

Engineering Evaluation of International Low Impact Docking System Latch Hooks

J. Martinez¹, R. Patin¹, J. Figert¹

¹ Structural Engineering Division, NASA Lyndon B. Johnson Space Center Houston, TX 77058

The international Low Impact Docking System (iLIDS) provides a structural arrangement that allows for visiting vehicles to dock with the International Space Station (ISS) (Fig 1). The iLIDS docking units are mechanically joined together by a series of active and passive latch hooks. In order to preserve docking capability at the existing Russian docking interfaces, the iLIDS latch hooks are required to conform to the existing Russian design. The latch hooks are classified as being fail-safe. Since the latch hooks are fail-safe, the hooks are not fracture critical and a fatigue based service life assessment will satisfy the structural integrity requirements.

Constant amplitude fatigue testing to failure on four sets of active/passive iLIDS latch hooks was performed at load magnitudes of 10, 11, and 12 kips. Failure analysis of the hook fatigue failures identified multi-site fatigue initiation that was effectively centered about the hook mid-plane (consistent with the 3D model results). The fatigue crack initiation distribution implies that the fatigue damage accumulation effectively results in a very low aspect ratio surface crack (which can be simulated as thru-thickness crack). Fatigue damage progression resulted in numerous close proximity fatigue crack initiation sites. It was not possible to determine if fatigue crack coalescence occurs during cyclic loading or as result of the fast fracture response. The presence of multiple fatigue crack initiation sites on different planes will result in the formation of ratchet marks as the cracks coalesce. Once the stable fatigue crack becomes unstable and the fast fracture advances across the remaining ligament and the plane stress condition at a free-surface will result in failure along a 45 deg. shear plane (slant fracture) and the resulting inclined edge is called a shear lip. The hook thickness on the plane of fatigue crack initiation is 0.787". The distance between the shear lips on this plane was on the order of 0.48" and it was effectively centered about the mid-plane of the section. The numerous ratchet marks between the shear lips on the fracture initiation plane are indicative of multiple fatigue initiation sites within this region. The distribution of the fatigue damage about the centerline of the hook is consistent with the analytical results that demonstrate peak stress/strain response at the mid-plane that decreases in the direction of the hook outer surfaces. Scanning electron microscope images of the failed sections detected fatigue crack striations in close proximity to the free surface of the hook radius. These findings were documented at three locations on the fracture surface : 1) adjacent to the left shear lip, 2) adjacent to the right shear lip, and 3) near the centerline of the section. The features of the titanium fracture surface did not allow for a determination of a critical crack size via identification of the region where the fatigue crack propagation became unstable.

The fracture based service life projections were benchmarked with strain-life analyses. The strain-range response in the hook radius was defined via the correlated finite element models and the modified method of universal slopes was incorporated to define the strain-life equation for the titanium alloy. The strain-life assessment confirmed that the fracture based projections were reasonable for the loading range of interest. Based upon the analysis and component level fatigue

test data a preliminary service life capability for the iLIDS active and passive hooks of 2 lifetimes is projected (includes a scatter factor of 4).

References:

- [1] Dowling, Norman E., **Mechanical Behavior of Materials : Engineering Methods for Deformation, Fracture, and Fatigue**, Prentice Hall, 1993, pp 154-155.
- [2] Richards, R. Jr., **Principles of Solid Mechanics**, CRC Press, 2000, pp 243-245.
- [3] MIL-HDBK-5H, **Metallic Materials and Elements for Aerospace Vehicle Structures**, 1998, pg. 5-54.
- [4] Gallagher, Giessler, and Berens, **USAF Damage Tolerant Design Handbook: Guidelines for the Analysis and Design of Damage Tolerant Aircraft Structures**, AFWAL-TR-82-3073, 1984, Section 3.4.

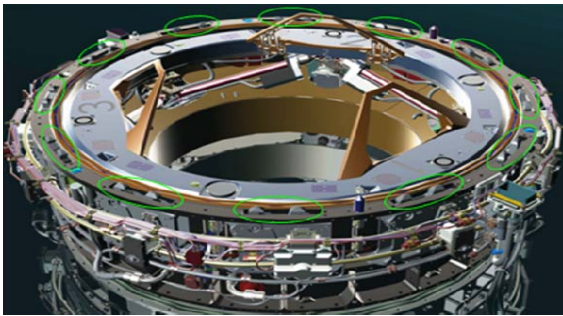


Fig 1. iLIDS solid model image that depicts the active and passive latch hook assemblies.

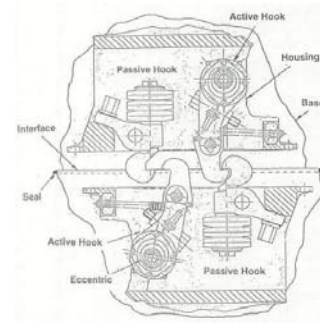


Fig 2. Russian drawings of a hook set with one pair of hooks latched and the other unlatched.



Fig 3. Post test photographs of the active hook test articles.



Fig 4. Post test photographs of the passive hook test articles.

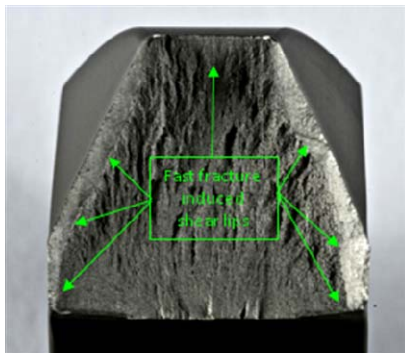


Fig 5. Active hook (10 kip fatigue loading) fracture photograph.

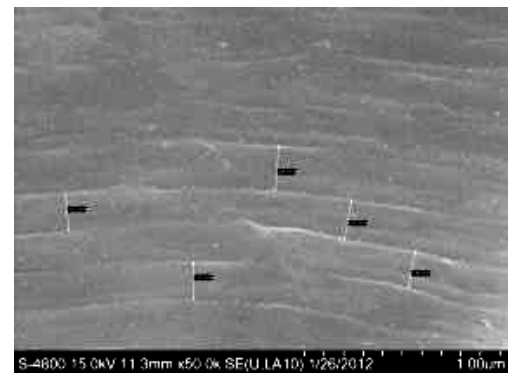


Fig 6. SEM image of fatigue striations adjacent to the shear lip-fatigue transition region.



