Application of Surface Residual Stresses for Durability and Damage Tolerance Improvements in Wing Attachment Lugs

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Structural Life Improvement

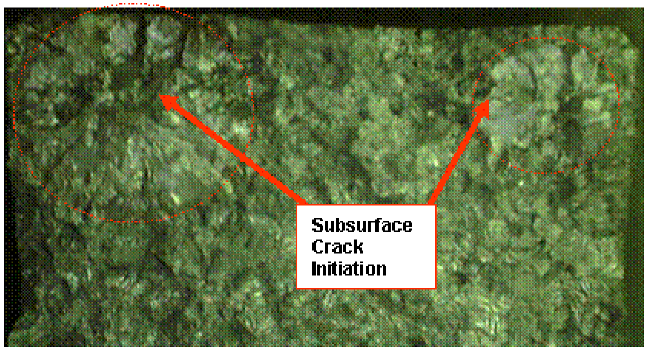
- **Opportunity: Structurally enhance wing fillets**
  - **Increase Aircraft Service Life**
  - **Increase Fleet Reliability**
  - **Eliminate Inspections**
  - **Increase A/C availability**

Solutions

- **Glass Bead Peening (GBP)**
- **Laser Shock Peening (LSP)**
- **Application**
  - **Peen During Aircraft Production**
    - » **Peening prior to active flight (t=0)**
  - **Peen Aircraft at Depot**
    - » **Peening after period of active flight (t>0)**

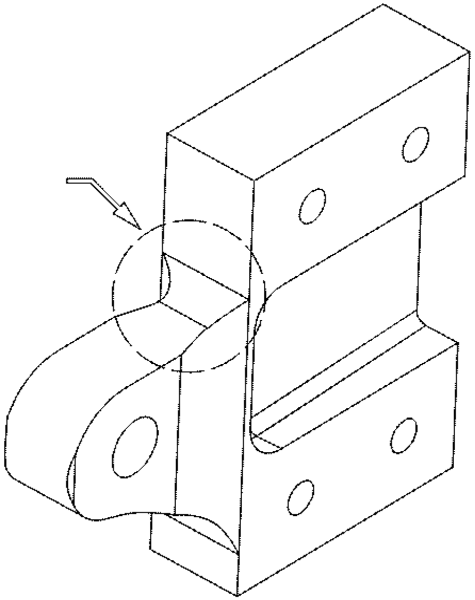
LSP Objectives

- **Optimize LSP Process for Aircraft Structure**
  - **Eliminate risk of subsurface initiation**
  - **No Distortion**



- **Developed Residual Stress Modeling Techniques Appropriate for frame geometries**

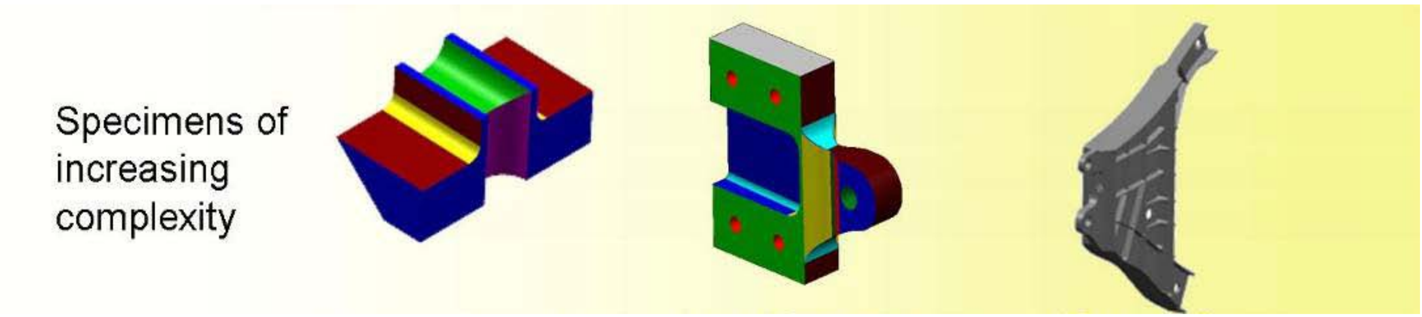
- **Perform Fatigue Tests**
  - **Use representative structure**



- **Define Benefit with Weibull Analysis**

Experimental Layout

- **Only minimal a priori LSP knowledge existed for frame configurations**
  - **Material: Ti-6Al-4V Beta Anneal**
- **Utilized a scale-up approach**



