Numerical simulation of multiple Fatigue crack growth in galvanised Panels

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1. Introduction

In order to extend the life duration of car bodies, the automotive sector uses the galvanising process. This technology consistsin immersing the steel sheet in a bath of liquid zinc, for sufficienttime to allow metallurgical reaction between steel surface andmolten zinc. However, after cooling few microcracks appear in thecoating and may propagate until the interface when the structureis subjected to in- service loading. The interaction between these microcracks has a major impact on the behaviour and the lifetime of the structure. Indeed, as these microcracks grow and approach each other under in-service loading conditions their interaction may considerably affect their growth up to the interface [1, 2].In this way, it is very interesting, through a numerical simulation, to apprehend the microcracks behaviour during propagation in presence of the bi-material interface. This behaviour has led to a number of research programs and many researchers have focused on the crack growth by fatigue loading.Paris and Erdogan introduced a stress intensity factor (SIF) based empirical relationship for crack growth analysis [3] called Paris law equation. Walker [4] modified the Paris law equation considering the mean stress effect. Elber [5] used an equivalent stress intensity factor to take into account crack closure under compressive. A homogenised XFEM approach has been proposed by [6] to evaluate the fatigue life of an edge crack plate in the presence of discontinuities. Chan [7] has developed a fatigue crack initiation model based on microstructure, which includes explicit crack size and microstructure scale parameters. The fatigue life prediction and the crack growth simulation have been studied by the extended finite element method by [8, 9, 10]. Pathak et al.[11] coupled the Paris law and the element free Galerkin method to simulate the fatigue crack growth of homogeneous and bi-material interfacial cracks. Ritchie [12] examined the mechanisms of fatigue crack propagation in ductile and brittle solids. Maziere and Fedelich [13] simulated 2D fatigue crack propagation using the finite element method and implementation of the strip-yield model. Shi and Zhang [14] simulated the interfacial crack growth of fiber reinforced composites under tension–tension cyclic loading using the finite element method. In their model, the energy release rate is calculated and utilised in Paris law in order to calculate crack growth rate [14].The present paper focuses on the study of the interaction between double cracks effects on the fatigue crack growth in galvanised panels. To this aim, an extended finite element method is coupled with the Paris Law and implemented in Abaqus software [15] using the Python code.

2. Numerical Formulation

2.1.XFEM Formulation

In 2-D formulation, at a particular node x, the displacement discontinuity field near defects such as cracks approached by :

$$u^h(x) = \sum_{i=1}^{N} N_i(x)u_i + \sum_{i\in W_b} N_i(x)H(x)a_i + \sum_{i\in W_s}\sum_{j=1}^{4} N_i(x)\gamma_j(x)b_{ji} \quad (1)$$

Where u_i is a nodal displacement vector of the standard finite element part at node$i$; $n$is the set of all nodes in the mesh; W_b is the set of nodes associated with the elements which are completely cut by the crack; $W_s$is the set of nodes associated with the elements which are partially cut by the crack, where, $H(x)$ is the discontinuous enrichment function or Heaviside function, defined for the elements which are completely cut by the cracks, and takes the value +1 on one side of crack and -1 on the other side of the crack; $a_i$is the nodal enriched degree of freedom associated with $H(x)$ and $b_{ij}$is the nodal enriched degrees of freedom vector associated with crack tip enrichment function, $\gamma_j(x)$. Considering a local polar coordinates system r and θ at the crack tip, the asymptotic crack tip enrichment functions can be written as [16].

$$\gamma_j(x) = \left[\sqrt{r}\sin\frac{\theta}{2},\ \sqrt{r}\cos\frac{\theta}{2},\ \sqrt{r}\sin\frac{\theta}{2}\cos\theta,\ \sqrt{r}\cos\frac{\theta}{2}\cos\theta\right] \quad (2)$$

2.2.Fatigue Life Calculation

In this section, the criterion for the crack growth direction is briefly described along with the fatigue life computation. The fatigue crack growth simulations are performed by XFEM under constant amplitude cyclic loading. The range of SIF for constant amplitude cyclic loading is defined as:

$$\Delta K = K_{max} - K_{min} \quad (3)$$

Where K_{max} and K_{min} are the stress intensity factors corresponding to maximum and minimum applied loads respectively. In real life problems, as the crack path is curved in nature, so the crack is modeled through many small line segments. To determine the direction of crack growth, several methods have been developed. There, the maximum principal stress criterion is employed to determine the crack growth direction, which dictates that the crack propagates in the direction of maximum circumferential stress. The equivalent mode-I SIF and the direction of crack growth θ_c at each crack increment is obtained by the following expression [17]:

$$\theta_c = 2arctan\frac{1}{4}\left(\frac{K_I}{K_{II}} - sign(K_{II})\sqrt{\left(\frac{K_I}{K_{II}}\right)^2 + 8}\right) \quad (4)$$

