Ares I-X Critical Initial Flaw Size Analysis

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An independent assessment was conducted to determine the critical initial flaw size (CIFS) for the flange-to-skin weld in the Ares I-X Upper Stage Simulator (USS). The USS consists of several "tuna can" segments that are approximately 216 inches in diameter, 115 inches tall, and 0.5 inches thick. A 6-inch wide by 1-inch thick flange is welded to the skin and is used to fasten adjacent tuna cans. A schematic of a "tuna can" and the location of the flange-to-skin weld are shown in Figure 1. Gussets (shown in yellow in Figure 1) are welded to the skin and flange every 10 degrees around the circumference of the "tuna can". The flange-to-skin weld is a flux core butt weld with a fillet weld on the inside surface, as illustrated in Figure 2. The welding process often creates loss of fusion or slag inclusion defects in the weld that could develop into fatigue cracks and jeopardize the structural integrity of the Ares I-X vehicle. The CIFS analysis was conducted to determine the largest crack in the weld region that will not grow to failure within 4 lifetimes, as specified by NASA standard 5001 [1].

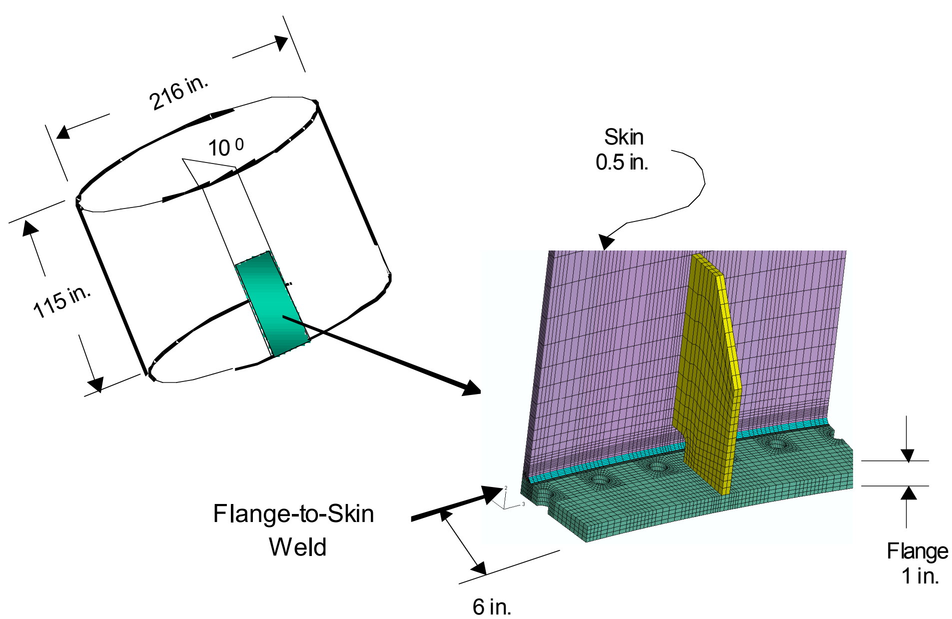

Figure 1. Schematic of an Ares I-X USS "tuna can".