Microscopy & Microanalysis 2013
Symposium P06 – Failure Analysis of Structural Materials
06 August 2013

**Engineering Evaluation of
International Low Impact Docking System
Latch Hooks**

J.E. Martinez, R.M. Patin, J.D. Figert
Structural Engineering Division
Lyndon B. Johnson Space Center
Houston, TX 77058





iLIDS Latch Hook Service Life Presentation Overview:

- Introduction
- Static Strength Testing
- Component Level Fatigue Testing of Latch Hooks
- Fractography of Latch Hooks
- Updated Analysis Methodology Based Upon Fractographic Results
- Definition of Latch Hook Mission Capability
- Summary

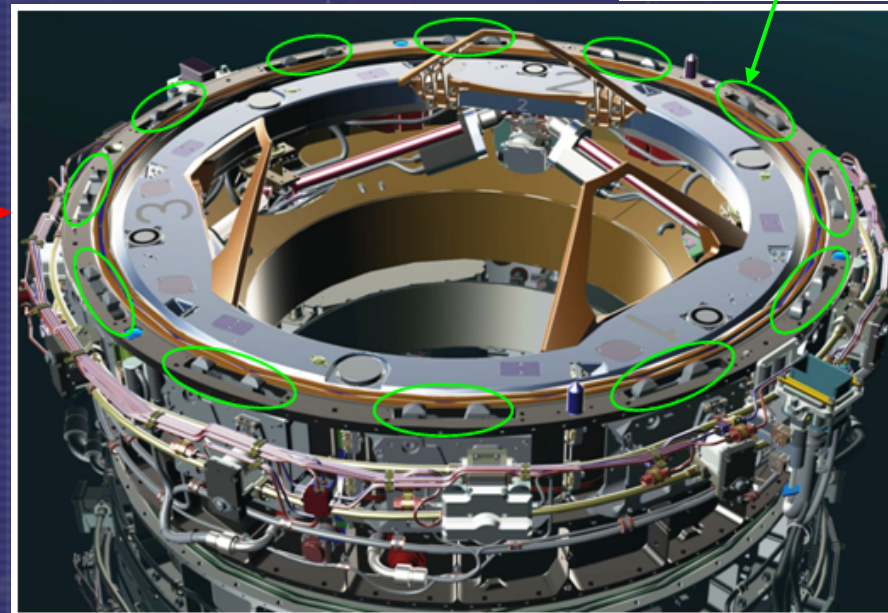
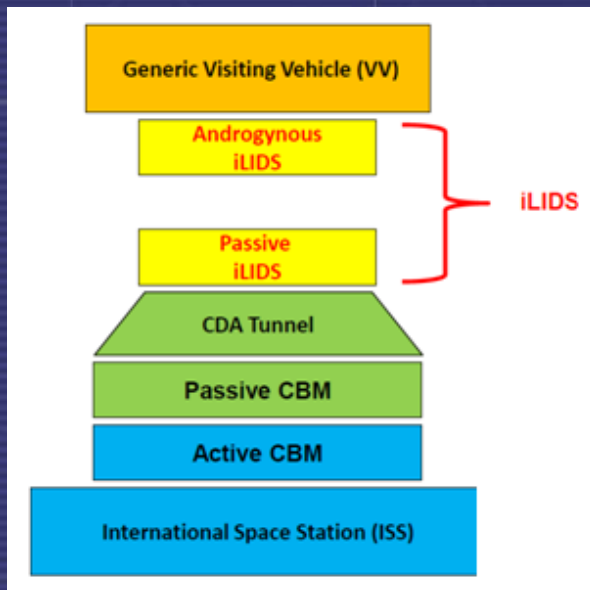


Introduction:

The international Low Impact Docking System (iLIDS) provides a structural arrangement that allows for visiting vehicles to dock with the International Space Station (ISS).

The iLIDS docking units are mechanically joined together by a series of 12 sets of active and passive latch hooks.

12 sets of active/passive
latch hook assemblies.



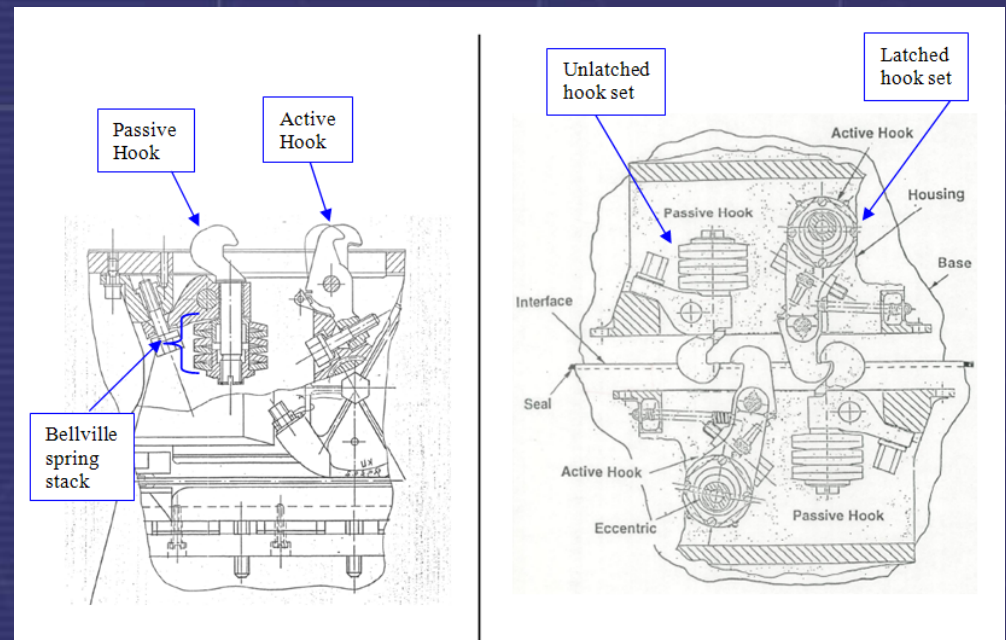
Introduction:

In order to preserve docking capability at the existing Russian docking interfaces the iLIDS latch hooks are required to conform to the existing Russian design.

The passive hook is stationary with a series of Bellville springs located on the mounting stem. The Bellville spring compliance allows for the resulting hook loads to be more uniformly distributed throughout the 12 sets of latch hook assemblies. The active hook is driven by a motor that rotates the hook through a small angular displacement followed by an inward translation which allows for engagement and preloading with the passive hook.

The latch hooks are classified as ‘fail-safe’ due to the structural redundancy that exists.

Since the hooks are not fracture critical (failure does not directly result in a catastrophic event) only a fatigue based service life assessment will satisfy the structural integrity requirements.



iLIDS Latch Hook Static Strength Testing:

The static strength testing was performed at 3 different temperatures in each of the 2 material candidates. The STA static strength failure loads exceed that of the annealed alloy - this result trend is consistent with the tensile coupon ultimate stress results^[1].