Where K_I and K_{II} are respectively mode *I* and mode *II* stress intensity factors. For quasi-static analysis, the fatigue life is obtained using the generalised Paris law [18], which can be written as,

$$\frac{da}{dN} = C(\Delta K)^m \quad (5)$$

Where a is the crack length, N is the number of loading cycles, C and m are material constants. Tanaka [19] gave a version of ΔK suitable for mixed-mode stress intensity factors where: $\Delta K = \sqrt[4]{K_I^4 + 8K_{II}^4}$ (6)

The incremental crack growth length is given by:

$$\Delta a = C.N.(\Delta K)^m \quad (7)$$

3. Geometrical Model

The bi-material elastic plate considered in this investigation has the following dimensions: height H = 30 mm and width W= 20 mm. The plate is subjected to a repeated tensile loading of $\sigma_{min} = 0\ MPa$ and $\sigma_{max} = 100\ MPa$ at the top edge of the plate and the conditions for plane stress are assumed. The bottom edge of the plate is constrained in the y-direction. The dimensions of the coating (zinc) and the base material (steel) are $h1$ = 0.08 mm and $h2$ = 19.84 mm, respectively as shown in Fig. 1.The plate is initiated by two parallel edge cracks, and separated by a distance h. The initial crack length is fixed to 0.02 mm. The mechanical properties of materials necessary for the computation are summarised in Table 1.

Table 1.Mechanical properties of zinc and steel.

	Elastic Modulus [GPa]	Poison's ratio
Steel	210	0.3
Zinc	100	0.3

The stress intensity factors analyses were performed using the finite element Abaqus software for XFEM method [15].The type of mesh elements used consists of four-node quadratic elements and the element size in the crack zone is about 1µm. To optimise the finite element mesh, a convergence study with varying mesh density is achieved until mesh-independent results were obtained.

4. Numerical Results and Discussion

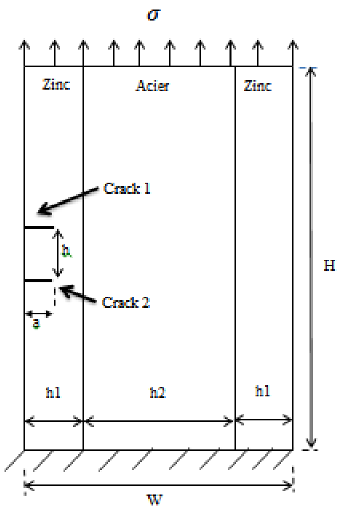

Fig.1. Geometry and general notation of the bi-material model considered.

To understand the effect of interaction between two cracks on the fatigue life, the distance h between two parallel cracks is progressively changed and the fatigue life corresponding to each crack is numerically computed. The results of Figs. 2 shows that the crack length according to a number of cycles for different distance h.The effect of the distance h on the behavior of the two cracks is well observed. A dominance of crack 2 than crack 1 during propagation when the two cracks are very close to each other (h = 0.04mm) is found. A shift of a number of cycles between two cracks to approach the bi-material interface is noted. This trend is justified by the interaction between the two cracks and the required energy to have the propagation. Moreover, this energy is stored in the structure and consumed by the crack tip in order to be incremented.In terms of crack growth rate, it is reasonable since delay for a first crack than second crack because the necessary energy is expended by the crack 2 (see Fig.2a and Fig 3a).