Radius Sample **Lug Element** **Frame**

A priori Knowledge & Data

Radius Res. Stress *Predictions*

Radius Res. Stress *Measurements*

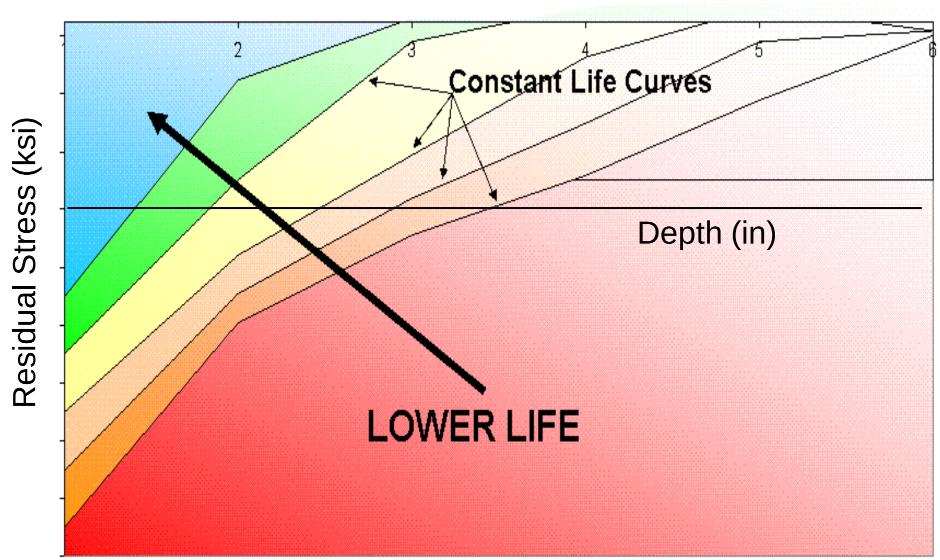
Lug Element Res. Stress *Predictions*

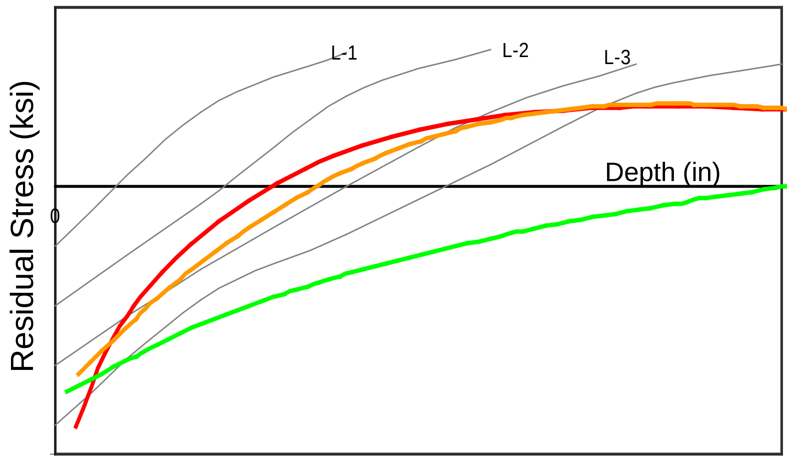
Lug Element Res. Stress *Measurements*

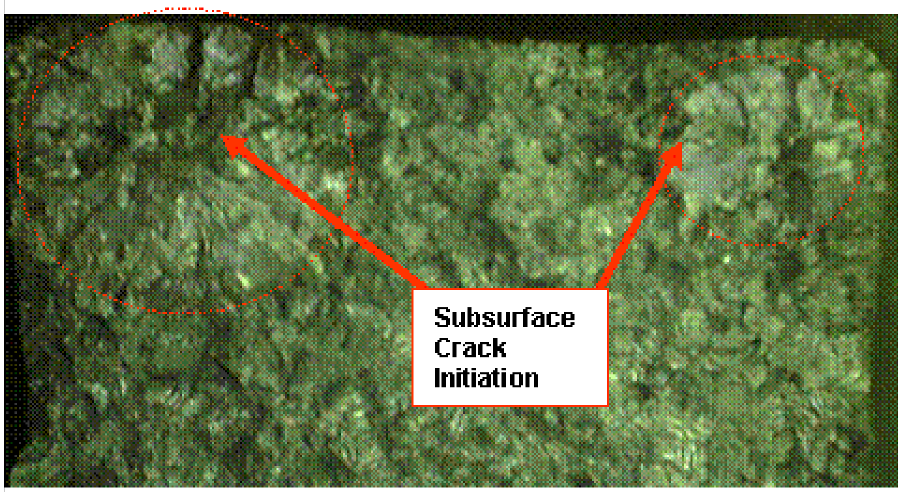
Frame Res. Stress *Predictions*

Frame Res. Stress *Measurements*

Design Criterion: Subsurface Initiation



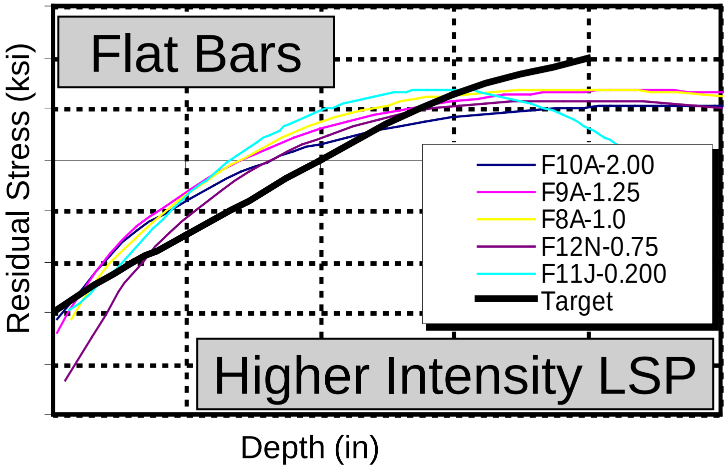


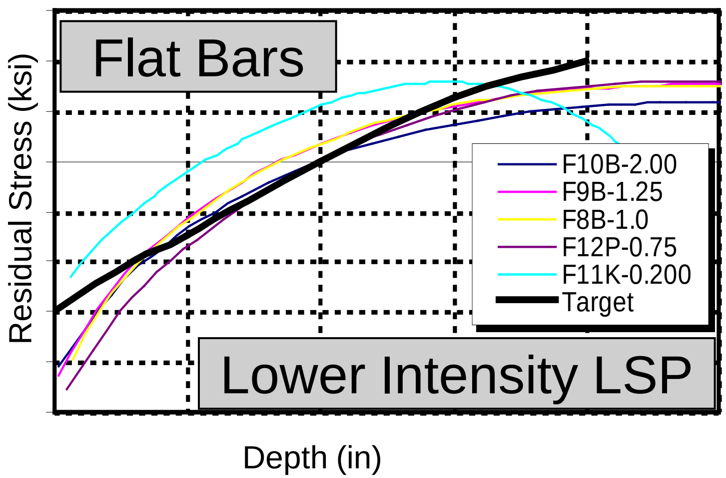


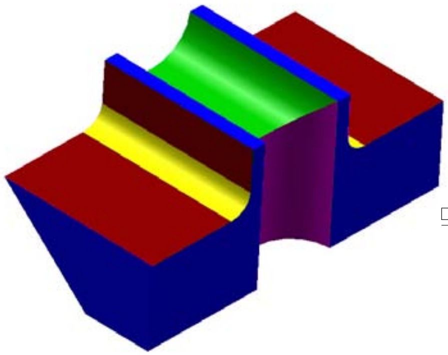
- **RED RS Curve**
  - **Shows Lowest life SUBSURFACE**
- **ORANGE RS Curve**
  - **Follows L3 Life Line; constant life near surface**
- **GREEN RS Curve**
  - **Life increases subsurface**

