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Fracture mechanics analysis of heterogeneous welds: Numerical case studies involving experimental heterogeneity patterns

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ABSTRACT

Weld flaw assessments require a quantification of crack driving force, and procedures to do so are generally based on the assumption of homogeneity. However, welds generally have a heterogeneous microstructure. The authors have developed a method to account for continuous strength property variations in the estimation of crack driving force. It considers average material properties along slip lines originating from the crack tip, thus defining a homogenized weld which is expected to produce a similar crack driving force response. This paper presents a numerical validation of the proposed homogenization approach. Weld heterogeneity is characterized in three pipeline girth welds by means of automatic hardness testing. The resulting distributions are input into a finite element model of a clamped SE(T) specimen with element-specific material properties. Following, crack tip opening displacement (CTOD) responses of heterogeneous and idealized welds are compared. Two loading modes are considered: pure tension (mode I) and in-plane shear (mode II). The homogenization approach is found to strongly simplify complex heterogeneous welds into homogeneous structures and, in doing so, maintain an acceptable level of accuracy with respect to mode I crack driving force.

1. Introduction

The integrity assessment of flawed structures requires a quantification of crack driving force under imposed loading conditions. Most flaw assessment procedures in elastic–plastic fracture mechanics assume a defect to be surrounded by homogeneous material (i.e. exhibiting a fixed constitutive behavior). This assumption was crucial to the development of fracture mechanics based concepts such as a path independent J contour integral [1]. Further, the mathematical foundations of established flaw assessment procedures rely on material homogeneity. For instance, the EPRI framework for estimation of J by Kumar et al. [2] assumes fixed true stress–true strain (σ–ε) properties, characterized by the well-known model of Ramberg and Osgood [3]:

$$\frac{\varepsilon}{\varepsilon_y} = \frac{\sigma}{\sigma_y} + \alpha\left(\frac{\sigma}{\sigma_y}\right)^n. \quad (1)$$

Linear elasticity theory implies that $\varepsilon_y = \sigma_y / E$, E being Young's modulus. It is challenging to assign unique values to the remaining three model parameters σ_y (yield strength), n (strain hardening exponent) and α (yield offset) to fusion welds, which are typically characterized by a wide variety of microstructures. For instance, yield strength variations up to 100 MPa have been observed in

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weld metal within a distance of 5 mm [4]. Changes of a similar order of magnitude have been observed in other studies such as [5] and are not exceptional.

A recent review article on fracture and crack propagation in weldments [6] recognizes the heterogeneous nature of a weldment as an important feature to take into account in weld flaw assessment. In particular, there is no generic approach to take into account such strongly variable strength distributions in the estimation of crack driving force. Most research efforts into the effect of weld properties — e.g. in the dedicated conference proceedings edited by Schwalbe and Koçak [7,8] — have been confined to so-called 'idealized' welds, defined by straight fusion lines and homogeneous weld metal (which is mismatched with respect to the base metal). The strength of the weld metal is then represented by a unique yield strength mismatch $M = \sigma_{yw} / \sigma_{yb}$, subscripts '*w*' and '*b*' referring to weld and base metal respectively.

Aiming to address the complex heterogeneous nature of fusion welds in flaw assessments, the authors have recently developed a framework to 'homogenize' welds with continuously varying strength properties [9]. A symmetrical situation was assumed for simplicity, i.e. the crack is located in the center of a symmetrical weld. A major outcome is that complex heterogeneous welds may be represented by an equivalent idealized weld (Fig. 1), whose crack driving force can be determined using published relations as for instance reported by Kim and Schwalbe [10]. As regards strength properties, this idealized weld has an 'equivalent' yield strength mismatch M_{eq}, given by:

$$M_{eq} = \frac{\int_{\mathbf{OF}} M(s)ds}{\|\mathbf{OF}\|} \tag{2}$$

with $M(s) = \sigma_y(s) / \sigma_{yb}$, the local yield strength mismatch of the complex weld at a point on the path **OF**, describing the slip line trajectory originating from the crack tip (**O**) up to the weld fusion line (**F**). In Fig. 1, the cracked geometry is assumed to be loaded in tension, giving rise to theoretically straight slip lines at an angle of 45° to the surface as analyzed in several studies [11,12]. Note that, although investigated for homogeneous specimens, similar slip line angle trajectories are observed in welds for a wide range of practical weld strength mismatch levels. For reasons of simplicity, it is therefore assumed that the theoretical solution of 45° slip lines remains valid. Eq. (2) implies that average weld strength properties along **OF** govern the crack driving force. As regards the simplification of geometry, the half width of the idealized weld H_{eq} is equal to the horizontal projection of **OF**. In other words, the point **F** remains located on the straight fusion line of the idealized weld. Note that heterogeneity of strain hardening was not considered in the original framework, i.e. all material is characterized by an equal strain hardening exponent *n*.

The assumed equivalency in crack driving force can be understood by combining the following statements:

- When assuming perfect plasticity, limit load is linked to the integration of stresses along a slip line trajectory and such integration would be equal for the complex heterogeneous weld and its homogenized equivalent where average properties are obtained through Eq. (2). This principle is elaborated in reference [11].
- Limit load is linked to crack driving force as for instance shown by the ability to include weld strength mismatch into a failure assessment diagram by calculating the abscissa using the limit load of the mismatched structure, without the introduction of significant error [13].

Note that the first statement, which motivates Eq. (2), relies on the assumption of perfect plasticity. In reality, materials show strain hardening and the influence of material properties close to the crack tip (where plasticity is more pronounced) may be more significant than that of properties away from the crack tip. A modified procedure including a weight function into the integrand of Eq. (2) may mathematically translate this consideration and is part of current investigation.

Further note that, once homogenized, crack driving force can be predicted using established techniques such as the 'law of mixtures'. This technique was developed by Lei and Ainsworth [14,15] and has been adopted by procedures such as FITNET [16]. Albeit

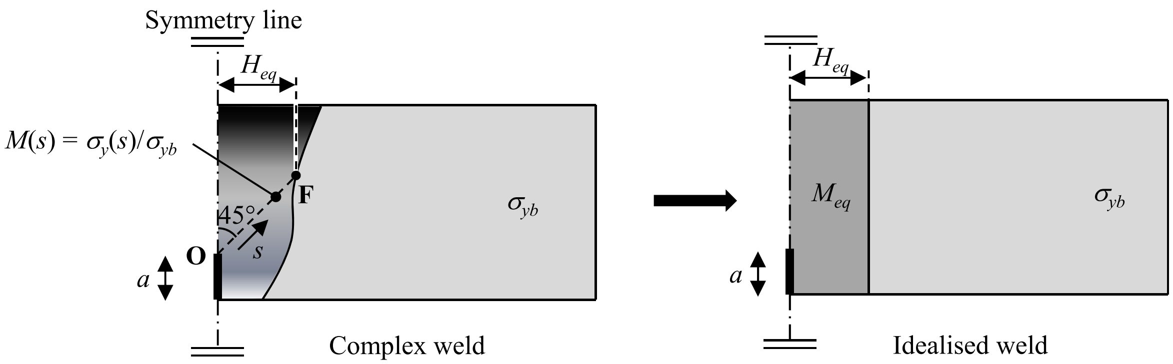

Fig. 1. The original approach to derive an idealized weld from a complex weld.
Taken from reference [9].