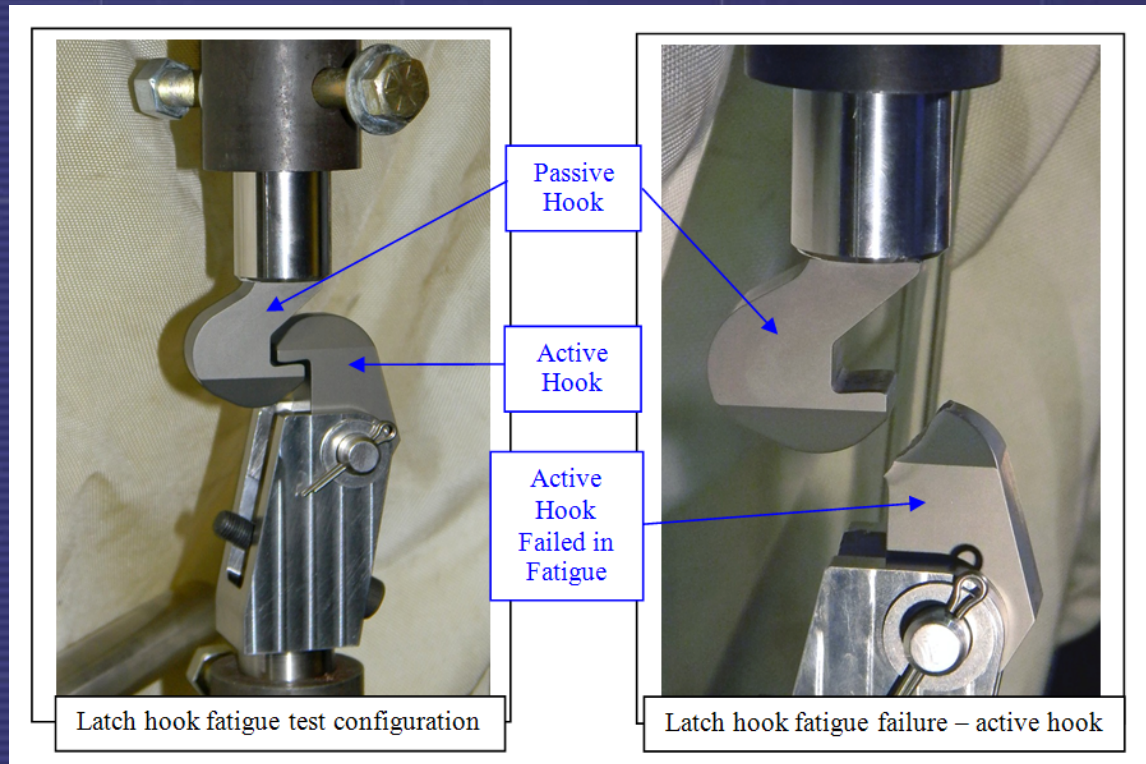
Passive latch hook static load failure location at the hook ledge transition radius.



Active latch hook static load failure location at the hook ledge transition radius.

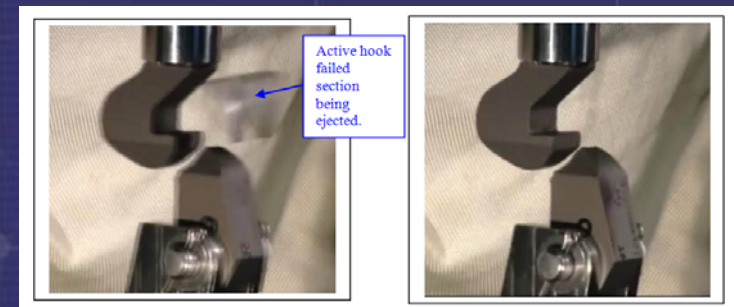
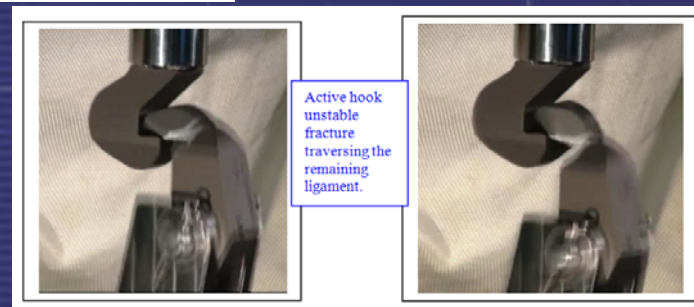
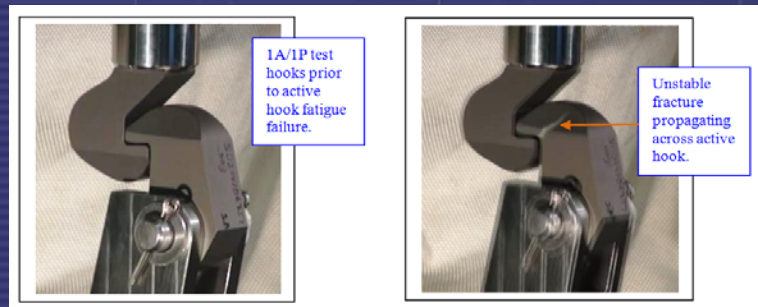
Latch Hook Fatigue Testing:

Constant amplitude fatigue testing of 4 sets of active and passive hooks to failure was conducted at hook loads of 10, 11, and 12 kips (2 hook sets were fatigue tested at 11 kips). Fatigue failure occurred in active hook at the contact shelf transition radius (consistent with the static strength failure location) for each test conducted.