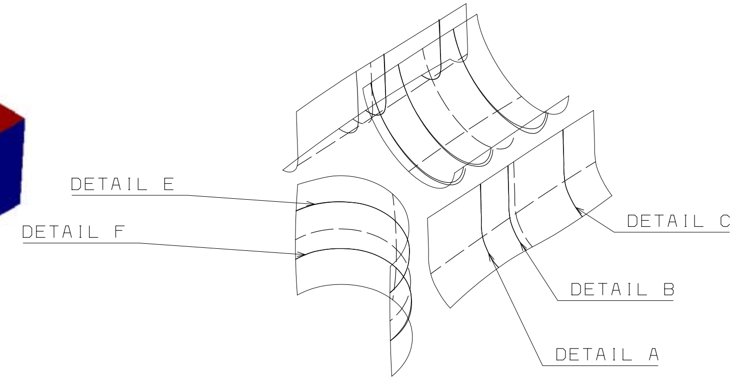
- **Select ORANGE/GREEN RS Curves**

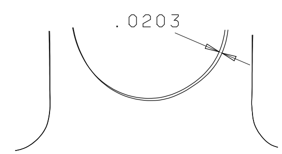
Flat Test Bars / Radii Coupons



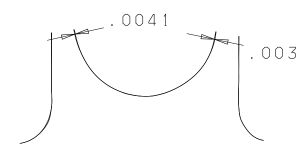








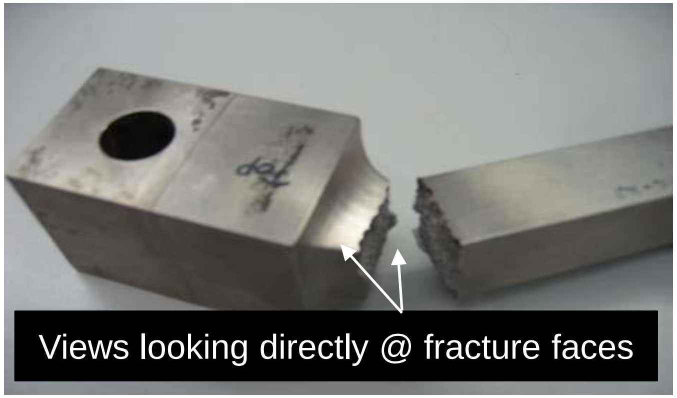
Higher Intensity LSP

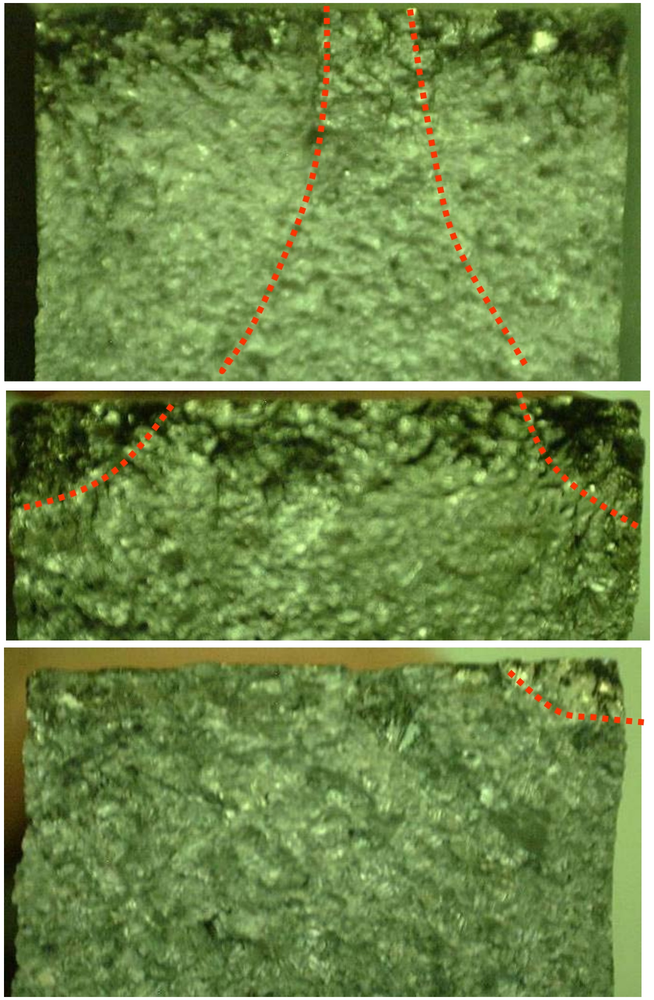


Lower Intensity LSP

- **Lower Intensity LSP Selected to match the target life curves and minimize distortion**

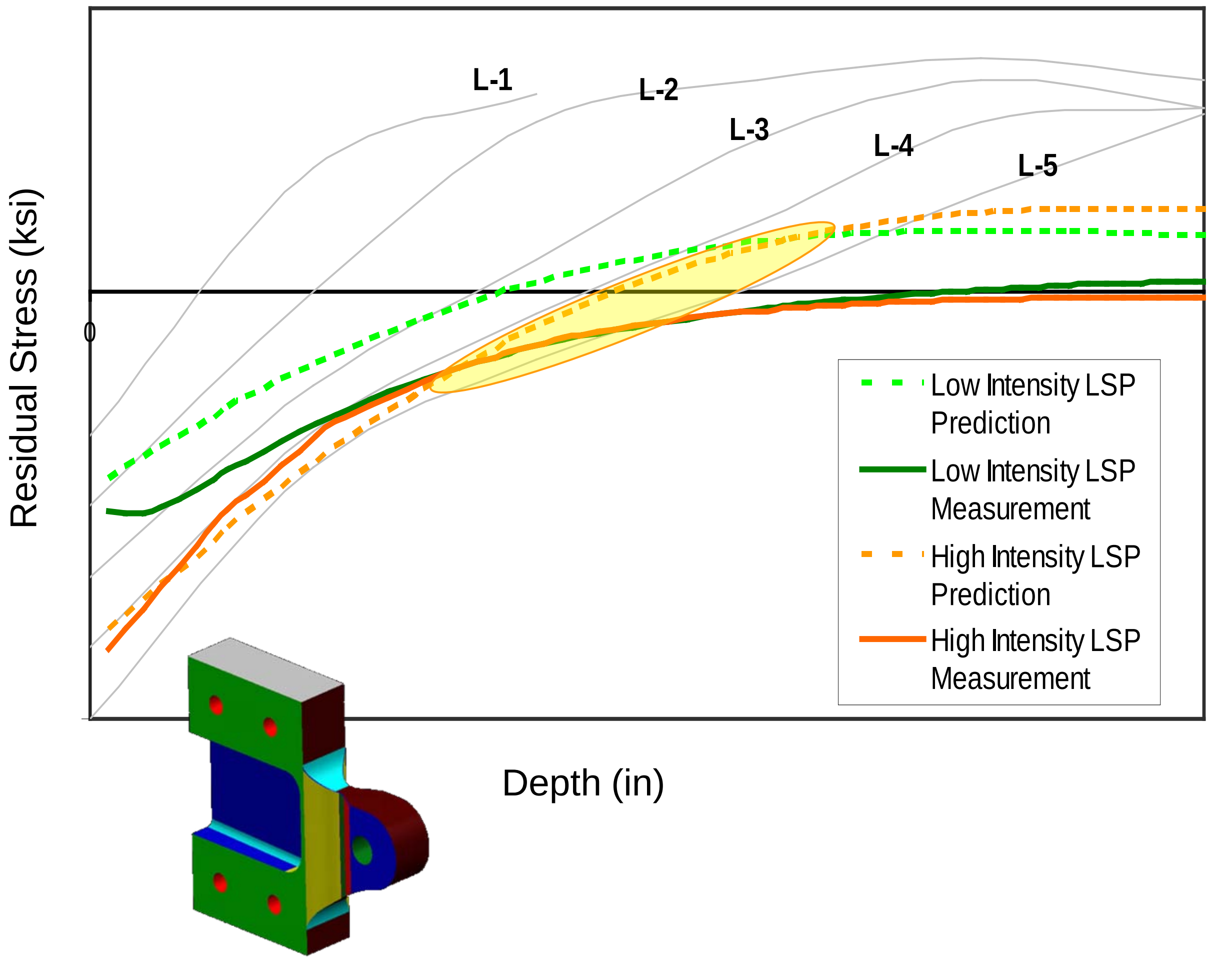
Lower Intensity LSP Applied to Fatigue Test





