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TO: Dan Holt

CC: B. McQuivey, V. Call, S. Graves, J. Lohrer, K. Parsons,

FROM: B. Tew, T. Lai
Thiokol Fracture Control Board

SUBJECT: Thiokol Fracture Control Board Response to Questions Raised by MSFC Fracture Control Board/Others Regarding Relative Radius of Curvature

1. Question/Issue: Relative Radius of Curvature residual stress calculation is based on numerous assumptions that have not been verified with test data. RRC methodology .... should be test verified before use for flight programs.

Thiokol should show test data that was used to anchor any of the models concerned. If test data was not used to anchor models or was not required, Thiokol should justify their position.

Response: The radius of curvature approach was developed to identify out-of-roundness in case segments (caused by a severe splashdown) beyond that measured by total indicator runout. Figure 1 shows an oval shape with a dashed circle inscribed that has a radius of curvature equal to that of the oval at their tangent point. Figure 2 is generally rounder than the oval in Figure 1; however, localized interior radii are substantially smaller. Localized residual stresses in a case shaped like that shown in Figure 2 may be significantly higher than the stresses seen in a generally oval-shaped case segment even though the TIR is smaller.

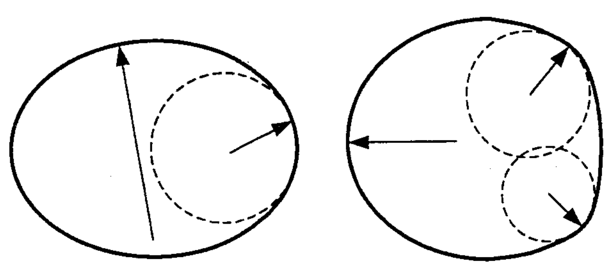

Figure 1 Figure 2

The selection of a limit for a localized radius of curvature was based on limiting residual stresses in the stiffener stub to 78 ksi. At this limit, the stress level is not high enough to cause a 0.025 by 0.025 corner crack in the stiffener stub outer ligament to propagate due to stress corrosion cracking. The 78 ksi stress limit was shown analytically to relate to a relative radius of curvature value of –900 in. (TWR-66632 p. 3).

The relative radius of curvature limit of –900 was incorporated in Thiokol engineering requirements in 1995.

Splashdown damage to stiffener stubs has been a concern for Thiokol for over 10 years. A Cracked Stiffener Stub Program Plan (TWR-19326 p.7) was developed in 1989 to enhance understanding of stiffener stubs damaged by splashdown. This plan included

- Comparison of three methods of measuring stub out-of-roundness,
- Development of a crack database,
- Measurement of residual stresses in parts damaged by splashdown using X-ray diffraction and strain gages,
- Nonlinear finite element analyses,
- Elastic-plastic fracture mechanics analyses,
- Analog testing of stiffener specimens,
- Evaluation of eddy current inspection system, and the
- Development of accept/reject/repair criteria.

Results of the X-ray diffraction and strain gage testing of residual stresses in the damaged stiffener segments are documented in TWR-19326. Residual stresses in three lightweight stiffener segments were evaluated. Lightweight S/N 023 (mislabeled S/N 032 in TWR) had not experienced a hard splashdown. Lightweight S/N 006 had experienced a hard splashdown and was so out-of-round (TIR of 0.72 in.) it could not be reassembled for proof test. Lightweight S/N 012 was not as badly damaged as S/N 006 (TIR of 0.25 in.) and was proof tested after water impact damage. Numerical TIR measurement data for these segments is no longer available, however, a graphical record of the TIR measurements is available in TWR-19326.

Residual stress measurements in TWR-19326 are similar to the elastic-plastic finite element analysis residual stress predictions given in TWR-66632. The following observations can be made:

Pre Proof Test (Comparing TWR-66632 Figure 16 with TWR-19326 Figure 27 near load centerline location)

- High tensile residual stresses are observed near the holes
- Residual tensile stresses near holes are higher than residual tensile stresses at outer edge of stiffener stub
- Residual stresses at inside surface of case wall are either fairly low tensile, or compressive

- Residual tensile stresses measured on outer edge of stub between holes are lower than those measured on outer edge of stub adjacent to holes

Post Proof Test (Comparing TWR-66632 Figure 24 with TWR-19326 Figure 28 near load centerline location)

- Residual stresses measured on stub outer edge are relatively small and tensile
- A substantial stress gradient exists across outer ligament of stiffener - tensile on stub outer edge, changing to moderate compressive stress near hole
- Compressive residual stress in inner ligament (between hole and case wall)

The X-ray diffraction data presented in TWR-19326 shows residual stress trends that are similar to elastic-plastic finite element analyses result provided in TWR-66632; however, no specific correlation between RRC and measured stress is provided. Several significant factors undoubtedly influenced the correlation between measured and predicted stress levels including:

- Residual stresses in stubs from heat treat quenching
- Residual stresses in stubs caused by glass bead or grit blast operations in refurbishment process
- Residual stresses caused by previous proof testing and splashdown events
- Variability in X-Ray diffraction measurement process, surface preparation, etc.
- Elastic-plastic finite element models did not include outer ligament cracks seen in measured parts
- Measured pre-proof and post-proof parts did not have same out-of-roundness (radius of curvature) values
- Stiffener segments had membrane material adjacent to stubs removed from one side (although ring continuity was maintained)

Any future residual stress measurements of out-of round stiffener segments will be influenced by many/all of these factors.

