Elastic-Plastic Fracture Mechanics Analysis Of Critical Flaw Sizes in Ares I Welds

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NASA's Ares 1 Upper Stage Simulator (USS) is being fabricated from welded A516 steel. In order to insure the structural integrity of these welds it is of interest to calculate the critical *initial* flaw size (CIFS) to establish rational inspection requirements. The CIFS is in turn dependent on the critical *final* flaw size (CFS), as well as fatigue crack growth resulting from transportation, handling and service-induced loading. Independent CFS, fatigue crack growth and CIFS calculations for weld flaws in the flange-to-skin weld of the ARES I USS have been reported in a companion paper in this conference. These calculations were made using linear elastic fracture mechanics (LEFM), which are thought to be conservative because they are based on a lower bound, so-called "elastic," fracture toughness determined from tests that displayed significant plasticity. Nevertheless, there was still concern that the yield magnitude stresses generated in the flange-to-skin weld by the combination of axial stresses due to axial forces, fit-up stresses, and weld residual stresses, could give rise to significant crack-tip plasticity, which might render the LEFM results to be non-conservative.

Crack-tip plasticity enhances crack-tip driving forces compared to the values determined from LEFM. In fracture toughness tests that involve non-linear load-displacement behavior due to crack-tip plasticity, this means that an elastic toughness value estimated using LEFM and the measured load and crack depth will under-estimate the actual toughness as this approach is equivalent to determining the driving force using only the area under the linear part of the load-displacement curve. The actual toughness is related to the total area under the load-displacement curve including the non-linear part arising from crack tip plasticity. Hence, an elastically estimated toughness will always be lower than the actual value when non-linear behavior is observed in a toughness test. Similarly, crack tip driving forces for cracks in structures that are evaluated using LEFM concepts will under-estimate the actual driving forces when crack tip plasticity is present. Thus, the LEFM approach will only be conservative if the ratio of the "elastic" toughness, $K_C^{elastic}$ to the elastic-plastic toughness, $K_C^{elastic-plastic}$) is less than the ratio of the linear elastic crack tip driving force in the structure ($K = K^{elastic}$) to the elastic-plastic crack- tip driving force ($K_J = K^{elastic-plastic}$).

The objective of the present study was to employ Elastic–Plastic Fracture Mechanics (EPFM) to determine CFS values, and then compare these values to CFS values evaluated using LEFM. CFS values were calculated for twelve cases involving surface and embedded center cracks, EPFM analyses with and without plastic shakedown of the stresses, LEFM analyses, and various welding residual stress distributions. For the cases examined, the computed CFS values based on elastic analyses were the smallest in all instances where the failures were predicted to be controlled by the fracture toughness. However, in certain cases, the CFS values predicted by the elastic-plastic analyses were smaller than those predicted by the elastic analyses; However, in these cases the failure criteria were determined by a breakdown in stress intensity factor validity limits for deep cracks ($a > 0.90t$), rather than by the fracture toughness. Plastic relaxation of stresses accompanying shakedown always increases the calculated CFS values compared to the CFS values determined without shakedown. Thus, it is conservative to ignore shakedown effects.