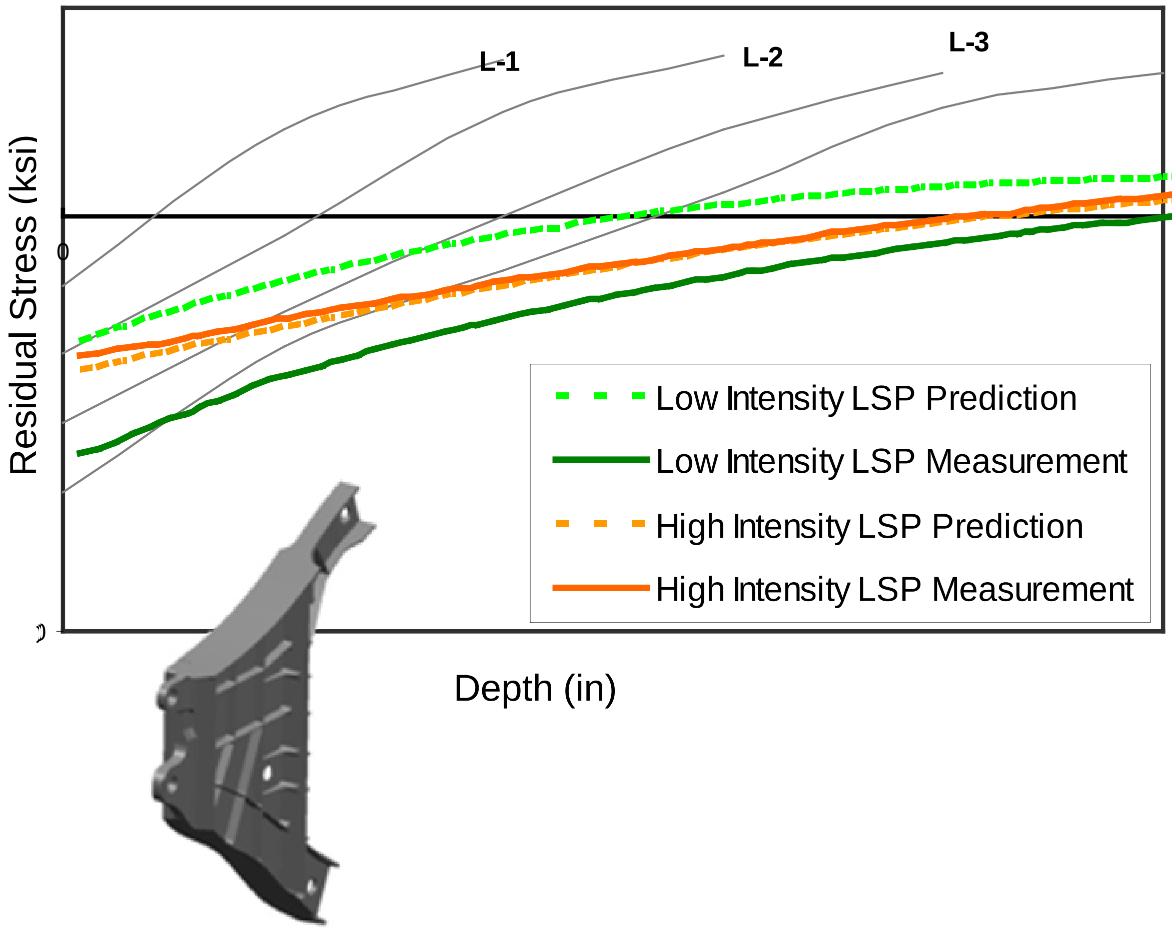
- **Lower Intensity LSP**
  - **Initiations examined at 3 different times in fatigue life**
  - **No Subsurface Initiations Found**
- **Next Steps:**
  - **Proceed with Scale-up**
  - **Predict RS for Lug and Frame**

Lug Element Residual Stresses



- **Low Intensity LSP**
  - **Prediction shows no subsurface potential**
  - **Measurement shows no subsurface potential**
- **High Intensity LSP**
  - **Prediction shows subsurface potential**
  - **Measurement shows no subsurface potential**

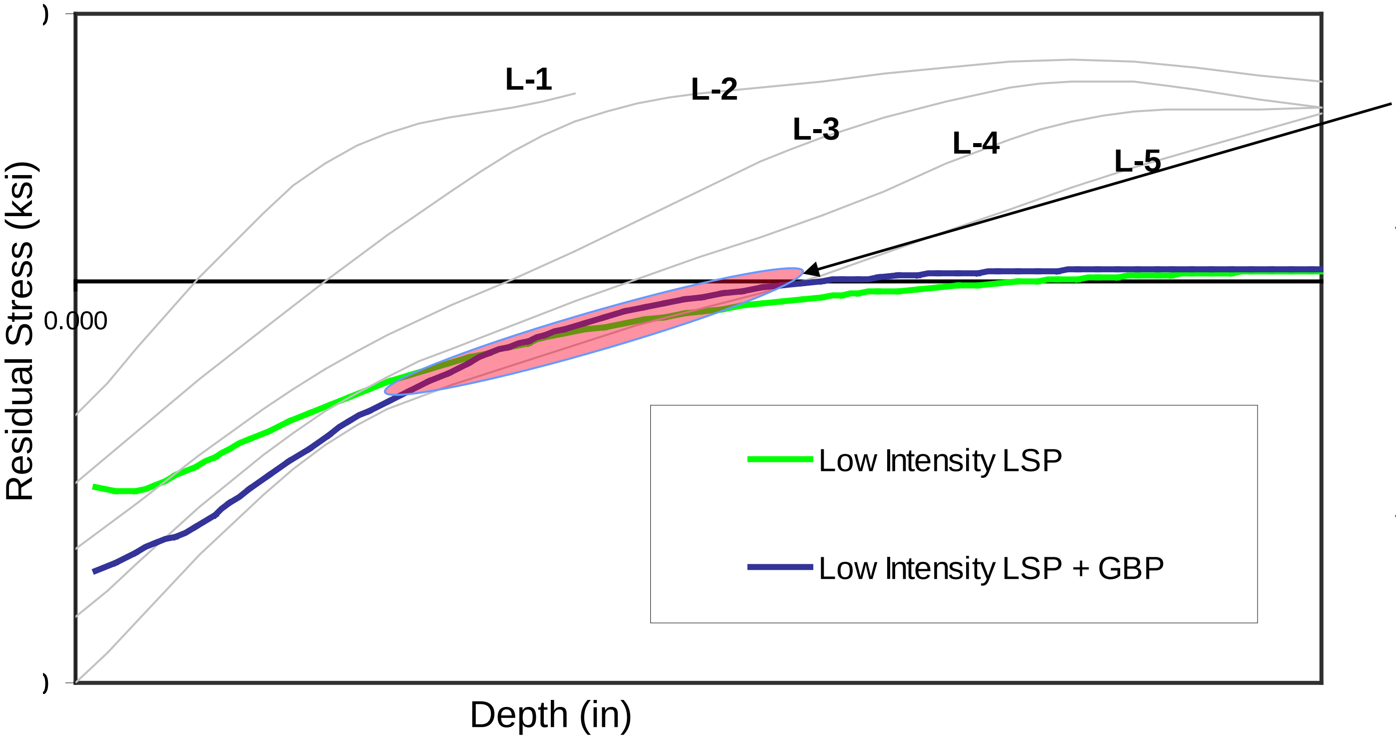
Frame Residual Stresses



- **All predictions and measurements show no subsurface potential**
- **Predictions improving and still slightly conservative**
- **Lower Intensity Peening shows to be better suited for frame applications**
  - **Distortion**
  - **Residual Stress**

