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Finite element ductile crack growth simulation of test specimen with residual stresses

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1. Introduction

Performing full-scale tests is important in defect assessments of structures, but it is very difficult to reflect the complex geometries and loading conditions that occur in practice in plant assessments. An efficient tool is therefore needed not only to design full-scale and complex tests but also to reduce the need to perform such tests. One possible tool is a virtual testing using finite element (FE) damage analysis based on the local approach [1-8].

Recently, the authors proposed a simple FE method to simulate ductile failure based on a phenomenological stress-modified fracture strain model [9, 10]. The method is not new in the sense that the stress-modified fracture strain model is based on the well-known concept that the fracture strain for ductile fracture strongly depends on the stress state [11-16].

Virtual testing using FE damage analysis should ultimately be used to simulate failure of large-scale components such as full-scale pipe tests (possibly with long, stable crack growth). To simulate long, stable ductile crack growth in full-scale cracked pipes, existing methods need to be modified to incorporate larger element sizes.

In this paper, an element-size-dependent damage model based on the stress-modified fracture strain model is proposed to simulate failure of full-scale cracked plates including the influence of residual stresses. The proposed method is then compared with published experimental full-scaled cracked plates with and without electron-beam welds [18, 19].

2. Ductile fracture simulation

The accumulated damage is associated with loss of load-carrying capacity of the material. When the accumulated damage at a point becomes unity, load (stress)-carrying capacity of the point should be reduced to zero. There can be several ways to simulate loss of load-carrying capacity. In the proposed method, it is simulated simply by sharply reducing all stress components at the gauss point to a small plateau value. Decreasing stresses sharply to zero can cause numerical problems. A sensitivity analysis for the effects of the decreasing slope and cut-off stress value led to the following conclusions [9]. Simulated results were not so sensitive to the choice of the decreasing slope, as long as it was smaller than 1/5000 (when the strain increases by 0.1, the stress decreases more than 500MPa). Similarly simulated results were not so sensitive to the choice of the cut-off value, as long as it was smaller than 10% of the yield strength. Based on these results, values of the decreasing slope and the cut-off values were chosen to be 1/5000 and 10% of the yield strength, respectively, in the present work.

The above failure simulation technique is implemented in the commercial FE program, ABAQUS [17] using user subroutines. For instance, when the accumulated damage becomes critical (unity), stresses are relaxed simply by changing the yield surface using the UHARD subroutine within ABAQUS. More detailed information can be found in Ref. [9].

It has been well known that (true) fracture strain ε_f for dimple fracture strongly depends on the stress triaxiality (defined by the ratio of the mean normal stress σ_m and equivalent stress σ_e) [11-16]:

$$\frac{\sigma_m}{\sigma_e} = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3\sigma_e} \tag{3a}$$

$$\sigma_e = \sqrt{\frac{1}{2}\left\{(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_3 - \sigma_2)^2\right\}} \tag{3b}$$

where σ_i (i=1,2,3) denote the principal stress components. Although detailed expressions differ slightly, the dependence of ε_f on the stress triaxiality can be modeled using an exponential function, for instance, by:

$$\varepsilon_f = A \exp\left(-C\frac{\sigma_m}{\sigma_e}\right) + B \tag{4}$$

where *A*, *B* and *C* are material constants. For a given material, an explicit form of the stress-modified fracture strain can be found from notched bar tensile tests. For instance, a step-by-step procedure to determine the stress-modified fracture strain was given in Refs. [9, 10]. Once the form of ε_f is available as a function of the stress triaxiality, incremental damage due to plastic deformation, $\Delta\omega$, is calculated (at each gauss point within finite elements) using

$$\Delta\omega = \frac{\Delta\varepsilon_e^p}{\varepsilon_f} \tag{5}$$

where $\Delta\varepsilon_e^p$ is the equivalent plastic strain increment, calculated from FE analysis. When the accumulated damage becomes unity, $\omega = \omega_c = 1$, ductile failure is assumed locally and incremental crack growth is simulated using the technique described below.

3D finite element models were used to predict the fracture behavior of the full-scale wide plate tests. A quarter model was used considering symmetry conditions. The models with the residual stress effect were provided to represent the electron-beam weld. The method to generate residual stresses in the specimens was by applying a thermal transient to elements positioned at the weld location and then eliminating a thermal transition. A constant thermal expansion coefficient of 24 $x10^{-6}K^{-1}$ was used. Simulated residual stresses agree well with experimental data. Following this simulation of residual stress fields, the defect was inserted instantaneously into the models by removing elements in front of the crack tip.

Primary loading was simulated by applying axial displacement to nodes located on the upper edge of the FE models.

3. Conclusions

This paper has presented the results from an element-size dependent model to predict the influence of residual stress effects on ductile tearing behavior of AL2024 and AL5083 alloys. The proposed method is based on the stress-modified fracture strain model, proposed previously by the authors [9, 10]. Incremental damage is defined by the ratio of the plastic strain increment to the fracture strain. In our work, progressive cracking was assumed to occur when the accumulated damage becomes unity and provided a proper finite element size. It has been shown that this method worked very well to simulate the ductile crack growth in laboratory specimens, simulating long, stable crack growth in large-scale cracked plates containing residual stresses.

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