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Double crack growth analysis in the presence of a bi-material interface using XFEM and FEM modelling

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ABSTRACT

Standard and extended finite element methods are used to analyse the interaction effect between two cracks and elucidate the parameters that govern the growth and the path of these cracks in a mono-material. The same investigation is then generalised to a galvanised zinc/Trip steel 800 bi-material. The obtained results are afterwards compared to a bi-material with a softer substrate to check the effect of the substrate rigidity on the crack behaviour. The crack length and the distance between the two cracks are found to have a substantial influence on the crack path divergence. In addition, it is found that the more the substrate is stiff the more the cracks move away from each other.

1. Introduction

To extend the life duration of car bodies, the automotive sector uses the galvanising process. This technology consists in dipping the steel sheets in a hot bath of zinc solution. The metallurgical reaction continues even after the sheets were withdrawn from the bath, as long as the sheets remain close to the bath temperature. These sheets are then cooled either by quenching in a passivation solution or water or being left in open air. After this process, a protective layer of zinc covers both sides of the galvanised steel and drastically reduces corrosion. It was found that cold work during fabrication can induce susceptibility to embrittlement in steel which, when combined with residual and thermal stresses, can result in cracking of the steel during galvanising [1]. While in several cases, few microcracks have been found in hot-dip coatings right after the processing [2]. The interaction between these microcracks has a major impact on the behaviour and the lifetime of the structure, making theoretical evaluations and experimental data from a single isolated crack case significantly inaccurate [3]. 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.

Few studies were dedicated to the understanding of multiple crack paths although it was well established that coalescence mechanism prevails before ultimate fracture. Yet, this phenomenon is somewhat misunderstood when it concerns bi-material structures. Indeed, the presence of the interface may have a beneficial or harmful effect depending on whether the substrate is stronger or softer. For this reason, it is very interesting through a numerical simulation to apprehend the auto interaction of the multiple cracks and with the interface.

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Nomenclature

XFEM	extended finite element method
FEM	finite element method
B	height of the plate
W	width of the plate
Δa	size of crack increment
a	crack length
h	distance between cracks
h_1, h_2	thickness of the coating and substrate
$f(\frac{a}{W})$	geometrical factor
E_1	Young's modulus of zinc
E_2	Young's modulus of steel
K_I	stress intensity factor in mode I
K_{II}	stress intensity factor in mode II
G_I	energy release rate
σ	applied stress
υ	Poisson's ratio
θ_f	bifurcation angle
r, θ	polar coordinates
σ_r, σ_θ, $\tau_{r\theta}$	Stress variables in polar coordinates

The computation of the stress intensity factors is proved to be a good tool for the assessment of the fracture strength of flawed structures. In this way, several approaches involving different methods were developed [4–14]. Some authors developed new XFEM-based techniques to calculate the crack growth [15] and to solve the singularity problems related to bi-material interfaces [16–19]. Fleming et al. [20] proposed an enriched element-free Galerkin formulation for fracture problems. Ventura et al. [21] introduced a new vector level set method for modelling crack growth in the element-free Galerkin (EFG) method. Vu-Bac et al. [22] incorporated the node-based smoothed finite element method (NS-FEM) into the extended finite element method (XFEM) to form a novel numerical method (NS-XFEM) for 2D fracture problem analysis. A review of the extended and generalised finite element methods with an emphasis on their application to problems in material science is proposed by Belytschko et al. [23] and Fries and Belytschko [24]. However, all these methods did not address the actual configuration encountered in engineering structures which is multiple cracks with the presence sometimes of interfaces as for galvanised steel sheets. Recently, the idea concerning how to model cracks interaction has emerged and became an important topic in fracture mechanics. Among all the existing methods, standard finite element method (FEM) is widely used since it offers more flexible and complete solution to cover the whole solution domain. But, not without special techniques that require a special meshing near the crack tip. Some researchers developed their computation approaches based on the boundary element method (BEM). This method is indeed very fast in computational time and cost because it implies less equation solving and only requires the discretisation of the boundary rather than the boundary and the domain. To this effect, Yan and Miao investigated the interaction of multiple cracks in a finite plate by using the hybrid displacement discontinuity method [25]. In an earlier investigation, Yan [26] proposed a numerical approach for modelling multiple crack fatigue growth by displacement discontinuity method with crack-tip elements. Wang et al. [27] studied the interactions of collinear and parallel cracks using finite element method. The investigation of flaw interaction effects and multiple crack growth modelling at high stress levels was presented by Van der Walde et l. [28]. Based on the Dugdale strip yield model and the distributed dislocation technique, Chang and Kotousov [29] proposed a strip yield model for two collinear cracks in plates of arbitrary thickness to investigate the interaction between two collinear cracks of equal length. Barbieri et al. [30] proposed a new weight function enrichment in meshless methods for multiple cracks in linear elasticity.

Since the interaction between cracks is considered in the present study, the whole finite body domain needs to be accounted in governing the differential equation and the finite element method is proved to be the suitable one. However, this technique has the disadvantage to be time consuming due to the remeshing required during the crack growth. For this reason, the extended finite element method XFEM was used for comparison [31]. Based on linear elastic fracture mechanics approach, this technique uses the crack tip enrichment functions to solve the singularity problems [20]. The results obtained from XFEM analysis were found to be similar to those generated from standard finite element method but with a short time consuming.

Based on the previous finite element methods, a numerical simulation is performed to investigate first the behaviour of two edge cracks in a homogeneous material. For this goal, a rectangular plate with two parallel edge cracks is subjected to uniaxial tension loading. Then, the study is generalised to bi-material structures where the effect of the interface is highlighted. The obtained results are afterwards compared to a bi-material with a softer substrate to check the effect of the substrate rigidity on the crack behaviour