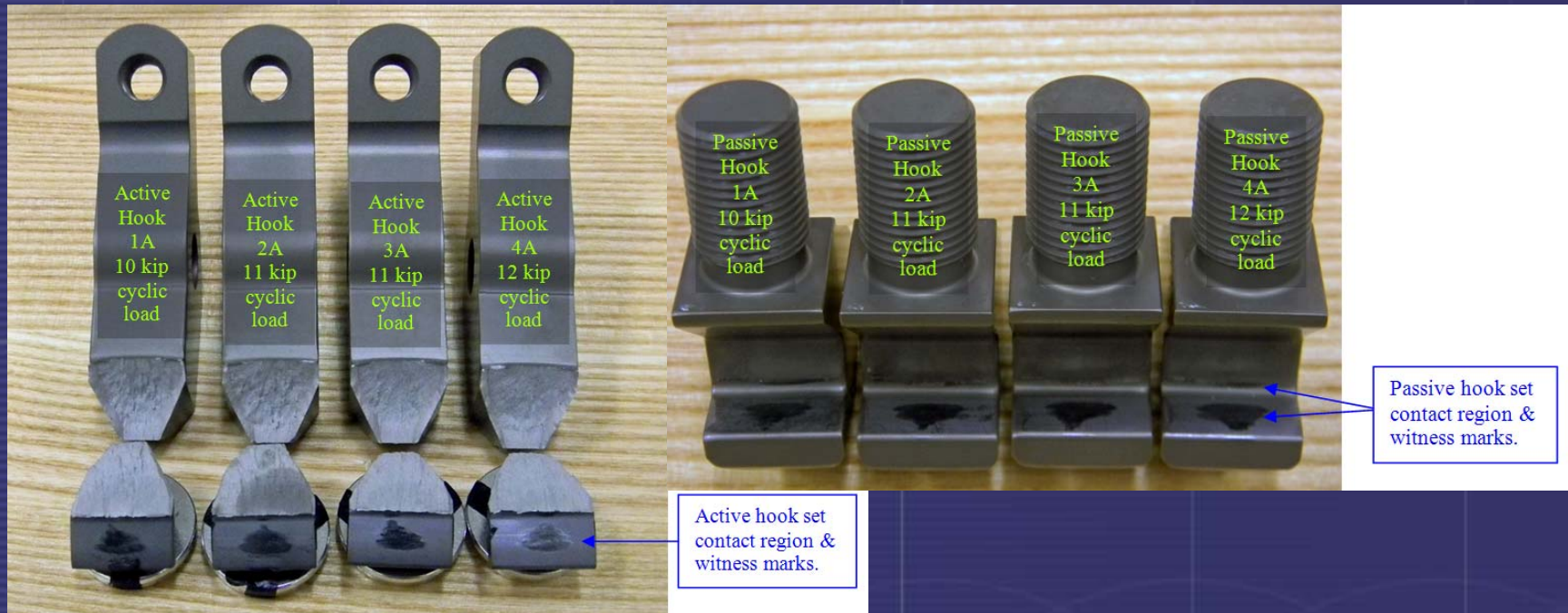


Latch Hook Fatigue Testing – (cont):

Frame by frame photographs of the 10 kip fatigue failure event are provided below.



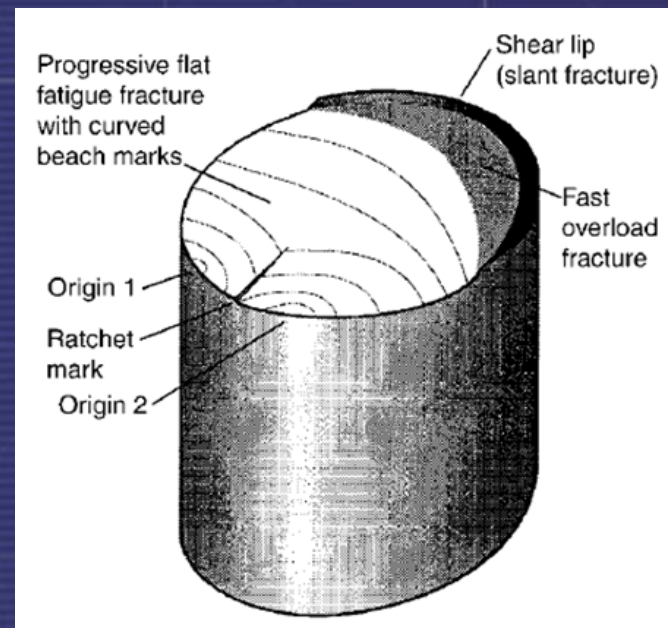
Latch Hook Fatigue Testing – (cont):



Post fatigue test photographs of the active and passive hook test article set are provided above.

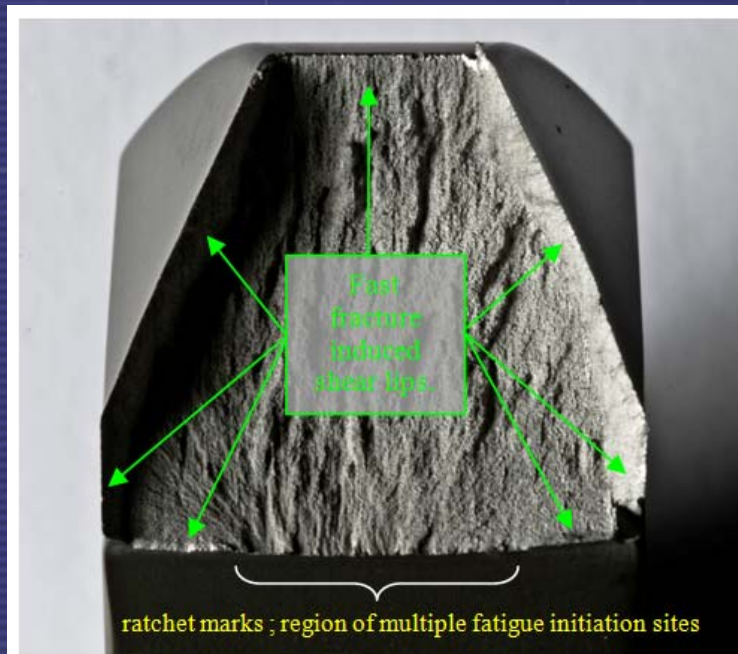
Fractography of Latch Hooks:

A schematic representation of a mode-I (tensile opening) fatigue failure is provided below^[2]. The presence of multiple fatigue crack initiation sites on different planes will result in the formation of ratchet marks as the cracks coalesce. Once the stable fatigue crack becomes unstable and the fast fracture advances across the remaining ligament the plane stress condition at a free-surface will result in failure along a 45° shear plane (slant fracture) and the resulting inclined failure region is called a shear lip.

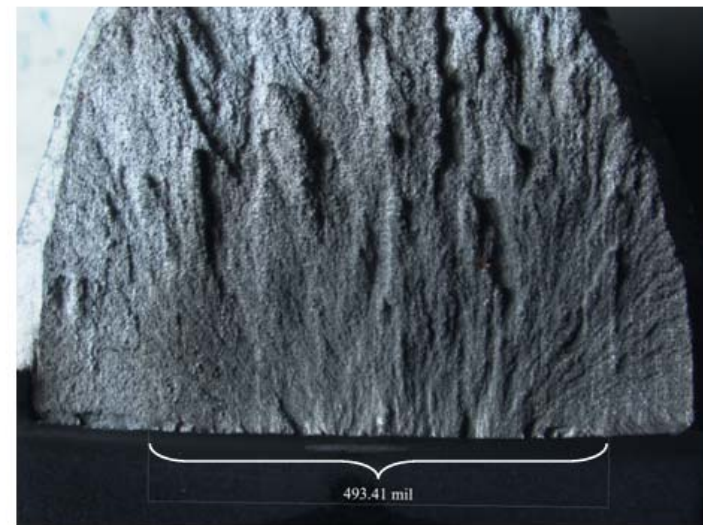


Fractography of Latch Hooks – (cont.):

Low magnification photos of the 2A hook are provided below. The numerous ratchet marks between the shear lips on the fracture initiation plane is indicative of multiple fatigue initiation sites within this region. The distribution of the fatigue damage about the centerline of the hook is consistent with the analytical results that demonstrate peak stress/strain response at the mid-plane that decreases in the direction of the hook outer surfaces.

