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Residual strength prediction of a complex structure using crack extension analyses

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Abstract

The residual strength of a flat panel (thickness 7.6 mm) with five stringers, machined from a monolithic block of Al2024-T351 material, which contained a crack that divided the central stringer, was to be predicted during a Round Robin organised by ASTM. The initial crack tips were right ahead of the stringers #2 and #4, respectively, so that crack branching along the skin and into the stringers occurred after initiation. The prediction has been achieved using finite element simulations including crack extension, for which a cohesive model was utilised. Conventional material properties, yield and ultimate strength as well as experimental results from M(T) specimens in terms of force, COD and Δa, were given. The residual strength prediction was performed in two-steps: First the crack extension parameters for the cohesive model, the cohesive strength, T_0, and the cohesive energy, Γ_0, were determined by numerical reproduction of the results of the M(T) specimen. With the optimised parameters, the five-stringer panel was modelled. These steps were conducted by two different finite element models: by a shell and a 3D finite element mesh. It turned out that it is possible to analyse the structure with both models. In the 3D case, the residual strength prediction was conservative and the deviation of the predicted from the experimental value was below 9%. The results of the shell simulation were even closer to the experiment (deviation approximately 3%), but the simulation was non-conservative.

Keywords: Residual strength; Cohesive model; Thin-walled structure; Ductile crack extension; Aluminium; Stiffened panel; Experimental validation

1. Introduction

Methods of conventional fracture mechanics are successfully used for the assessment of engineering structures for a very long time. In many cases the K-concept of linear elastic fracture mechanics extended by plastic zone corrections, in the following called the K_{eff}-concept, which goes back to the 1960s [1], is still applied to components due to its high level of standardisation and experience. More recently, methods of elastic–plastic fracture mechanics are applied, often in combination with numerical simulations using the finite element method.

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Advanced methods for the prediction of residual strength and thus structural fracture assessment use models for crack extension. One model that has gained increasing attraction is the cohesive model, which is based on an idea proposed by Dugdale [2] and Barenblatt [3] also in the early 1960s. The first one, who used the cohesive model in combination with the finite element method for the simulation of ductile failure in metals, was Needleman in 1987 [4]. The application to the assessment of metallic structures has been focused in several publications, see e.g. [5,6].

Naturally, due to computational limitations, the cohesive model has been used for two-dimensional simulations first, but in the late 1990s, when computers became more powerful, 3D simulations were performed as well [7–10], which gave a more realistic approximation of the processes ahead of the crack tip. For example, the numerical reproduction of crack front tunnelling as shown in [10], is only possible by a 3D analysis.

Thin-walled structures are also a point of interest since a couple of years, and so cohesive elements have been developed for plane stress and shell elements. The problem with these types of structures is that the thickness change cannot directly be accounted for in the cohesive elements, since the interface only consists of a line, which by definition has no thickness. One approach to overcome this problem is to model the row of continuum elements adjacent to the cohesive interface line as plane strain elements. An application of this approach to thin aluminium fracture specimens is presented in [11,12]. Later on, cohesive elements have been developed that were able to take the actual thickness of the adjacent plane stress or shell elements into account. This has been done by different groups, see e.g. [13–16].

Even though the cohesive model is in a state, in which it can be applied to complex engineering structures, this application field has gained only very little attention, see e.g. [17]. Therefore, the current investigation is aimed at demonstrating the applicability to components, for which the standard fracture mechanics procedures (see e.g. [18]) cannot be applied with sufficient accuracy.

The structure under investigation is a five-stringer panel, which is part of an ongoing Round Robin organised by ASTM [19]. During the first phase of the Round Robin, three different panels machined from a monolithic Al2024-T351 block, had to be analysed with respect to fatigue crack growth, but only one of them, shown in Fig. 1, was tested for residual strength afterwards. The load was applied to the grip ends shown in the figure under displacement control.

The rolling direction is the direction of the stringers, so that the crack configuration can be regarded as L–T orientation.

As displayed in the figure, the thickness of the main panel is almost 8 mm, and therefore the question is raised whether the component is really a thin-walled structure. Since there are several explanations for “thin-walled”, it should be defined beforehand. Three different types of definitions exist [20]:

Geometrical definition: A structure is called *thin-walled*, if the thickness is much (e.g. more than 10 times) smaller then all other relevant dimensions, which is usually expressed in its slenderness ratio, β.

According to this definition, the panel can be called thin-walled, even though the stringer height is only six times larger than its thickness, since the skin length to thickness ratio is more than 10.

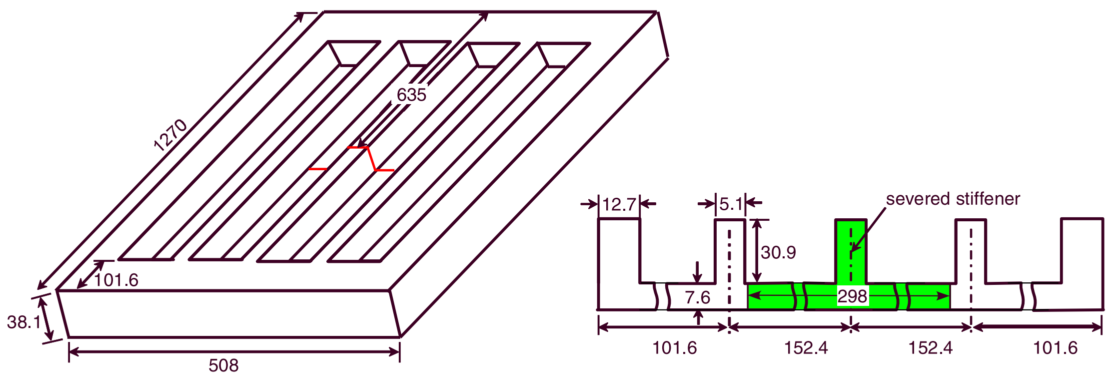

Fig. 1. Five-stringer panel containing a crack that divides the central stringer. All dimensions in mm.