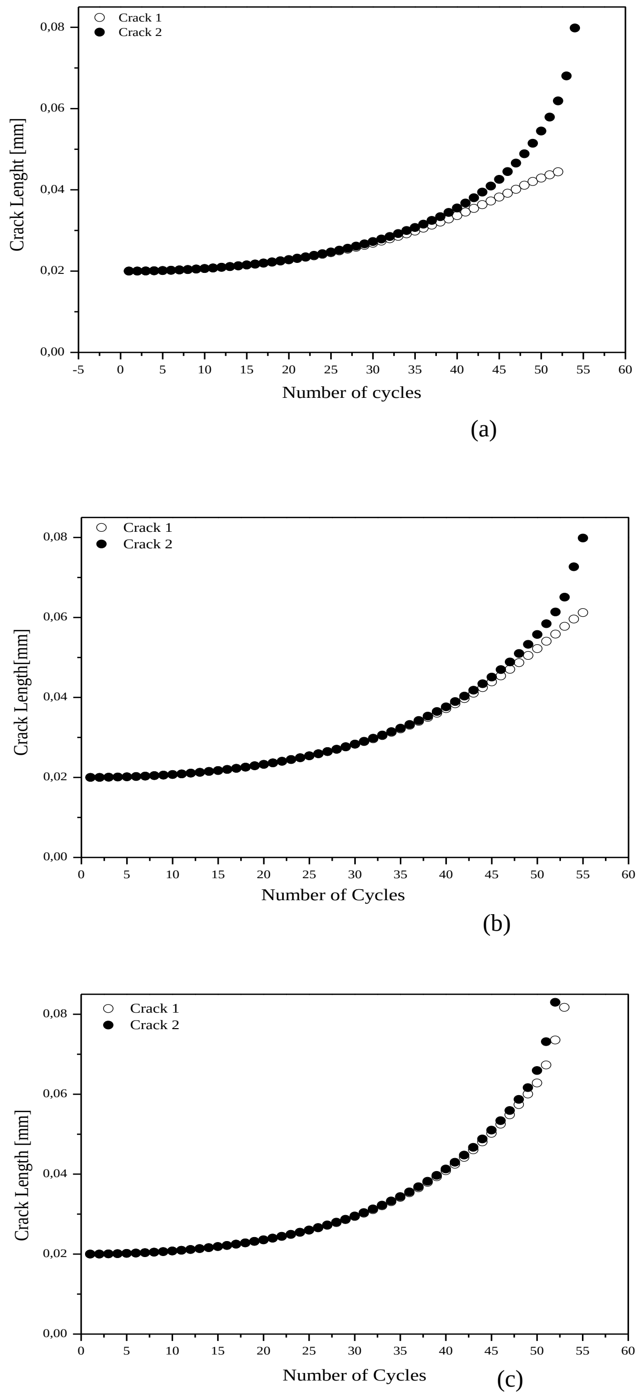

Fig.2. Fatigue life variation of two cracks with crack length for different distances h:
(a) h = 0.04mm(b) h = 0.08 mm(c) h = 0.12 mm

When the h distance increases, the interaction effect between the cracks decreases up to the value of h =

0.12mm, after this distance, the two cracks has the same behaviour as that associated with the single crack case. Moreover, this is why the two cracks have the same crack growth rate and the same way of propagation (see Figs.2 and Figs.3). Thus, the results obtained show a good agreement with the available literature result investigation [20].

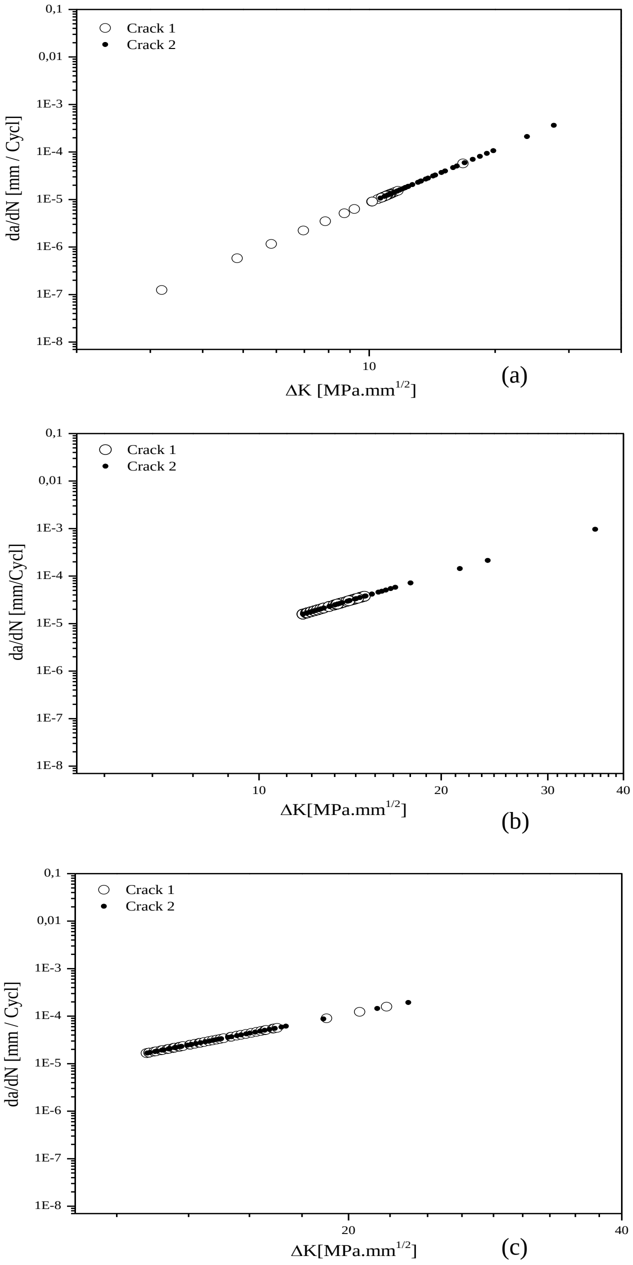

Fig.3. Crack growth rate variation with ΔK range for various distances *h*:
(a) *h* = 0.04mm(b) *h* = 0.08 mm(c) *h* = 0.12 mm

5. Conclusions

In this study, the eXtended Finite Element Method has been coupled with the Paris law and implemented in Abaqus software to compare the fatigue life between two cracks of bi-materials plates. The results obtained in this study yield the following conclusions:

- The two cracks reaches to the interface with a different number of cycles;
- An Override of one crack than other during propagation when the two cracks are very close to each other;
- The crack growth rate is significant in one crack in comparison with the other crack when the two cracks are very close to each other;
- When the distance *h*is considerable (*h*> 0.12mm), the two cracks have the same crack growth rate, the same way of propagation and the interaction effects are vanished.

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