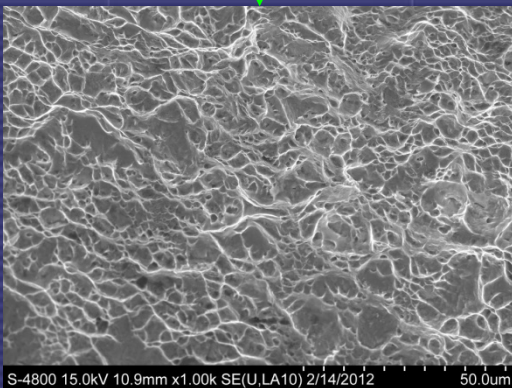
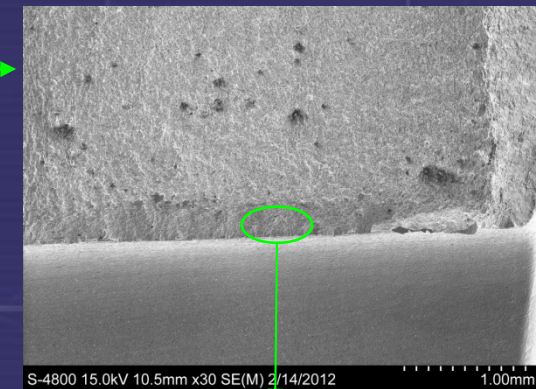
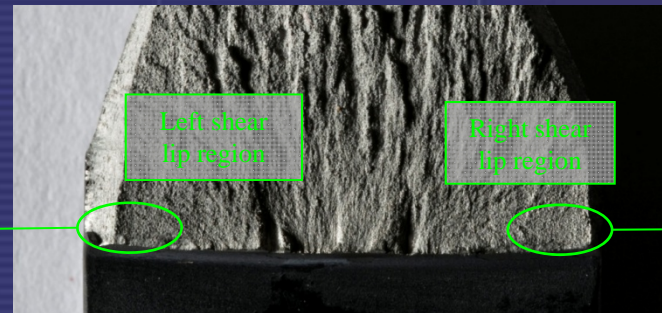
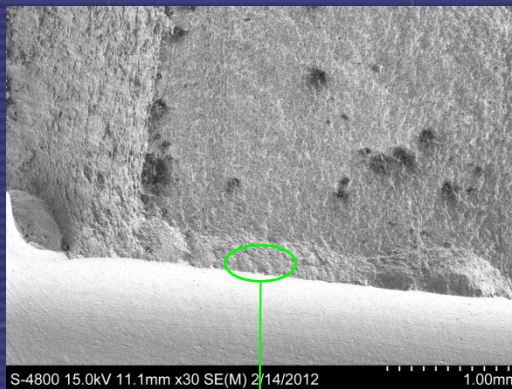


2A: 11 kip fatigue fracture surface

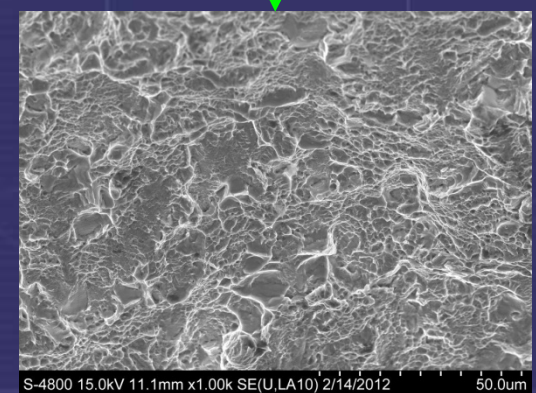


2A: ratchet mark zone ; crack initiation plane

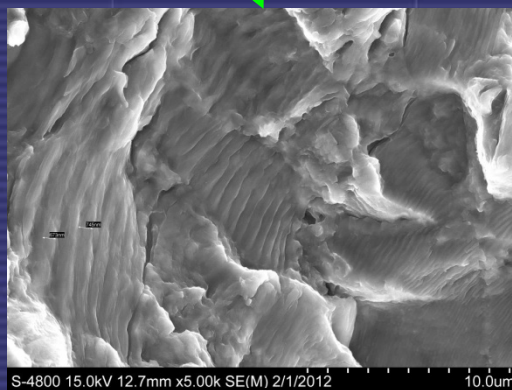
Fractography of Latch Hooks – (cont.):



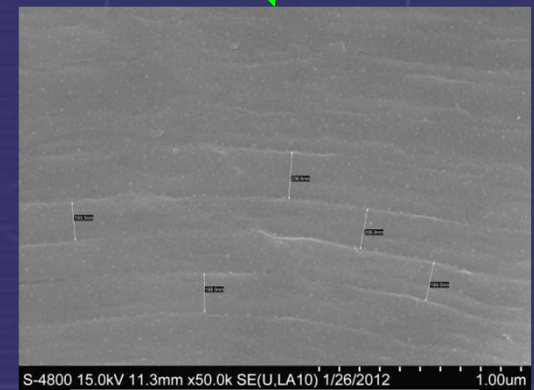
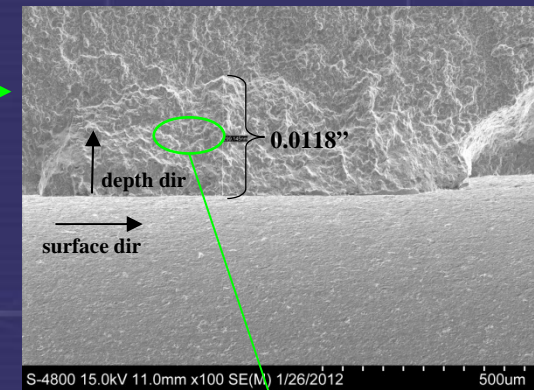
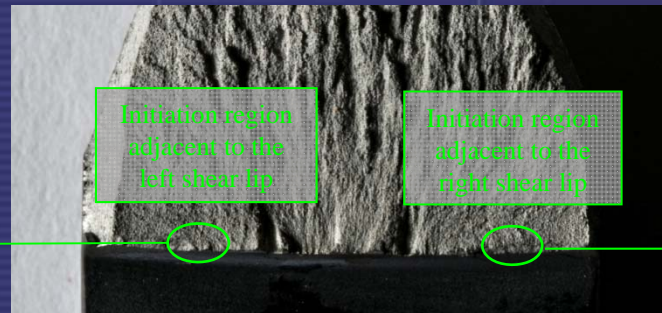
Low and high magnification images of the 1A shear lips on the crack initiation plane. The dimple rupture features within the slant fracture region confirm the overload induced shear lip formation. By fracture topography and similarity with the 2A, 3A, and 4A specimens shear lips exist at these locations in all the active hook fatigue test failures.