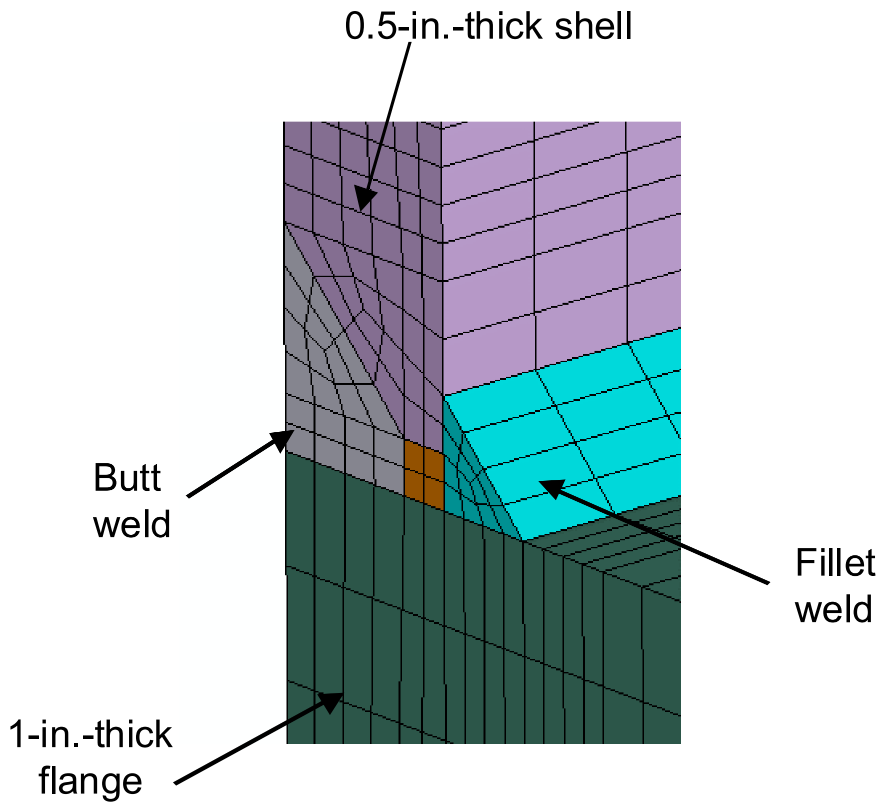

Figure 2. Schematic of the flange-to-skin weld.

A CIFS analysis assumes an initial crack size (a_i) and grows that crack according to the material behavior (fatigue crack growth rate and fracture toughness), loading spectrum for the structure, and the stress intensity factor for the crack configuration. The critical flaw size (a_{CFS}) is obtained when the maximum stress intensity factor for any one cycle of the loading spectrum exceeds the fracture toughness value. The number of spectrum repeats necessary to grow the crack from a_i to a_c is N_c. The CIFS crack length (a_{CIFS}) is defined as the largest crack length that will survive 4 repeats of the spectrum, as illustrated in Figure 3. A CIFS analysis requires the following information:

- Loading spectrum
- Stress intensity factor solution
- Material behavior that describes the fatigue crack growth rate
- Material behavior that describes the critical stress intensity factor
- A fatigue crack growth rate code

A number of conservative assumptions were made in the analysis to account for uncertainties in the material behavior, weld process, loading spectrum, and manufacturing process. The goal of the analysis was to obtain a lower bound on the critical initial flaw size that could be used to provide guidance for inspection requirements.

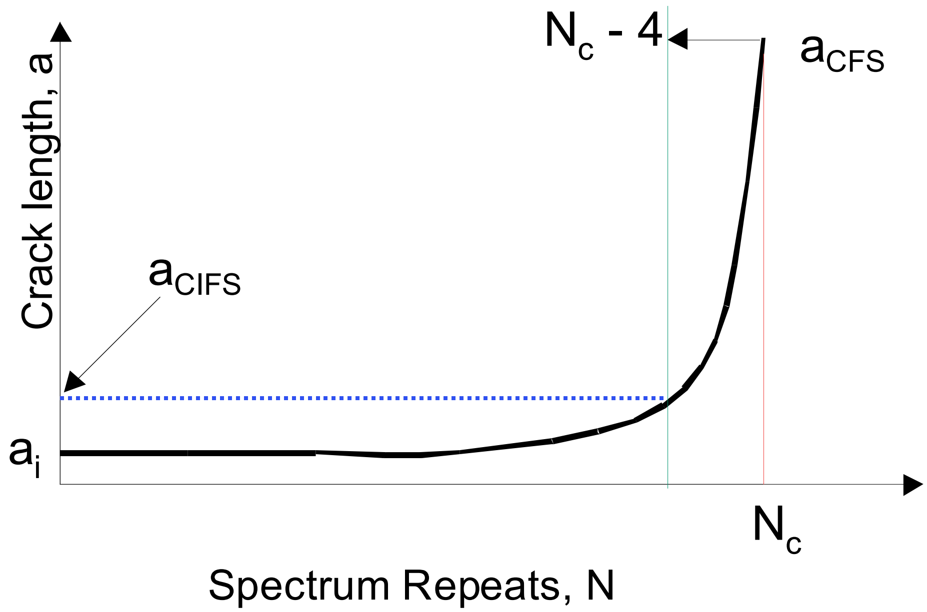

Figure 3. Schematic of the CIFS approach.

