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Characterisation of crack tip stresses in elastic-perfectly plastic material under mode-I loading

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ABSTRACT

Asymptotic crack tip stress fields are developed for a stationary plane strain crack in incompressible elastic-perfectly plastic material under mode-I loading. Detailed investigations have revealed that in between the two extreme conditions of crack tip constraint, that is, between the fully plastic Prandtl [1] field and the uniform stress field the most general elastic–plastic crack tip fields can be completely described by the 5-sector stress solution proposed in this article. The 3-sector stress field proposed by Li and Hancock [2] and the 4-sector field proposed by Zhu and Chao [3] are subsets of the general elastic–plastic field proposed in this work. This study has revealed that cases arise where the severe loss of crack tip constraint can lead to compressive yielding of crack flank. This particular situation leads to 5-sector stress field. Detailed studies have revealed that, in the most general case of elastic–plastic crack tip fields, the T_π parameter proposed by Zhu and Chao [3] cannot be used as a constraint parameter to represent a unique state of stress at the crack tip. A new constraint-indexing parameter $T_{CS\text{-}2}$ is proposed, which along with T_p is capable of representing the entire elastic–plastic crack tip stress fields over all angles around a crack tip. Excellent agreement is obtained between the proposed asymptotic crack tip stress field and the full-field finite element results for constraint levels ranging from high to low. It is demonstrated that the proposed constraint parameters are adequate to represent the crack tip constraint arising due to specimen geometry and loading conditions as well as the additional constraint that arises due to weld strength mismatch.

1. Introduction

Characterisation of crack tip stresses has been an area of active research for many decades. Williams [4] in his landmark paper showed that the crack tip stress fields in an isotropic elastic material can be expressed as an infinite series where the leading term exhibit a $1/\sqrt{r}$ singularity and the second term is independent of r. Classical fracture mechanics theory neglects all but the singular term and, thus, came the concept of characterisation of crack tip stresses by a single parameter. Although the third and higher order terms of Williams's series vanish near the crack tip, the second term (that is constant) remains finite and has a strong effect on the stresses in the plastic zone. This second term has been referred in the literature as T-stress. The single parameter characterisation is rigorously correct only for $T>0$. It is important to note that T-stress is an elastic parameter and has no physical meaning under large-scale plasticity. Then, assuming small-strain formulation, Hutchinson [5] and Rice and Rosengren [6] proposed the dominant term of the singularity field (often referred as HRR solution) for plane strain mode-I crack based on the J-integral [7]. Thus, the HRR singularity is the natural extension of one-parameter characterisation concept to a non-linear elastic material. However, it has been realized that the specimen geometry and loading conditions significantly affect the crack tip fields and, thus, the HRR field has limited application to real cracked structures. For a Ramberg–Osgood material model, the crack tip fields in the plastic zone can be expressed in terms of a power series where the HRR solution is the leading term. The higher order terms of this power series were grouped together and its amplitude was denoted as Q by O'Dowd and Shih [8]. Other representative two parameters that are used to characterise the crack tip stress fields are J–T of Betegon and Hancock [9] and J–A_2 of Chao et al. [10].

For a rigid plastic material (non-hardening), slipline fields (SLF) have been extensively used to estimate crack tip stresses in fully plastic state under plane strain condition. Results indicate that for a non-hardening material, under fully yielded condition, the stresses near the crack tip are not unique but a strong function of specimen geometry and loading condition. An excellent compilation of various SLF solutions has been given by McClintock [11]. For high constraint geometries like deeply cracked Double Edge Crack Plate in tension (DECP) plasticity completely surrounds the crack tip (Prandtl field) and SLF analysis can be used to obtain crack tip stress distribution

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