Fractography of Latch Hooks – (cont.):



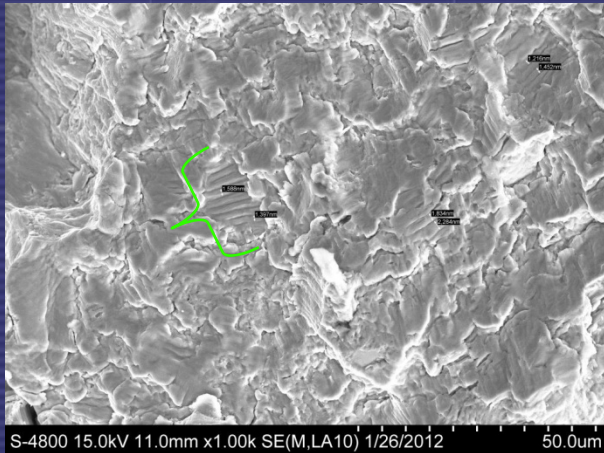
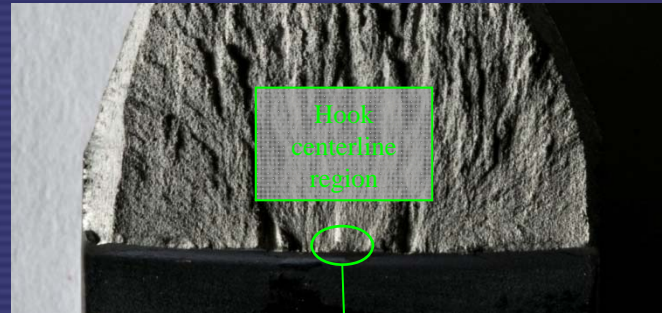
Local striation spacing $\approx 2.9e-5$ in/cycle (surface direction)



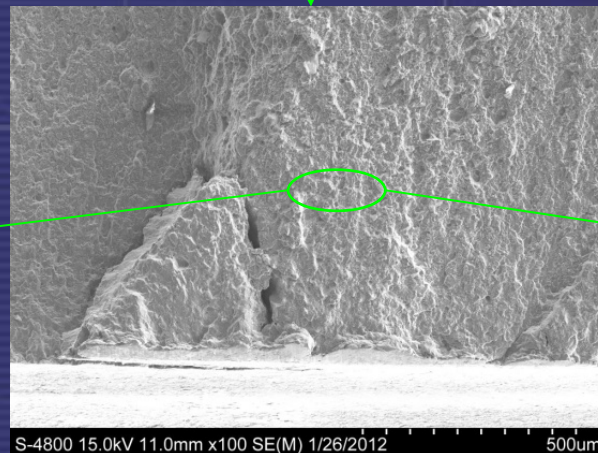
Local striation spacing $\approx 9.3e-6$ in/cycle (depth direction)

The 1A fracture surface and scanning electron microscope images of regions adjacent to the shear lip regions. Active hook 1A (10 kip fatigue loading). Scanning electron microscope images of fatigue cracks adjacent to the shear lip / fatigue transition region.

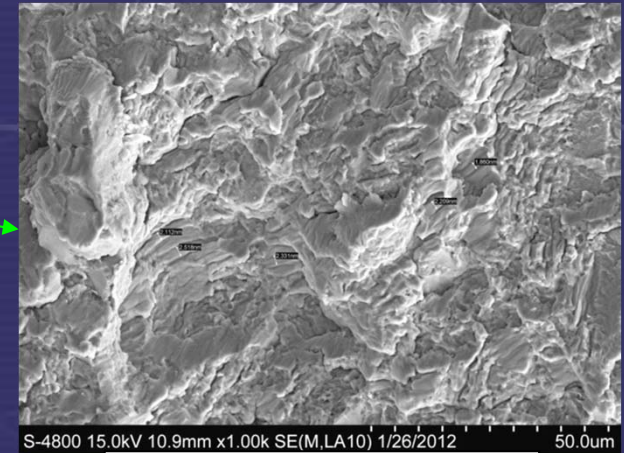
Fractography of Latch Hooks – (cont.):



Local striation spacing $\approx 9.0e-5$ in/cycle (depth direction)



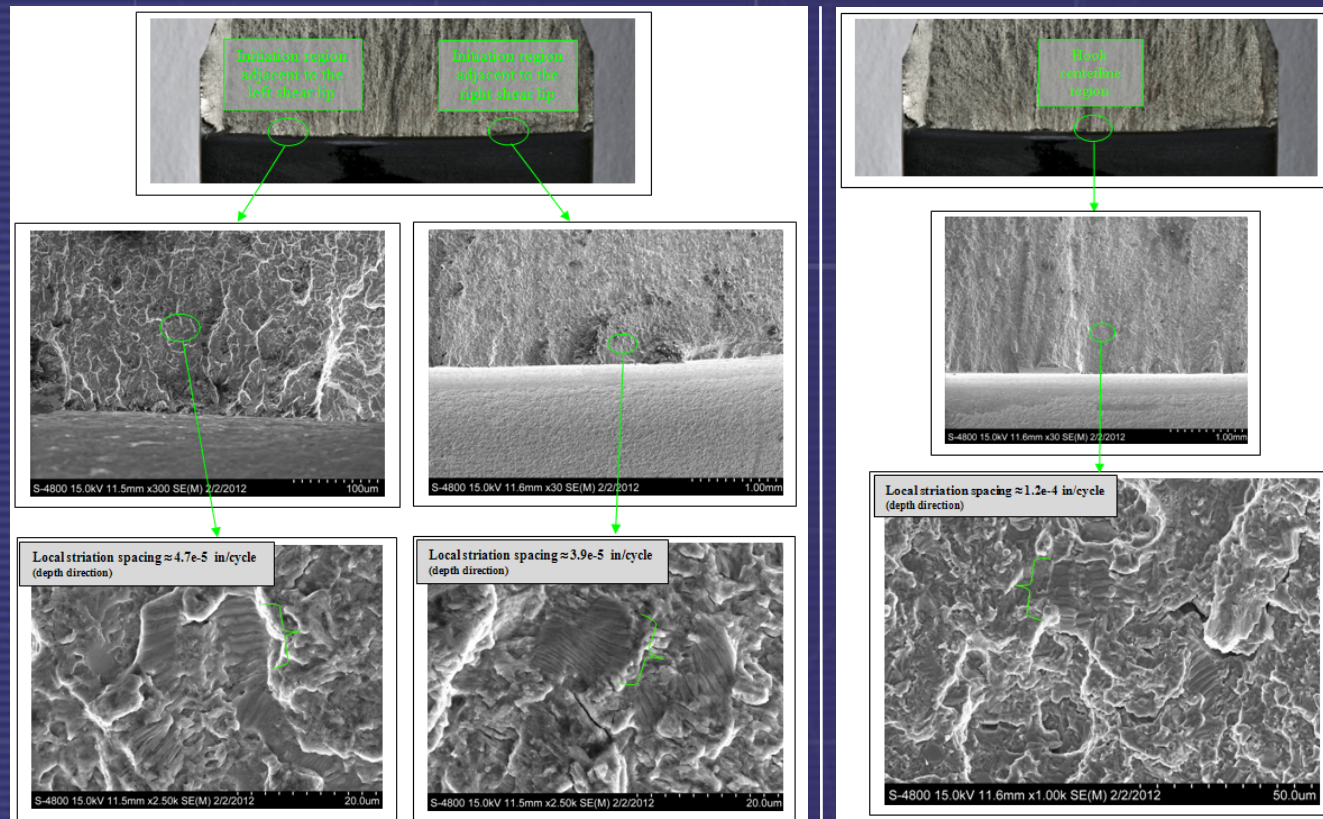
Active hook 1A (10 kip fatigue loading). Scanning electron microscope images of fatigue in the centerline region of the hook initiating surface.