The loading spectrum for the Ares I-X USS consists of a cyclic operational stress spectrum, a mean stress component due to the weld residual stresses, and a mean stress component due to fit-up mismatch of the mating flanges. The cyclic operational stress spectrum consists of 7 blocks: lifting, transportation, rollout, pad stay, liftoff, thrust oscillation, and ascent. Each block consists of one or more steps that contain pairs of maximum stress and minimum stress and the number of times (cycles) that the pair was repeated. The lifting block was estimated from the total weight of the anticipated number of "tuna cans" that would be lifted together. Three types of lifts were anticipated: 1.5 proof test, multiple segment lift, and single segment lift. The transportation block was estimated from transportation loads for the Space Shuttle External Tank. The remaining load blocks were estimated from available Ares I-X design loads, general environment, and response data. The pad stay block was modified to include a peak wind loading that was 1.7 times the nominal peak load. The resultant cyclic operational spectrum is a bounding estimate of the load magnitudes and number of cycles and is show in Figure 4 in terms of the number of cycles for each cyclic stress range in the 7 blocks.

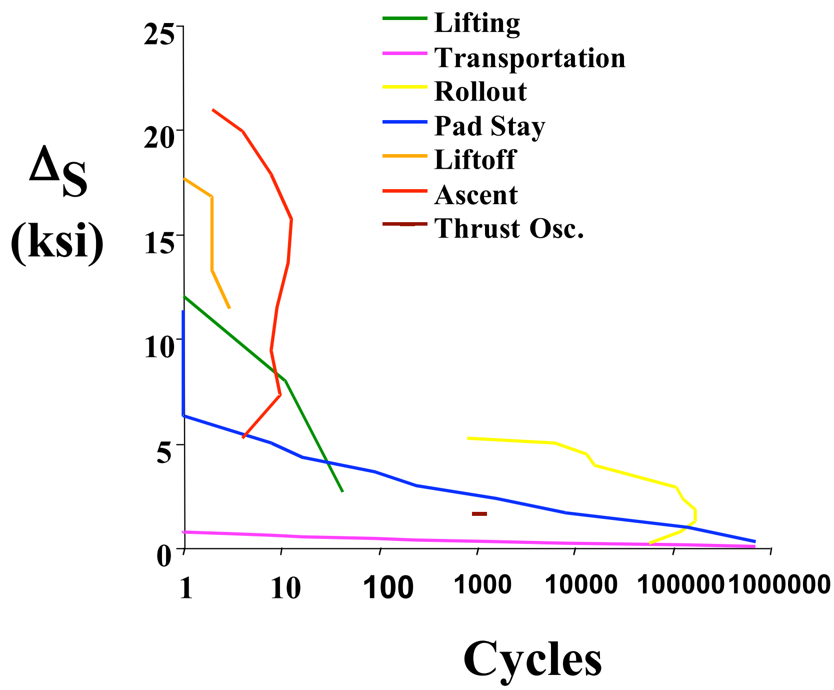

Figure 4. The number of applied cycles for each cyclic stress range for the 7 spectrum blocks.

The stress intensity factor solutions used in the Ares I-X Upper Stage Simulator (USS) flange-to-skin weld CIFS analysis were obtained from the NASGRO fatigue crack growth analysis code [2]. Two types of crack configurations were considered in the CIFS analysis: surface crack and embedded crack. The length of the crack is designated “2c” and the depth of the crack is designated “2a” for the embedded crack and “a” for the surface crack, as illustrated in the schematics shown in Figure 5

