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Numerical and experimental study of the plastic zone in cracked specimens

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The crack propagation is influenced by what happens at both the surface and the interior of the component. Traditional experimental tools allow the surface behaviour to be characterised accurately but the information obtained from the bulk is much more limited. In this work, a study of both bulk and surface behaviour is presented. The material behaviour is studied by powerful 3D ultrafine finite element analysis in terms of the crack tip plasticity for a range of different conditions. The analysis is performed on a wedged opening loaded specimen made of an Aluminium alloy. The results are then validated with full-field digital image correlation data. The validation is used to enhance the model used in our analyses.

1. Introduction

Numerical methods have been increasingly used to solve complex engineering problems since the development of computers and, specially, since the significant growth of their computing power in the last decades. This has been particularly true for Fracture Mechanic problems. Nevertheless, numerical solutions are subjected to a great number of uncertainties and a validation process is required to evaluate the quality of these solutions.

Mesh refinement studies or error estimation techniques can help to evaluate the quality of the numerical solutions. Nevertheless, uncertainties in the numerical modelling process are difficult to remove without comparing with experimental data. Until the development of the Digital Image Correlation Technique, this comparison could only be done with a few selected parameters, such as the strain value measured with a gauge in a particular position, being the conclusions obtained very limited [1].

In recent years, DIC technique has matured into a stable and reliable method for measuring displacement and strain fields. In the last few years, this technique has been applied in the field of Linear Elastic Fracture Mechanics [2–4]. Full-field measurements constitute an opportunity to validate numerical simulations by direct displacement and/or strain comparison with full field experimental measurements.

In the present paper, a combined numerical-experimental approach is proposed and analysed in order to study a Fracture Mechanic problem. Finite Element (FE) is used as numerical method and digital image correlation (DIC) is applied to obtain a full image of the experimental displacement field at the surface of the specimen. The comparison of both results provides the opportunity to validate the numerical model on the one hand, and to study specific issues of the problem on the other hand.

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Nomenclature

a	specimen crack length
b	specimen thickness
c	cross-correlation product
$I(x, y)$	matrix of intensity values depending on the coordinates of the pixel
N	size in pixels of the subregions
r_{pD}	Dugdale's plastic size
rc	radius of curvature
(tx, ty)	vector which define the translation of the crack tip
u, v	horizontal and vertical distances between the centre of subregions
α	constraint factor
γ	rotation angle of the crack plane

A validated finite element model provides much more information than experimental tests. This is the case of some three-dimensional effects of crack propagation, which the classical Linear Elastic Fracture Mechanic theory ignores. Issues like the influence of the specimen thickness and the crack front curvature are not considered. These issues could influence the fatigue life of metallic materials strongly affected by crack closure effects [5]. FE methods allow the study of crack closure with great detail and can provide valuable information about phenomena occurring in the bulk of the material in 2D and 3D cases [6–12]. Experimental investigation of such bulk mechanisms is possible [13,14], but requires access to 3rd generation synchrotron facilities [15,16] which are only available in few research centres.

The size and shape of the yielded area around the crack front is a factor of great importance in the fracture and fatigue behaviour of metallic materials and can be used to predict the fatigue initiation [17], crack orientation, the propagation model, etc. [18–20]. Since 1960, many attempts have been made in order to determine the plastic zone size. The first ones were limited because the consideration of purely elastic conditions [21–23]. The effect of the yielded area on the redistribution of stresses was neglected, and when considered, only two dimensional analyses were developed because of the computing power limitations of those times [24].The yielded areas were then related to two extreme stress states: plane stress or plane strain, but no clear information about the evolution of these yielded areas along the thickness was provided. The plastic zone was also studied with analytical tools in order to evaluate the influence of mixed-mode, T-stress or specimen thickness [25–27].

As the stress states depends on the load applied and the thickness of the specimen, most of the mechanical components are subjected to variable stress states during their service life. Consequently, the two-dimensional theory has become a barrier for the deep understanding of the mechanisms affecting the fracture and fatigue behaviour of metallic materials.

To this end, some works considered elastic-plastic 3D analysis of thin plates under mode I [28–30] and mixed mode (mode I + II) [31] loading condition, characterising parameters such as plastic zone sizes, stresses, strains and constraint variations along the thickness. The main difficulty of these analyses is the abrupt transition in the stress and strain fields [32] and the considered crack front shape which usually is straight. It is well known that the crack front often presents some curvature and previous works have shown the large influence of the crack front curvature on the yielded area close to the surface [33]. When considering the use of combined numerical-experimental approach, recent work by Chernyatin and co-workers should be borne in mind [34,35]. In the present work, a methodology employing DIC experimental technique is presented in order to validate results of previous FE studies [32,33]. As a first step, it is employed to successfully validate the distribution of stresses through the thickness of a cracked wedged opening loaded (WOL) specimen when considering a straight crack front. Secondly, the effect of the crack front curvature is analysed. A better correlation between the experimental DIC results and the FE ones is shown when the crack front of the modelled specimen has some curvature. By means of this correlation, it was possible to estimate the presence and magnitude of this curvature.

The paper is structured in the following sections: Section 2 describes the finite element analysis methodology employed. The numerical model has been developed supported by previous experience acquired modelling fracture and fatigue problems, but adapted to the geometry analysed in the present work. Section 3 describes the experimental procedure used for validating the numerical results. The numerical results obtained with straight crack front are shown in Section 4 and then validated in Section 5. Then, the numerical results obtained with different crack front curvatures are presented in Section 6 and are then validated with experimental data in Section 7. The key modelling parameters are also discussed in Sections 4 and 6. Validation Sections 5 and 7 also describe the comparison process that is applied and explains the main findings extracted out of the comparison. Finally, the principal conclusions of the study are presented in Section 8.

2. Finite element modelling methodology

In this study, a three-dimensional elastic-plastic FE model of a WOL (Wedge Opening Loaded) specimen geometry [36] has been developed. The WOL geometry is similar to the common compact tension (CT) geometries employed in fracture toughness testing. The difference is the ligament, which is slightly longer in case of the WOL specimen. The dimensions of the WOL specimen are shown in Fig. 1. The loads applied to the WOL specimen are pure mode I. Different specimen thick-