Local striation spacing $\approx 9.8e-5$ in/cycle (depth direction)

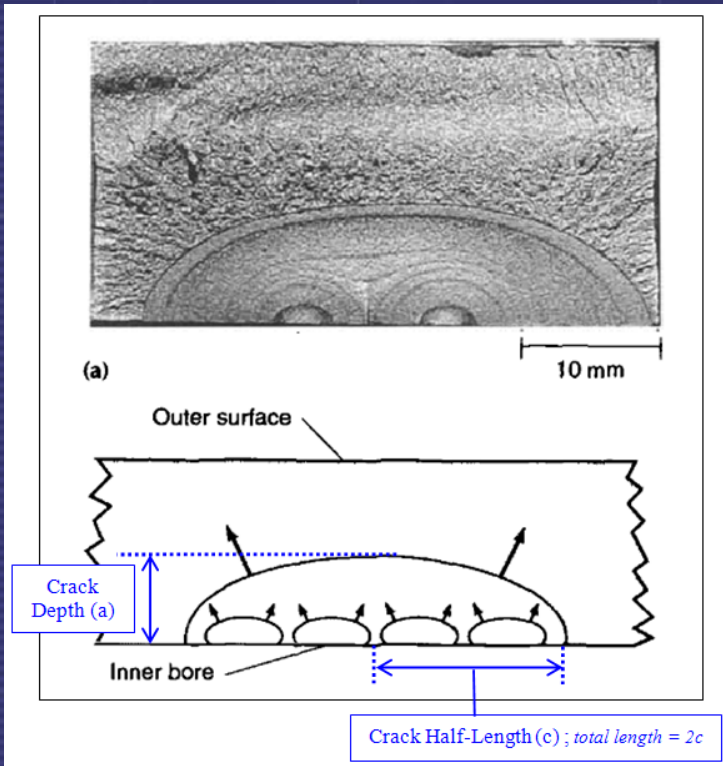
Fractography of Latch Hooks – (cont.):

Scanning electron microscope (SEM) images of the 2A fracture surface adjacent to the shear lips and near the centerline of the section are provided below; striations (microscopic tear ridges resulting from cyclic loading induced crack front advancement) were detected all along the crack initiation front.



Fracture Mechanics Analysis Update:

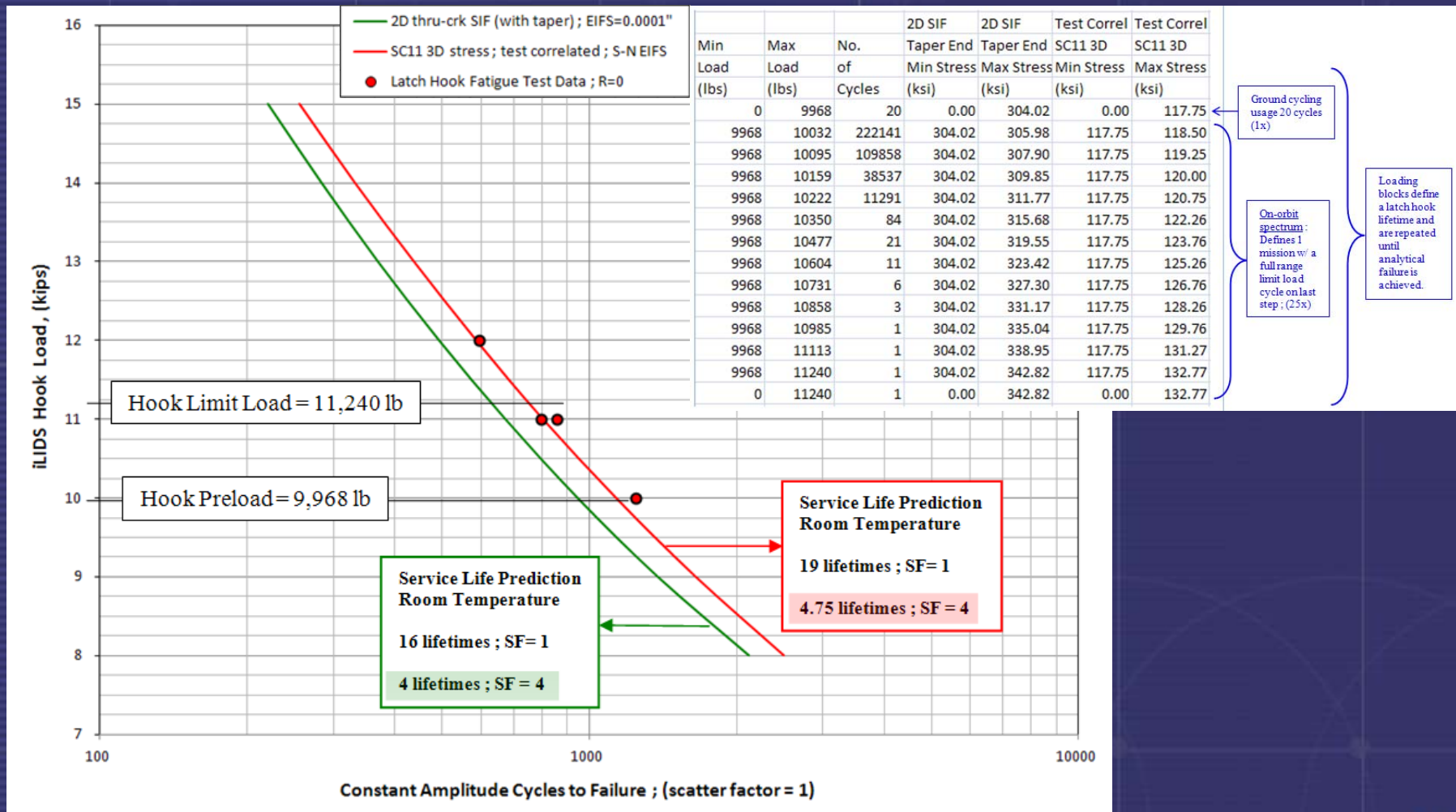
The failure analysis investigation demonstrates that the fatigue damage progression results in numerous close proximity fatigue crack initiation sites distributed over a length of approximately 0.48" centered over the 0.787" section width. Close proximity coplanar fatigue cracks will coalesce into a larger effective crack with increased surface length with respect to the crack depth (crack aspect ratio = crack depth (a) over crack half length (c) ; $(a/c) \ll 1$). The crack tip stress intensity factor for a very low aspect ratio is dominate in the depth direction and approaches that of a thru-thickness crack of the same depth^[3].