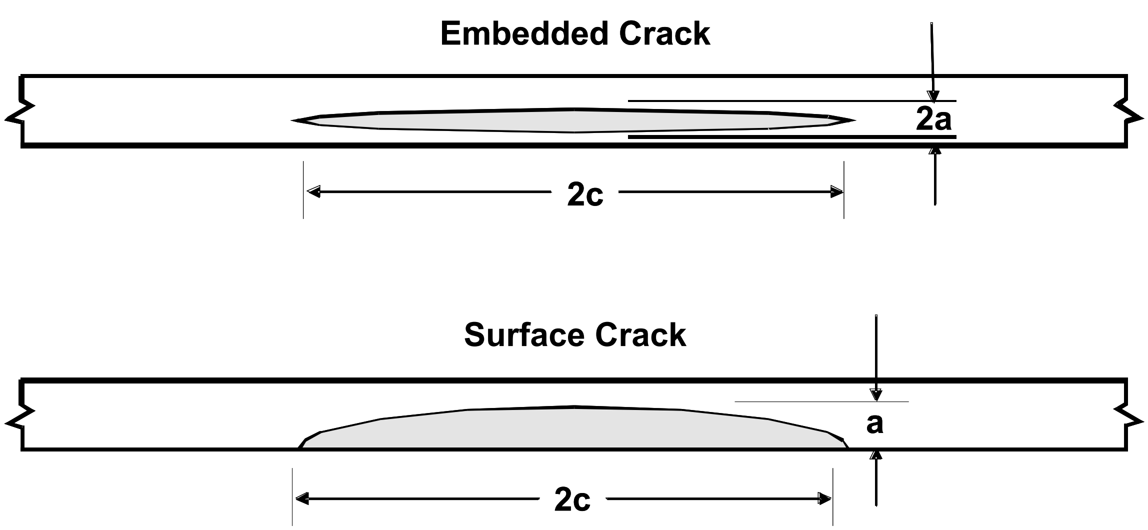

Figure 5. Schematics of the crack configurations considered in the CIFS analysis.

The skin and flange of the Ares I-X USS segments are made of normalized A516 steel. The flange-to-skin weld was performed using a flux-core welding process. Tests were conducted to evaluate the material behavior of the A516 steel with particular attention to the material behavior that could be influenced by the weld process. Fatigue crack growth rate tests were conducted on the parent material and fracture toughness tests were conducted on the welded material. The fatigue crack growth rate tests were conducted at high stress ratios (R=0.7) provide a conservative bound on the influence of mean stresses. Tests were conducted to determine the fatigue crack threshold, but the CIFS analysis ignored the beneficial influence of the threshold.

J_{IC} fracture tests were conducted according to ASTM Standard 1820 [3] for single bevel flange-to-skin welds manufactured using a flux cored welding process. Both the flange and skin material were normalized A516 steel. The configuration of the flange-to-skin weld is illustrated in Figure 1 and the orientation of the bevel is shown in Figure 2. The tests were conducted using an automated system for controlling load and displacement, recording crack mouth opening displacement (CMOD), calculating the crack length using compliance measurements, and calculating the J_{IC} values. The tested configuration was a 2-inch wide compact tension (CT) specimen that was machined flat and parallel after the weld process to remove any distortion due to welding. This resulted in a variation of specimen thickness that ranged from 0.43 to 0.48 inches. Each specimen was measured and the actual thickness was used in the J_{IC} calculations. Each CT specimen was etched to reveal the through-the-thickness cross section of the weld, as shown in Figure 6. The etching revealed interfaces between the parent material and heat affected zone (HAZ) and between the HAZ and the weld. The CT specimens were machined to allow the notch to coincide with one of the two locations (A and B). Location A is located at the interface of the weld and the HAZ at the narrow end of the bevel. Location B is located in the weld material. The CT specimens were precracked to obtain a sharp crack tip and side grooves machined prior to the fracture tests. During the fracture tests visual crack length measurements were not performed because the side grooves prevented accurate crack length measurements. Instead, the crack length measurements were estimated from the CMOD measurements. The J_{IC} value and the elastic component of the J_{IC} were calculated according to ASTM Standard 1820 [3]. The elastic component of the J_{IC} was used as the critical value in the CIFS analysis.

The critical initial flaw size (CIFS) analyses were conducted using the NASGRO fatigue life code [2]. The analysis considered long surface and embedded cracks and determined the combination of crack length and depth that would grow to a critical value in 4 repeats of the spectrum. A plot of the critical crack depth as a function of the critical crack length will indicate the safe and non-safe combinations of crack length and depth, as illustrated in Figure 7. Parametric studies were conducted to determine the influences of residual stress, fracture toughness, and fit up stresses on the CIFS and a lower bound was determined, as shown in Figure 8.

