. The effect of the patch is most significant at the outer surface and its influence reduces through the thickness towards the mid-plane.

## Acknowledgement

The author wishes to acknowledge the contribution of his former students and research associate: P.D. Roberts, F. Ozah and Z. Xia, at various stages of this project.

## References

[1] A.A. Baker, R. Jones (Eds.), Bonded Repair of Aircraft Structure, Martinus Nijhoff, Dordrecht, The Netherlands, 1998.
[2] F. Ellyin, Carbon Fiber-Reinforced Polymer Patch for Defect Repair of a Structural Steel Component, United States Patent No. 5,972,141, 1999.
[3] D. Craig, F. Ellyin, D. Kujawski, The behaviour of small corner cracks in a ferritic/pearlitic steel: experiments and analysis, Fatigue Fract. Engng. Mater. Struct. 18 (1995) 861-873.
[4] F. Ellyin, H.-P. Li, Fatigue crack growth in large specimens with various stress ratios, J. Pressure Vessel Technol. Trans. ASME, 106, (1984) 255-260.
[5] J.J. Schubbe, S. Mall, Modeling of cracked thick metallic structure with bonded composite patch repair using three layer technique, Compos. Struct, 45(3) (1999) 185-193.
[6] B.B. Bouriadira, M. Belhouari, B. Serier, Computation of stress intensity factors for repaired cracks with bonded composite patch in mode I and mixed mode, Compos. Struct, 56(4) (2002) 401-406.

[7] D.C. Seo, J.J. Lee, Fatigue crack growth behavior of cracked aluminum plate repaired with composite patch, Compos. Struct. 57 (2002) 323-330.
[8] W.Y. Lee, J.J. Lee, Successive 3d FE analysis technique for characterization of fatigue crack growth behavior in composite repaired aluminum plate, Compos. Struct. 66 (2004) 513-520.
[9] F. Ellyin, F. Ozah, Z. Xia, 3-D modeling of cyclically loaded composite patch repair of a cracked plate, Compos. Struct. 78 (2007) 486-494.
[10] F. Ellyin, Fatigue Damage, Crack Growth and Life Prediction, Chapman & Hall, London, UK, 1997, Ch. 6.
[11] J. Wu, F. Ellyin, A study of fatigue crack closure by elastic-plastic finite element analysis for constant-amplitude loading, Int. J. Fract. 82 (1) (1996) 43-65.