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Length scale of secondary stresses in fracture and fatigue

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Abstract

In an attempt to provide a consistent framework for the analysis and treatment of secondary stresses associated with welding and thermal loading in the context of fracture mechanics, this paper starts with an effective stress characterization procedure by introducing a length-scale concept. With it, a traction-based stress separation procedure is then presented to provide a consistent characterization of stresses from various sources based on their length scale. Their relative contributions to fracture driving force are then quantified in terms of their characteristic length scales. Special attention is given to the implications of the length-scale argument on both analysis and treatment of welding residual stresses in fracture assessment. A series of examples is provided to demonstrate how the present developments can be applied for treating not only secondary stresses but also externally applied stresses, as well as their combined effects on the structural integrity of engineering components.

Keywords: Length scale; Secondary stresses; Residual stresses; Welded joints; Fracture mechanics; Stress category; Stress classification; Mesh insensitivity; Structural stress; Nodal force; FEA; Modelling; Welded structures; Fatigue

1. Introduction

In performing structural integrity assessment of engineering structures, various Codes and Standards as well as Recommended Practices (e.g., [1–4]) define fracture driving force in terms of contributions from primary and secondary stresses. Here, primary stresses are defined as stresses generated by mechanical loading while secondary stresses are typically defined as residual stresses and thermal stresses based on their different origins. In fracture driving force calculations [1–4], for example, the contributions of welding-induced residual stresses are essentially treated in the same way as those of the primary stresses, without explicit considerations to the fact that the welding-induced residual stresses by definition are governed by displacement-controlled conditions [5–7]. For instance, as recently summarized in [8–11], these fracture assessment procedures essentially treat residual stresses as direct add-on terms to the stress intensity factor solution (K) contribution of the primary stresses. This was done through a plasticity interaction parameter in the form of ρ [4] or V [2], which was introduced to recognize the different origins in stress classifications between primary stresses and secondary stresses. In fact, as demonstrated recently in [6,7], the interaction of a crack with a given residual stress field is more than just the plasticity interaction captured by ρ [4] or V [2]. As a crack advances, the surrounding residual stresses re-distribute to achieve a new self-equilibrium, while the far-field primary stress distribution at the crack location remains stationary. The former phenomenon is governed by the length-scale characteristics of a given residual stress distribution [5–7], while the latter can be fully described by the existence of a global scaling parameter, e.g., a load factor. It is this fundamental difference that has motivated the developments described in this paper. By introducing length-scale-based considerations of secondary stresses as whole and residual stresses in particular, their contributions to fracture driving force can be assessed quantitatively at various length scales, instead of simply identifying the secondary stresses based on their origins.

Furthermore, the welding-induced residual stress prescriptions in the existing assessment procedures [1–4] are based on a compilation of residual stress distributions inferred from historical experimental measurement data and limited finite element modelling results on limited joint

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types. Given the complexity of the residual stress development and their dependency on joint geometry, welding processes/procedures, as well as material behaviours, it was difficult to synthesize the residual stress information generated by different sources using different analysis techniques. As a result, various bounding techniques were used [1–4] to establish an upper bound by imposing a criterion that was believed to yield conservative residual stress estimations. Depending upon the specific data sets used, an assessment procedure [1–4] often stipulates a drastically different residual stress prescription from others for a given joint geometry with identical conditions, leading to a wide range of fracture assessment results, as demonstrated in [12]. To reduce the inconsistency in residual stress profile prescriptions, some of the important governing parameters in determining residual stress distributions in various joint geometries must be identified. A length-scale-based treatment of an arbitrary residual stress distribution will be used in this paper to facilitate the identification of some of the governing parameters, which can then be related to joint geometry and welding conditions.

In an attempt to address some of the above issues in a little more comprehensive manner, this paper starts with the definitions of primary and secondary stresses in a more general context such as those used in the ASME Code for design by analysis [13]. Then, a length-scale-based stress classification or categorization procedure will be presented to derive the statically equivalent membrane and bending stress components that are consistent both with the stress category definitions in ASME Code [13] and with fracture mechanics principles. In doing so, the third component, i.e., through-thickness self-equilibrating stresses, can be shown to possess a characteristic length scale beyond which their effects are indeed mechanistically ‘‘self-limiting’’, as suggested intuitively by [13], which may be referred to as the true secondary stresses induced by external loading. Its effects on fracture driving force share a great deal of similarity with the secondary stresses that satisfy through-thickness self-equilibrating conditions.

This slight digression from the main theme of this paper set out earlier on thermal and residual stresses is necessary for the following reasons. The length-scale-based stress characterization will be shown in this paper to provide a consistent stress characterization procedure from stress classification to fracture mechanics treatment regardless of their sources, i.e., external loading, thermal loading, and welding-induced residual stresses. Otherwise, a general reference of primary stresses and secondary stresses simply by their physical origins [1–4] does not provide sufficient means by which they should be treated in FE-based design to comply with stress category definitions in ASME Code [13] as discussed in [14–17]. Nor does it differentiate the fact that, on one hand, a part of loading-induced stresses may contribute to the total fracture driving force in the same way as a part of thermal and residual stresses [6,7,18], and on the other, a part of the secondary stress can operate on a crack in a way similar to that of external-loading induced stresses, depending on the length scales inherent in the stress distributions of concern.

Then, both stresses from welding and thermal loading will be discussed. On welding-induced residual stresses, instead of indulging in a few detailed case studies, attention will be given to some of the important governing parameters that can be used to generalize characteristic residual stress distributions. Again the length-scale concept established in the previous section will be used to quantify the contributions of the residual stress distributions to fracture driving force along with discussions on their appropriate treatment techniques. In characterizing thermal stresses, a time-scale consideration in addition to length scale is required to characterize transient thermal problems in terms of their length-scale effects on their relative contributions to fracture.

Finally, two examples are given to highlight the implications of the developments presented in this paper on structural integrity assessment of engineering structures.

2. Stresses from external loads

As briefly eluded earlier, the definition of primary stresses in the ASME pressure vessel design code [13] is different and much more rigorous than fracture assessment procedures [1–4]. In the latter, all stresses caused by applied external loading are termed as primary stresses, while the secondary stresses are defined as thermal stresses and residual stresses. The definition of primary stresses (P) in the ASME Code [13] is according to the classical structural mechanics theory as those solely responsible for global equilibrium with applied load, which can be solved analytically under statically determined conditions. This solution technique has been proven effective in simple and standard vessel and pipe configurations which are essentially of the type with primary stresses being defined as pr/t and $pr/2t$ under internal pressure loading conditions in a thin wall vessel with radius r and wall thickness t. The definition of the secondary stresses, i.e., Q in [13], consists of two parts based on their sources. One is the secondary stresses due to external loading, which are defined as only those stresses that are solved solely by imposing displacement continuity conditions (or often referred to as discontinuity analysis). The other is thermal stresses due to temperature gradients or thermal expansion mismatch. These secondary stresses are typically expressed in the form of through-thickness bending stresses in classical structural mechanics.

In addition, a peak stress (F) in [13] is defined as the difference between the actual through-thickness stress distribution and the sum of the primary (P) and secondary (Q) stresses. As such, the primary stress (P), secondary stress (Q) and peak stress (F) in [13] are originally defined according to classical structural mechanics theory for simple-vessel geometries, for which analytical solutions can be derived. The separation of P, Q, and F is