LSP + GBP

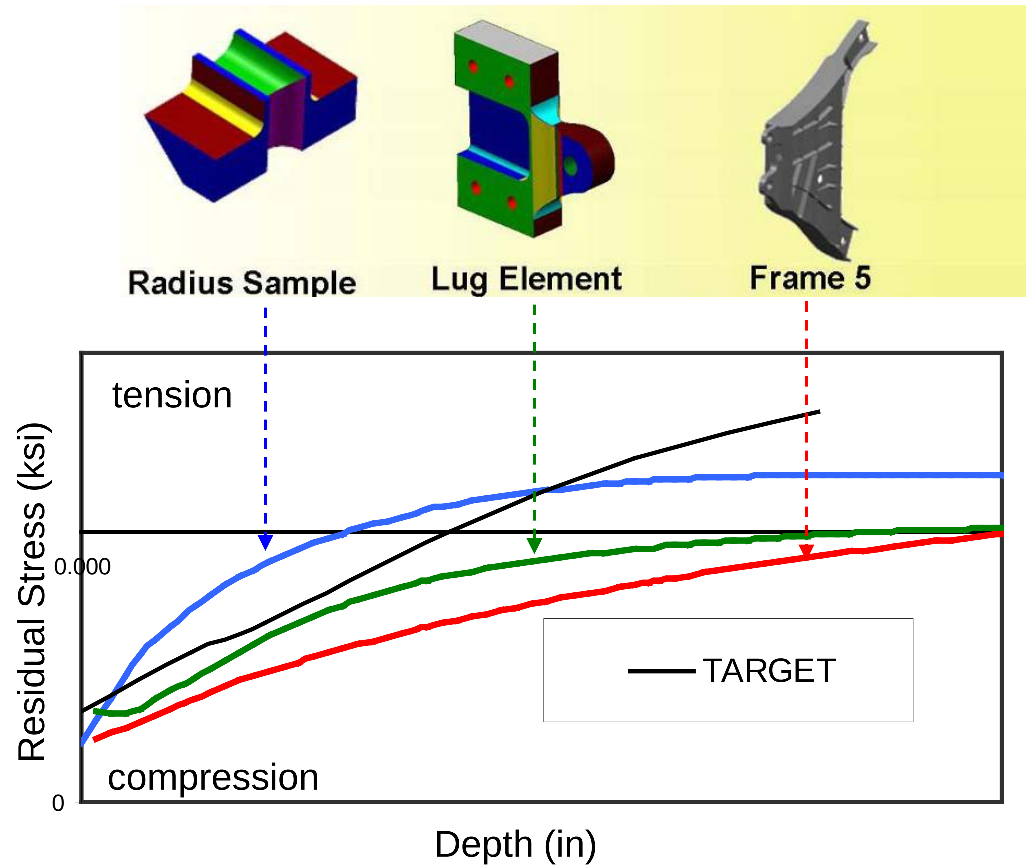
- **Current fleet conditions only allow LSP to be applied on top of GBP**

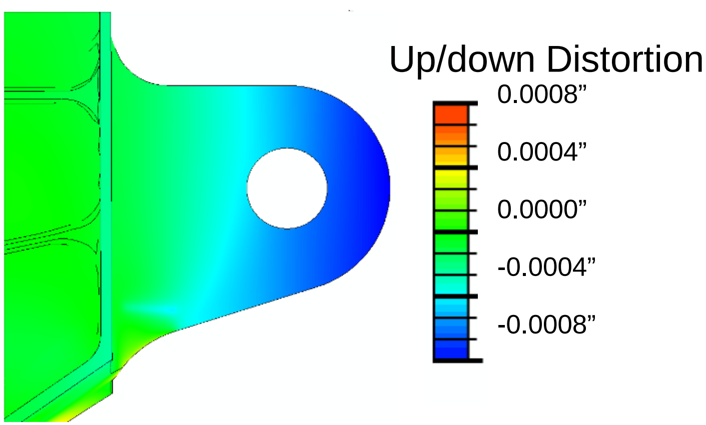


- LSP + GBP has a small subsurface cracking vulnerability
- Low intensity chosen to minimize vulnerability
- Fatigue Tests showed no subsurface cracks

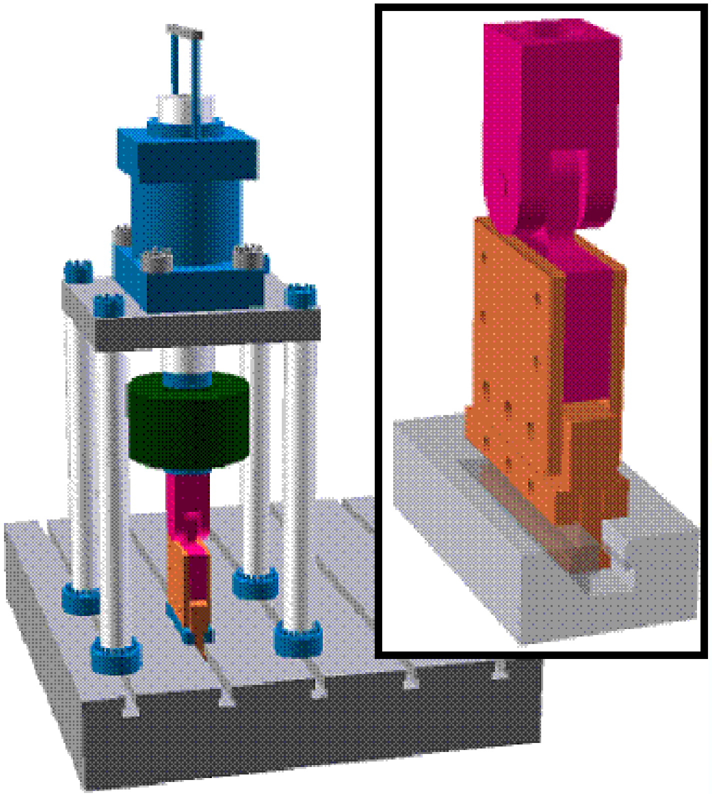
Geometry Effects on Residual Stresses

- **Increasing geometries (mass & configuration):**
  - **Decreased distortion**
  - **Similar surface compression RS**
  - **Deeper compression RS layer**