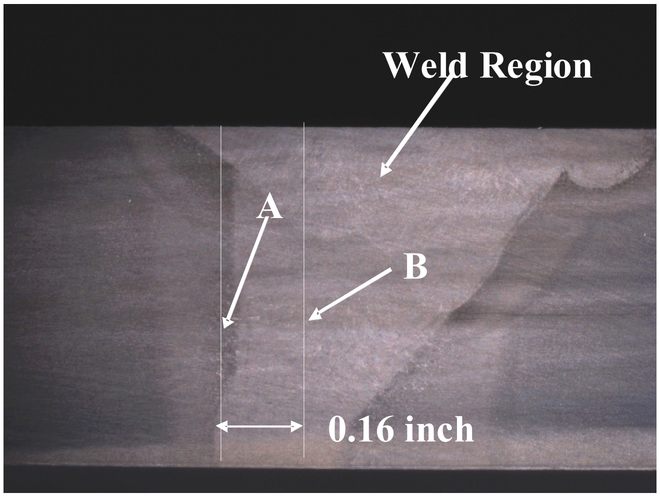

Figure 6 Location of the notch locations in the CT specimens

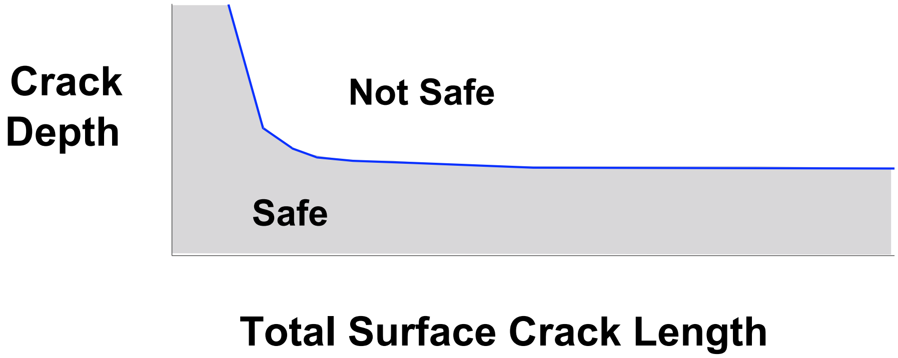

Figure 7. Schematic of the CIFS results

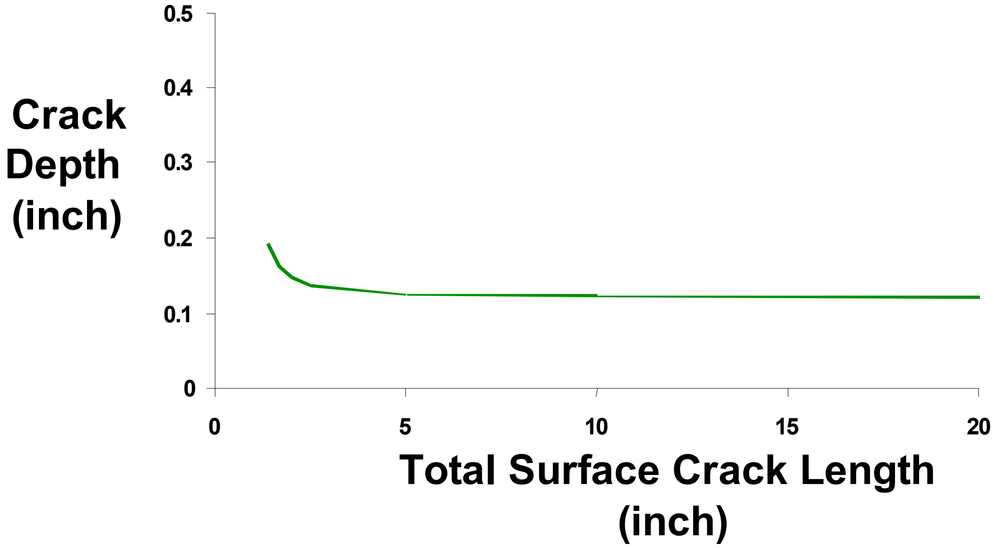

Figure 8. Lower bound calculated for the CIFS.

References:

1. Structural Design and test factors of safety for space flight hardware, NASA Standard on Factors of Safety, NASA STD-5001A, 2006.

2. NASGRO User's Manual, South-West Research Institute, 2006.

3. ASTM Standard Test Method 1820 for J_{IC} testing, American Society for Testing of Materials, ASTM, 2006.