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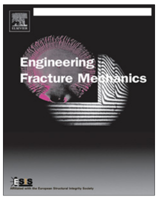

A practical approach to modeling aluminum weld fracture for structural applications

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ABSTRACT

This paper addresses the numerical simulation of plasticity and ductile fracture of large scale structures (e.g. ships, railcars, automobiles) fabricated with welds that exhibit appreciably lower strength than the plate material, often referred to as weld undermatching. It has been observed, both numerically and experimentally, that for such structures the weld undermatching often leads to plasticity and fracture being limited to the weld and heat affected zone (HAZ). While the large size of the structures of interest precludes the use of a refined three-dimensional element mesh capable of capturing the details of the weld/HAZ behavior, cohesive zones are ideal for capturing the overall effects of undermatched weld plasticity and fracture on a structural scale. This paper focuses on establishing a systematic calibration process for determining the cohesive zone constitutive behavior and examining the validity of this approach in the context of mode I tearing of a large welded two-layer AA6061-T6 sandwich panel. First, test data from a welded coupon is used to calibrate the cohesive law. Tearing fracture of this panel is examined using the established cohesive law to represent weld/HAZ along with elastic-plastic shell elements, with in-plane dimensions much greater than the layer thickness, to represent the parent metal. It was verified that, for this structure, plasticity was indeed confined to the welds and heat affected zones, and that the behavior of the panel was captured with reasonable fidelity.

1. Introduction

Structural aluminum alloys possess several properties that make their use desirable for a variety of structures. In particular, transportation structures (e.g. ships, aircraft, trains, and automobiles) utilize the high strength-to-weight ratio, ductility and corrosion resistance to improve vehicle efficiency and performance. One problem area for aluminum structures is the reduced strength of welded connections—the welding process involves local heating of the metal resulting in a local strength reduction in the weld and/or in the region immediately adjacent to the weld, referred to as the heat affected zone (HAZ). Often, fracture initiates and remains in this weakened HAZ rather than the parent or base metal (BM). This local strength reduction, referred to as undermatching, results in welded joints largely controlling the structural failure of welded aluminum structures. Furthermore, the quality of aluminum welds is highly sensitive to the weld fabrication technique. Thus,

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Nomenclature

T	nominal cohesive traction
δ	cohesive separation
$T(\delta)$	traction-separation relation
$\hat{T}$ peak	cohesive traction
t	plate thickness
$\delta_1, \ldots, \delta_n, \delta^F$	traction-separation relationship shape parameters
Γ	cohesive energy/area
Δx	distance ahead of the pre-crack
$\Gamma(\Delta x)$	cohesive energy/area as functions of distance Δx ahead of the pre-crack
E	elastic modulus
n	hardening exponent
σ	trues stress
ε	trues strain
σ_y	yield stress
$\Gamma_{ss-weld}$	steady-state tearing energy of the weld/HAZ
Γ_{ss}	steady-state cohesive energy
t	thickness

even for combinations of aluminum alloy and welding process that minimize the reduction of strength in the weld/HAZ, it is common to see fracture occur purely in the welded region due to manufacturing defects.

An important characteristic of undermatched welds is that, with sufficient undermatching, the development of large-scale plasticity as a means of energy dissipation may be curtailed as plastic straining tends to localize in the weld region (e.g. Liu et al. [10], Sutton et al. [29], Wang et al. [38,39]). Thus, undermatched weld properties must be accounted for in the design process likely resulting in a significant weight penalty. For transportation structures, this weight penalty comes at a cost to system level performance including crashworthiness, weight, fuel economy, etc.

For reasons of computational efficiency, the only feasible way to model plasticity and fracture of large-scale structures and structural components with length scale on the order of several to tens of meters is to use shell finite elements with the in-plane dimension larger than the shell thickness (Kõrgesaar and Romanoff [8], Voyiadjis and Woelke [35,36], Woelke et al. [40–42,44–47]). The intention of this paper is to present a simulation methodology for weld fracture in large-scale aluminum plate and shell structures having long linear welded joints under predominantly tensile loading conditions. The proposed methodology exploits the existence of appreciable weld undermatching resulting in the majority of the plastic dissipation and fracture occurring in the weld and/or HAZ. Such behavior can be well represented by a finite element model where a cohesive zone is used to capture necking, localization and fracture in the weld/HAZ and large elastic-plastic shell elements are used to simulate deformation in the parent metal.

This approach has many parallels with the previous investigation by Woelke et al. [42], where mode I crack growth in a large monolithic Al5083-H116 plate under large scale yielding was simulated. A cohesive zone was used to represent necking, localization and fracture at the scale of the plate thickness (and below), while large shell elements were used to model the deformation of the plate away from the crack. This allowed separation of the work of the fracture processes, including necking, from the plastic work dissipated in the surrounding field. This recent paper can in turn be considered a continuation of the early simulation of mode I crack growth under small scale yielding plane strain conditions performed by Tvergaard and Hutchinson [31]. Other contributions relevant to the current work include efforts to simulate aluminum spot weld failure using cohesive zone by Cavalli et al. [4] as well as Zhou et al. [53,54]. Behavior of spot welds is however quite different than continuous linear welds, mainly due to different levels of constraint. An important aspect of the work by Cavalli et al. is the use of fully annealed work-hardenable alloy Al5754-O for which fusion joints will not exhibit material strength degradation in the HAZ. The focus of the current work is on significantly undermatched welds, which in most cases causes plastic dissipation to be confined to the weld and/or HAZ regions.

The main objective of this paper is not on development of a general numerical modeling capability based on use of a cohesive zone. Rather, the main focus is on addressing a specific problem of undermatched weld fracture in large-scale structures, thereby demonstrating that a method employing a properly calibrated cohesive zone is ideally suited for modeling tearing fracture of plate and shell structures with linear undermatched welds. We refer to the proposed procedure as the Welded Aluminum Fracture Modeling Method (WALFRAM). While the present interest is in aluminum structures, we note that any metal that derives its strength from quenching will likely undergo local annealing during welding, which may result in significant weld undermatching. For example, hot-stamped martensitic steels exhibit such behavior during welding, as evidenced by significant ($\sim$35–40%) hardness reduction in the HAZ comparing to the base metal (Banik et al. [3]). In addition,

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