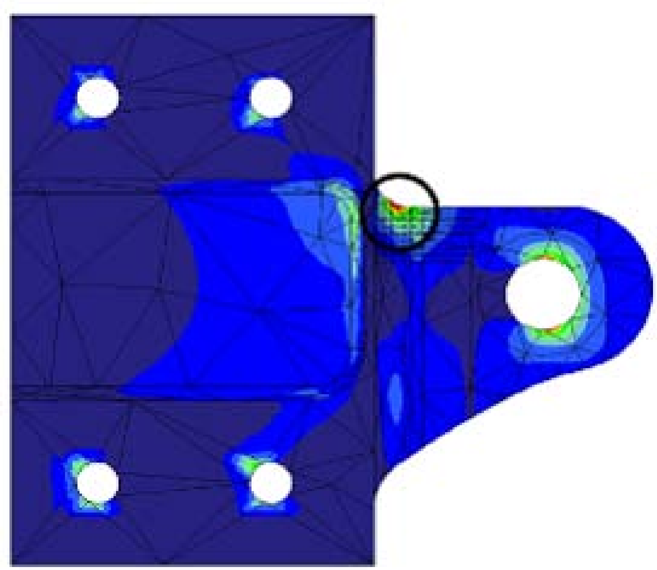


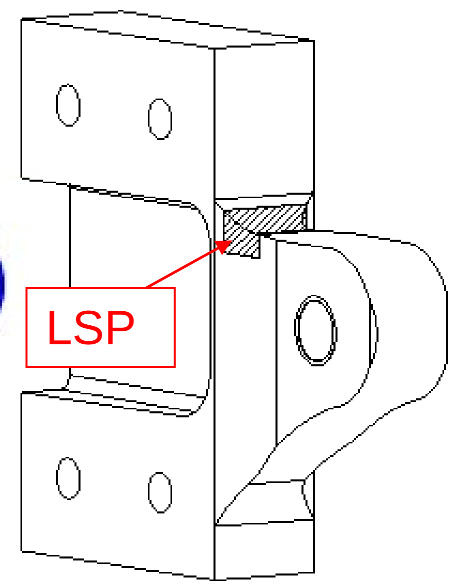


Fatigue Testing



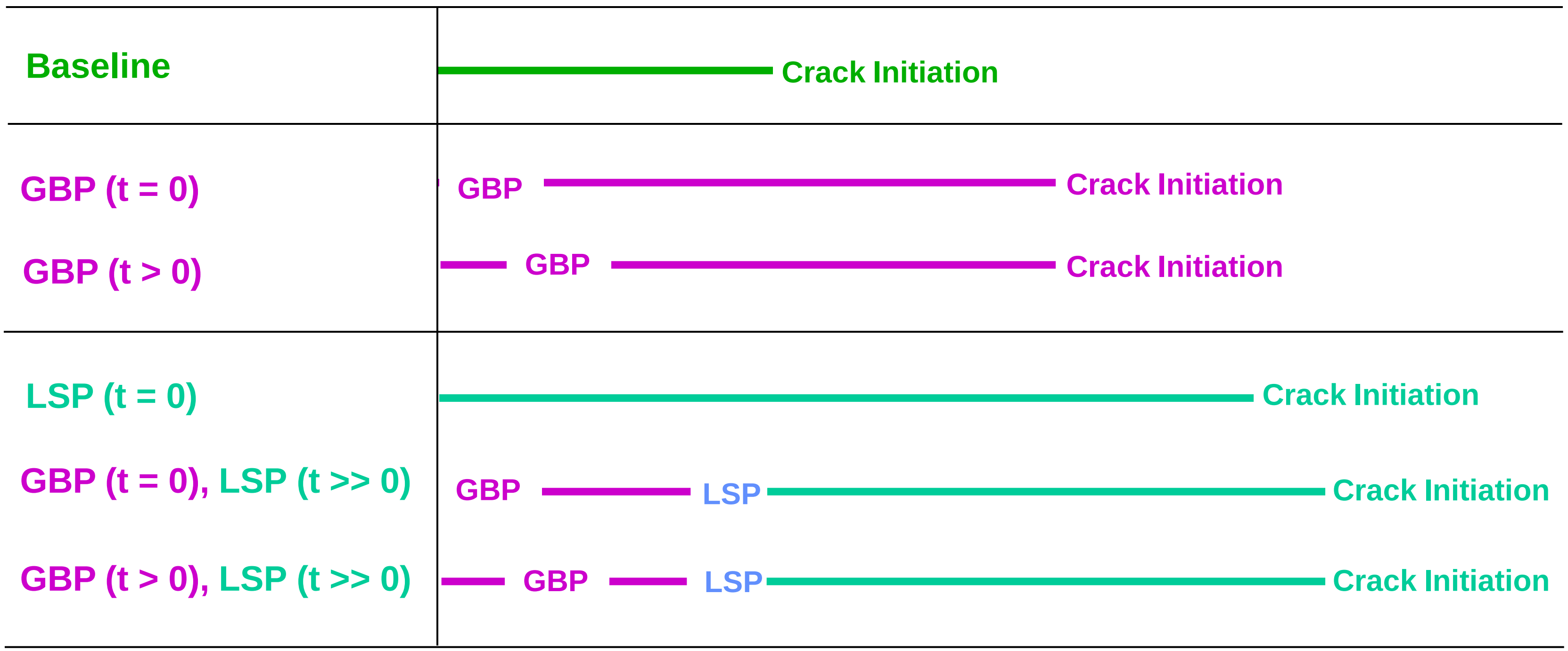
- Lug Elements tested to match frame stress gradient
- Wing Up-bending spectra
- Specimens peened to add LSP compression over tension "hotspots"





Test Conditions

- **Peening Must be verified with Structural Testing**
  - **Structured test matrix used to define benefits of each of the following fleet scenarios**



Crack Initiation Fatigue Results

Baseline

GBP (t > 0)

GBP (t = 0)

LSP (t = 0)

GBP (t > 0), LSP (t >> 0)

GBP (t = 0), LSP (t >> 0)

Failures

Run-outs

Normalized Test Lives

Weibull Crack Initiation Analysis

$$\ln(L) = \Lambda = \sum_{i=1}^{F_e} N_i \ln\left[\frac{\beta}{\eta}\left(\frac{T_i}{\eta}\right)^{\beta-1} e^{-\left(\frac{T_i}{\eta}\right)^{\beta}}\right] - \sum_{i=1}^{S} N_i' \left(\frac{T_i'}{\eta}\right)^{\beta}$$