2. Question/Issue: Can Thiokol quantify how much not using radius of curvature weakens flight rationale? We flew for years using total indicator runout (TIR), and radius of curvature (ROC) is more conservative than TIR.

Response: Radius of curvature is a better screening approach than TIR simply because it identifies badly distorted localized regions in the case segment that are more likely to have residual stresses high enough to facilitate SCC under certain conditions.

In order for SCC to become a flight concern, pre-flight stress corrosion cracking must not only crack the outer ligament of the stub, but must also form a crack in the inner ligament. Since the stresses between the stiffener holes and the case wall are very low after proof testing, it is unlikely that this scenario is even a possibility. TWR 66632 Rev A (released November, 1997) shows stresses in the region adjacent to the splashdown load centerline, near the stiffener holes in the inner ligament are near zero or compressive. TWR-19326 (released July, 1991) shows measured residual stresses in this same region are compressive after proof test and prior to the installation of the T-ring. Following T-ring installation measured residual stresses near the centerline are 20 ksi or lower. Measured residual stresses in the knuckle region following T-ring installation are highly compressive.

Stress corrosion cracking requires high tensile stress, a wet environment, and an existing flaw or crack in the material. In addition to minimizing the residual tensile stresses in the stiffener stubs by radius of curvature screening and machine repair, Thiokol uses a very rigorous nondestructive inspection program with magnetic particle, eddy current, and visual inspection techniques to assure the structural integrity of the hardware. Additionally, case hardware is carefully protected from moisture by primer, paint, grease, rubber, and K5NA epoxy ablative material. Surface protection is verified when it is initially applied in the Insulation Work Center and is reverified several times prior to launch.

Another consideration is that undetectable flaws or cracks oriented perpendicular to primary proof test loads develop a residual compressive stress at the crack tip following the release of the proof test pressure. This means that potential crack propagation sites are effectively eliminated.

Limiting the residual stress in the outer ligament of a stiffener stub to a value below the stress corrosion cracking threshold removes any concern about stress corrosion cracking in the stiffener stubs causing flight safety issues. Even if residual stress is not precisely controlled, the probability of any flight safety issues due to SCC is extremely remote. The larger problem with SCC and residual stresses lies in hardware inspection, protection, and attrition.

3. Question/Issue: FCB would like to know if the stub ring is the highest stressed part due to cavity collapse loads or if the local deformation also highly loads the membrane. Does cavity collapse leave any residual loads in the membrane? If so, identify why it is not a concern.

Response: The highest residual stresses associated with splashdown are in the stiffeners. Finite element analyses show relatively low residual stress levels in the membrane adjacent to the stiffener stubs. Near the stubs, the membrane is also thickened approximately 0.100 in. to provide additional load carrying capability.

TWR-19326 Figure 33 shows residual stresses in a membrane section between the stiffener stubs before and after T-rings were installed. The highest tensile residual stress is 6 ksi near the load centerline on the inside of the case prior to the installation of the T-ring. The highest compressive residual stress is 20 ksi located on the outer surface of the membrane near the knuckle measured before the T-ring is installed. Following T-ring installation, the highest compressive residual stress (18 ksi) is on the outer surface near the load centerline. High tensile residual stresses in the case membrane near the stub may cause local yielding; however, the associated strain in flight is very low and not a cause for concern. Even if residual stress values seen in finite element models and X-ray diffraction testing are not representative of those seen in all stiffener segments, the successful proof test demonstrates the ability of each segment to safely undergo four additional flight pressurizations.

4. Question/Issue: A final issue is the multi-cycle reuse of hardware and tracking of the plastic stress and strain over a segments life. The FCB is concerned with the potential low cycle fatigue and crack initiation that can be caused by multiple plastic cycles.

Is low cycle fatigue a concern? Are loads needed to drive low cycle fatigue higher than those needed to drive stress corrosion cracking? Do we actually have multiple plastic cycles to be concerned about?

Response: Low cycle fatigue is a concern that we deal with. A plastic load cycle occurs when hardware is subject to a hard splashdown and again when it is subsequently proof tested. Stresses generated during splashdown and proof testing regularly exceed the yield strength of the material in localized regions. Fortunately, these high stress cycles occur in non-flight-critical times – at splashdown and during proof test in Clearfield.

From a crack initiation and growth standpoint, non-destructive inspection and proof testing provide a very effective screen for hardware that has been damaged in flight, splashdown, or subsequent transportation. Hardware that passes the inspection and proof test is capable of withstanding four additional pressurizations to MEOP without having cracks grow to a critical length.