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An insight of the structure of stress fields for stationary crack in strength mismatch weld under plane strain mode-I loading—Part I: Pure bending specimen

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ABSTRACT

In-service inspections of many nuclear power plants have revealed that cracks are most likely to occur in or the regions near the weld. Interfacial cracks under elastic as well as in elastic–plastic conditions have already been extensively discussed in literature. However, the problem of crack lying at the centre of weld is less understood. Though several detailed numerical studies have been performed to investigate the influence of weld strength mismatch on crack-tip stress fields till date, however, the detailed insight of the structure of stress fields under large scale plasticity is still lacking. The present article is intended to bridge that gap. In this work, detailed structure of the global plastic fields which occur in a deeply cracked ($a/W>0.3$) mismatch welded pure bending specimen, under fully plastic condition, is presented. Aspects related to the state of stress at the interface of two materials are discussed. It is shown that a family of five fields proposed in this work is adequate to cover all practical cases of weld mismatch. Proposed fields were confirmed by detailed full-field finite element analyses. Excellent agreement is observed between the proposed theoretical solutions and the numerical results.

1. Introduction

Welding is one of the most widely used fabrication process in the nuclear power plants. It has been observed that weld joint locations are generally critical in comparison to base metal and, thus, their fracture integrity must be assured. Conventional defect assessment procedures that are being used at present were essentially developed for cracks lying in a homogeneous material. In view of the variations in the tensile and fracture properties of base and weld material, the integrity assessment of strength mismatch welds is not straightforward. Here, mismatch means that the weld and base material differs in yield strength and in hardening behaviour. In addition, the difference in elastic modulus and Poisson's ratio also occurs in certain cases. However, for engineering materials that are used in bridges, offshore equipments, piping and pressure vessels, the difference in elastic properties is usually small [10]. Thus, these structures need specific attention on the mismatch problem under elastic–plastic condition. Since, the state of stress near the crack-tip plays an important role in the fracture process special emphasis is laid on the understanding of these local fields. For a single homogeneous material many detailed studies have been performed to examine the influence of specimen geometry and loading conditions on the nature of near-tip stress fields [1,21,4]. Even more extensive studies are required for strength mismatch welds as the strength mismatch ratio (defined as the ratio of yield strength of weld to yield strength of base material) and weld slenderness ratio (defined as the ratio of uncracked ligament to half weld thickness) are the additional variables affecting the crack-tip constraint [2,19].

In this work, detailed theoretical and numerical studies were performed on an elastic–perfectly plastic (non-hardening) material. It is well recognised that such an idealised material model does not adequately represent the real material's behaviour, however, insight into the nature of crack-tip stress fields can be obtained by this simplified material response. Moreover, crack tip constraint evaluated for a non-hardening material model can be used for materials with low strain hardening [21]. Thus, in present investigation, both base and weld materials were modelled as elastic–perfectly plastic. The two materials were assumed to have same elastic modulus and Poisson's ratio but mismatch in their yield strength. In many engineering applications and particularly in thick walled pressure vessels and piping, the state of stress near the crack-tip is essentially plane-strain. All the investigations in this work are based on this assumption. Crack was postulated at the centre of weld. Numerical studies were performed within the framework of continuum scale plasticity (J_2 flow theory) and the effects of micro-structural heterogeneity and the presence of residual stresses were not accounted.

This article presents the detailed structure of the global plastic fields which occur in a deeply cracked ($a/W>0.3$) mismatch welded pure bending SE(PB) specimen, under fully plastic condition

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Nomenclature

a	crack length
F_x	net force in x-direction ($i=1$)
F_y	net force in y-direction ($i=2$)
h	crack tip constraint parameter
H	half weld width
k	shear yield strength
k_B	shear yield strength of base material
k_w	shear yield strength of weld material
l	uncracked length ($W-a$)
M	weld strength mismatch factor
M_L	limit moment
M_{homog}	limit moment of homogeneous specimen made from base material
n_i	direction cosines of a unit vector
R, R_1	radii of circular arcs
dS	surface of a differential element
T_i	surface traction
W	width of specimen
x, y, z	parameters describing the plastic fields
ψ	weld slenderness ratio ($\psi=l/H$)
θ_b	angle made by α-slip line with respect to some fixed axis in base material
θ_w	angle made by α-slip line with respect to some fixed axis in weld material
ω	relative angular velocity
φ, β, γ	angles describing extent of circular arcs
σ_{ij}	stress components ($i=1,2$)
σ^k	mean(hydrostatic) stress at a given point 'k'
σ_b^k	mean(hydrostatic) stress at a given point 'k' in base material
σ_{eq}	Von-Mises stress
σ_y	yield strength
σ_{yb}	yield strength of base material
σ_{yw}	yield strength of weld material
σ_{ij}^*	kinematically compatible stress field
v^*	tangential velocity (constant in magnitude)
SE(PB)	single edge cracked specimen in pure bending
M(T)	middle tension specimen
MUB	modified upper bound theorem
C(T)	compact tension specimen
SLF	slip-line field
FEA	finite element analysis