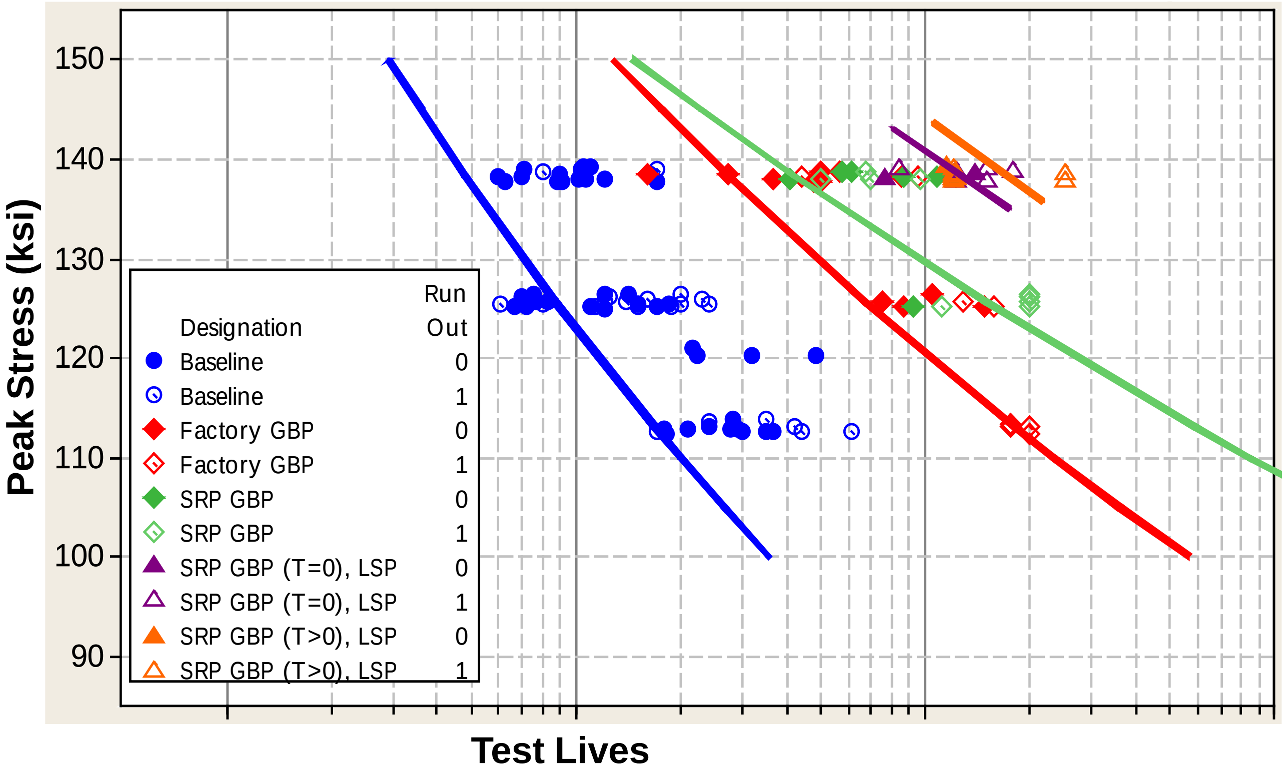
Weibull Maximum Likelihood Function

- Set β=3 for titanium
- Solve for η

F_e is the number of groups of times-to-failure data points
N_i is the number of times-to-failure in the ith time-to-failure data group
β is the Weibull shape parameter
η is the Weibull scale parameter
T_i is the time of the ith group of time-to-failure data
S is the number of groups of suspension data points
N_i‘ is the number of suspensions in ith group of suspension data points
T_i‘ is the time of the ith suspension data group

Weibull Analysis Benefit Factors	
GBP (t>0)	***9.0***
GBP (t=0)	***6.1***
LSP (t=0)	***6.0***
LSP over GBP (t>0)	***30.2***
LSP over GBP (t=0)	***19.2***

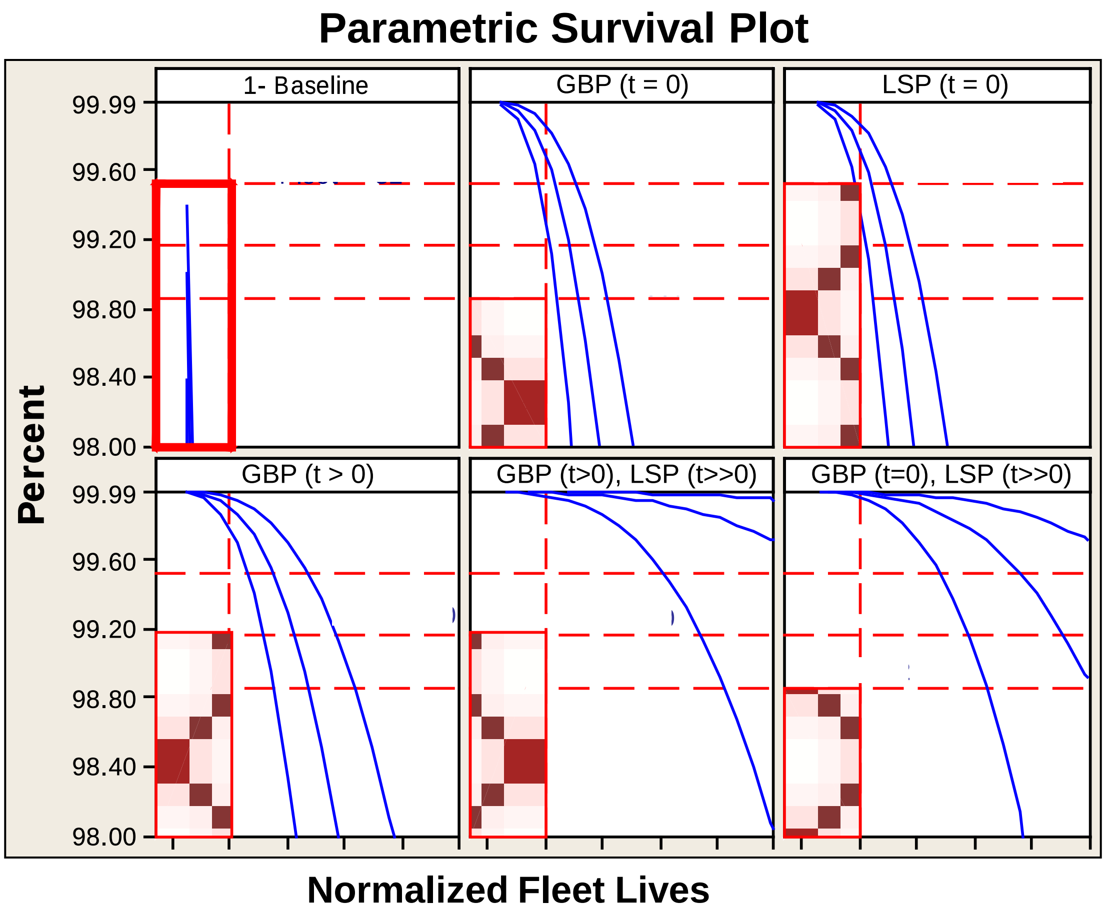
Stress-Life Summary

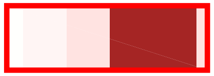


- **σ-n curves for lugs in wing up-bending**
- **Budget/Time restricted extended testing**
- **Significant life improvements available from both peening technologies**