Latch Hook Mission Capability – Room Temp / Lab Air

The latch loading spectrum and resulting mission capability are provided below.





Latch Hook Mission Capability – Final Result:

The latch hook operational temperature regime of $-100^{\circ}\text{F}/+163^{\circ}\text{F}$ in a vacuum environment does not result in a detrimental fatigue damage accumulation trend with respect to the lab air room temperature result.

The analytical model that is slightly conservative with respect to the component level fatigue test data is utilized for the final service life projection. This is due to the complexity associated with achieving accurate similitude between the test configuration and the actual flight units with respect to boundary conditions, alignments, tolerances, reactions, loadings, time, environments, and potential operational usage variations.

Based upon the analysis and component level engineering testing performed a 4x lifetime capability is assigned to the iLIDS active/passive latch hooks (includes a scatter factor of 4; 1 lifetime = ground test cycles + 25 missions).





Summary – iLIDS Latch Hook Service Life Analysis:

The prescribed usage for iLIDS active/passive latch hook components results in appreciable localized plastic straining at the contact shelf transition radius in both hooks. The latch hooks are fail-safe and thus definition of the fatigue capability is all that is required (non-fracture critical).

Static strength testing was performed that defined the stiffness and static strength capability of mated hooks.

Constant amplitude fatigue testing of 4 latch hook sets to failure was performed (1 @ 10 kip, 2 @ 11 kip, and 1 @ 12 kip). The component level fatigue test data fell between the analysis established upper and lower bounds.

Failure analysis of the hook fatigue failures identified multi-site fatigue initiation that was effectively centered about the hook mid-plane. This implies that the fatigue damage accumulation effectively results in a very low aspect ratio surface crack.





Summary – iLIDS Latch Hook Service Life Analysis (cont):

The room temperature latch hook mission capabilities based upon a correlation through the test data points and for the slightly conservative 2D thru-crack cases were generated (170 and 140 missions respectively; with a scatter factor of 4).

The component level fatigue test data and analysis predictions are at room temperature in a lab air environment. The operational environment of the latch hooks is the vacuum of space (hooks are located outboard of the pressure containment seals) over a temperature min/max range of -100°F/+163°F. Literature data demonstrates that the material fatigue properties improve at temperatures less than room temperature and that fatigue crack growth rates in argon (inert gas) demonstrate an insensitivity to temperatures above room temperature beyond the currently defined upper limit. The same reference also demonstrates a markedly improved fatigue crack growth response for material alloy in the vacuum environment over the inert argon result.

Based upon the analysis and component level engineering testing performed a 4x lifetime capability is assigned to the iLIDS active/passive latch hooks (includes a scatter factor of 4 ; 1 lifetime = ground test cycles + 25 missions).





References:

1. Lawrence, Victor, **iLIDS Hook Pull Test Report**, ESCG-4520-11-TL-MEMO-0002, 1-24-2011.
2. Lund, R.A., *Fatigue Fracture Appearances*, **ASM Handbook, Volume 11: Failure Analysis Prevention**, W.T. Becker, R.J. Shipley, editors, 2002, p627-640.
3. K.S. Ravichandran, **Effect of Crack Shape on Crack Growth**, *ASM Handbook, vol. 19, Fatigue and Fracture*, 1996, p 161.
4. International Docking System Standard (IDSS) Interface Definition Document (IDD), Rev. A, 2011, pg.





Back-Up Reference Slide:

- Dowling, Norman E., **Mechanical Behavior of Materials : Engineering Methods for Deformation, Fracture, and Fatigue**, Prentice Hall, 1993, pp 154-155.
- Richards, R. Jr., **Principles of Solid Mechanics**, CRC Press, 2000, pp 243-245.
- Stowell, R.E., **Stress and Strain Concentration at a Circular Hole**, NACA TN 2073, 1950.
- MIL-HDBK-5H, **Metallic Materials and Elements for Aerospace Vehicle Structures**, 1998, pg. 5-54.
- Gallagher, Giessler, and Berens, **USAF Damage Tolerant Design Handbook: Guidelines for the Analysis and Design of Damage Tolerant Aircraft Structures**, AFWAL-TR-82-3073, 1984, Section 3.4.
- Newman, J.C., Jr., Phillips, E.P., Swain, M.H., and Everett, R.A., Jr., “**Fatigue Mechanics : An Assessment of a Unified Approach to Life Prediction**,” *Advances in Fatigue Lifetime Predictive Techniques*, ASTM 1122, M.R. Mitchell, and R.W. Landgraf, Eds., American Society for Testing and Materials, Philadelphia, 1992, pp. 5-27.
- Bannantine, Comer, and Handrock, **Fundamentals of Metal Fatigue Analysis**, Prentice-Hall, 1990, pp 130.
- Manson, S.S., Halford, G.R., **Fatigue and Durability of Structural Materials**, ASM International, 2006, pp 54-55, 81.
- Dowling, N. E., “Local Strain Approach to Fatigue,” Chapter 4.03, *Volume 4, Cyclic Loading and Fatigue*, R. O. Ritchie and Y. Murakami, volume editors, part of the 10-volume set, **Comprehensive Structural Integrity**, B. Karihaloo, R. O. Ritchie, and I. Milne, overall editors, Elsevier Science Ltd. Oxford, England, 2003.
- Bell, R.P., Shah, S., and Alford, R.E., Equivalent Initial Flaw Size Using Small Crack Data, Structural Integrity Department, Lockheed Martin Aeronautical Systems, Marietta, Georgia, USA and C-141 System Program Office, WR-ALC, Robins AFB, Georgia, **Small Fatigue Cracks: Mechanics, Mechanisms and Applications**, R.O. Ritchie and Y. Murakami (Editors), 1999 Elsevier Science Ltd.
- Wang, D.Y., **A Study of Small Crack Growth Under Transport Spectrum Loading**, AGARD-CP-328, *Behaviour of Short Cracks in Airframe Components*, 1983, pp. 14-1 thru 14-15.
- IDSS IDD, International Docking System Standar (IDSS) Interface Definition Document (IDD), Rev. A, May 13, 2011, pg. 21.
- AFML-TDR-64-280, **Cryogenic Materials Data Handbook**, August 1968, pp 721.
- S. Lampman, **Fatigue Data Book: Light Structural Alloys**, ASM International, 1995, pp. 292-293.