(at limit state). Results for compact tension, C(T) specimen and middle tension, M(T) specimen would be presented in part-II of this article. Aspects related to the state of stress at the interface of two materials are discussed in detail. It is shown that a family of five fields proposed in this work is adequate to cover all practical cases of weld mismatch. Extreme under-match cases where plastic fields get fully confined in the weld material were not considered as sufficiently detailed results for these cases already exist in literature [10,11]. The proposed fields were utilised to obtain analytical solutions of the limit moment and crack-tip stresses using the Modified Upper Bound (MUB) theorem, recently proposed by Khan et al. [14]. Rigorous mathematical basis of this load bounding technique and its equivalence with the classical slip line field (SLF) analysis, for a homogeneous rigid–plastic body in plane strain, was presented by [15]. Various simplifications resulting from the use of this new load bounding technique over SLF method were demonstrated. Apart from accurate evaluation of the limit load, detailed examination of crack tip stresses, for various standard (homogeneous) fracture mechanics specimens, was performed using this new form of work principle [15]. One of the most striking features of this new load bounding technique is that it requires no information about the state of stress in the rigid regions, the stress field in the deforming zones only should be statically admissible. This important feature of the proposed approach has enabled us to theoretically examine the problem of crack lying at the centre of weld. Proposed fields were confirmed by detailed full-field finite element analysis. Excellent agreement is observed between the proposed theoretical solutions and the numerical results.

2. Background

In-service inspections of many nuclear power plants have revealed that cracks are most likely to occur in or the regions near the weld. From integrity assessment point of view the problem of crack lying at the interface of two materials or in the centre of weld is of equal importance. The behaviour of crack lying anywhere else in the weld region is likely to be explained by these two limiting crack locations. Description of crack tip stress field for an interfacial crack under elastic condition [6,5,22,23] and in elastic–plastic condition [25,8,9,26,27,24] have already been extensively discussed in the literature. However, the problem of crack lying at the centre of weld is (theoretically) less understood. This problem was first systematically studied by Varias et al. [28]. They numerically (finite element) examined the case where a crack was postulated at the centre of ductile metal foil sandwiched between two rigid ceramic blocks. In their analysis, ceramic blocks were modelled as elastic while the plastic deformation of metal foil was governed by the finite strain J_2 flow theory. The focus of this study was to understand the ductile failure mechanisms that are likely to occur in the metal foil under such a high constraint state. However, in the welds that are typically encountered in many engineering applications the mismatch in yield strength is not so high. Thus, in the more general case both the materials are elastic–plastic and plasticity passes through the interface of two materials. This was the focus of a numerical study by Burstow et al. [2]. They performed a series of two-dimensional finite element analyses within the framework of the modified boundary layer formulation. Both base and weld materials were assumed to have same elastic properties and were modelled as elastic–perfectly plastic. Elastic T-stress was applied to model different constraints at the crack-tip arising due to actual specimen geometry and loading conditions. The effect of strength mismatch on crack-tip constraint was studied systematically by changing the yield strength of base material. Such formulations are valid, however, as long as the remotely applied elastic displacement field is not influence by the plastic behaviour at the crack-tip. Since welded structures are intended to withstand sufficiently high loading such an assumption of small-scale yielding strictly does not hold good.

Initial studies on the problem of weld centre cracks, under large-scale plasticity, were carried out by Joch et al. [12] and Burstow and Ainsworth [3]. Main objective of these studies was to quantify the influence of weld strength mismatch on the limit load and plastic η-factors. Classical upper bound theorem of limit analysis was used to derive analytical solutions. These studies establish the influence of weld mismatch on the shape of global plastic fields at least qualitatively. However, more detailed description of this problem is due to Hao et al. [10,11]. They attempted to extend the work of Varias et al. [28] by