Solid lines represent a lower 90% Weibull regression on peak stress and accounting for run-outs

Crack Initiation Risk Analysis

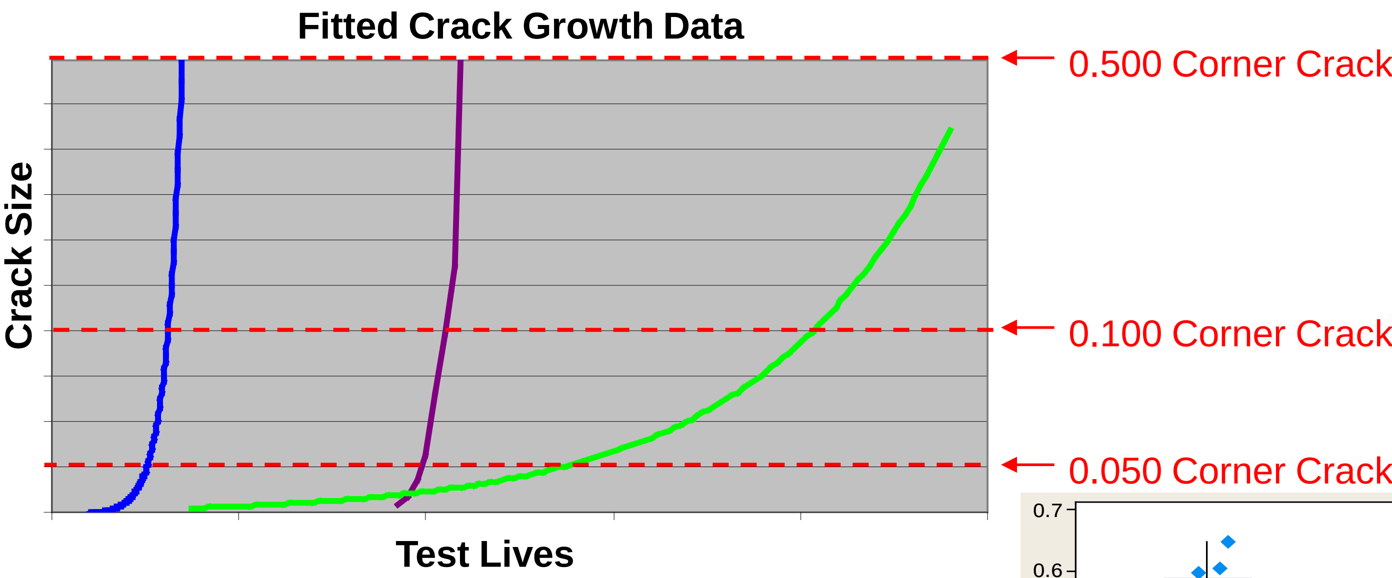


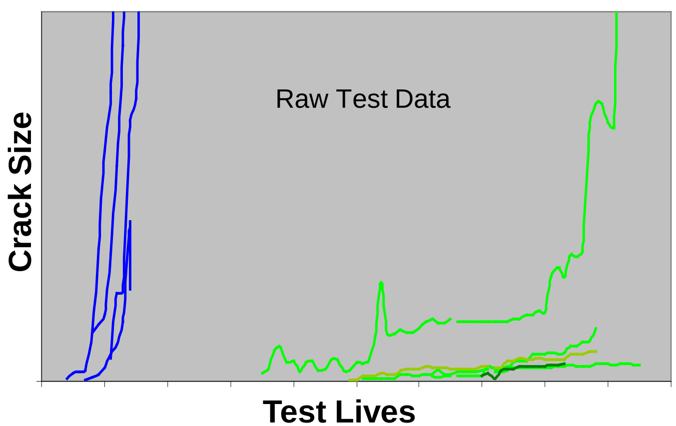


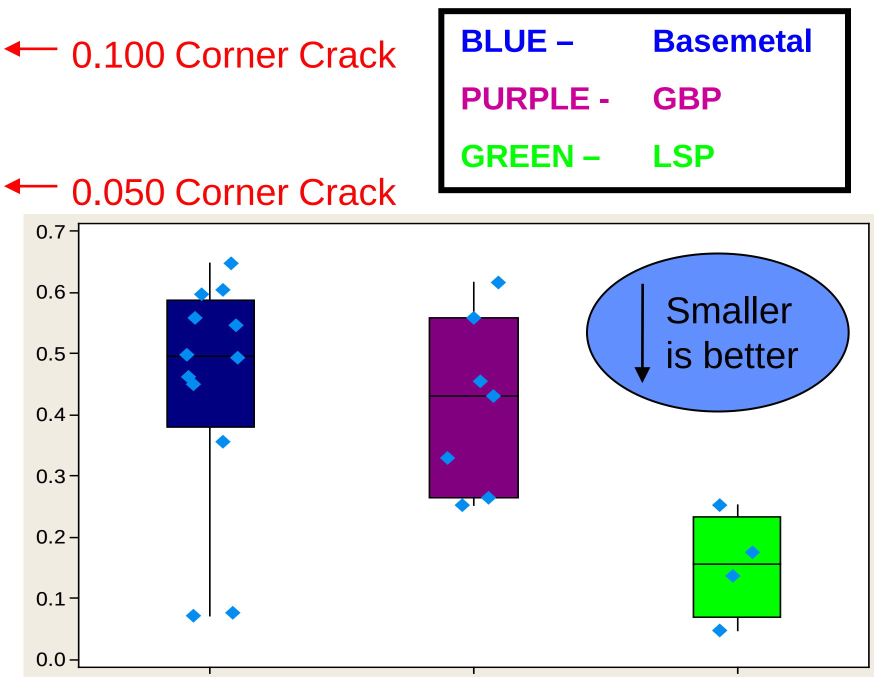
Areas where cracking risk is not met

- **Fleet Risk measures the left tail of a distribution**
- **Peening technologies keep the left tail very small**
- **GBP/LSP/GBP+LSP all improve the fleet reliability by significant factors**

Crack Growth







Exponent of Arrhenius Growth Fit (Cracks >0.100")

Summary

- **LSP Optimized for Aircraft Applications (wing up-bending spectrum)**
  - **Distortion & Subsurface cracking mitigated**
- **Hill Engineering, LLC has developed empirical residual stress prediction models**
- **GBP & LSP Benefits Defined**
  - **Reduced Fleet Risk**
  - **Extended Crack Initiation Life**
  - **Arrested Crack Growth Rates**
- **Next Steps: Validate with further Full-scale Frame Testing**

Acknowledgements

- **478th AESG**
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  - **Vernon, CA – Glass Bead Peening**
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- **Hill Engineering, LLC**


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