



U.S. AIR FORCE



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

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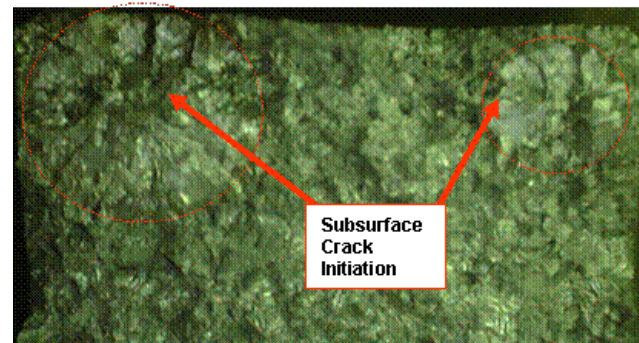


- **Opportunity: Structurally enhance wing fillets**
 - Increase Aircraft Service Life
 - Increase Fleet Reliability
 - Eliminate Inspections
 - Increase A/C availability

- **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 ($t>0$)**

- **Optimize LSP Process for Aircraft Structure**

- Eliminate risk of subsurface initiation
- No Distortion

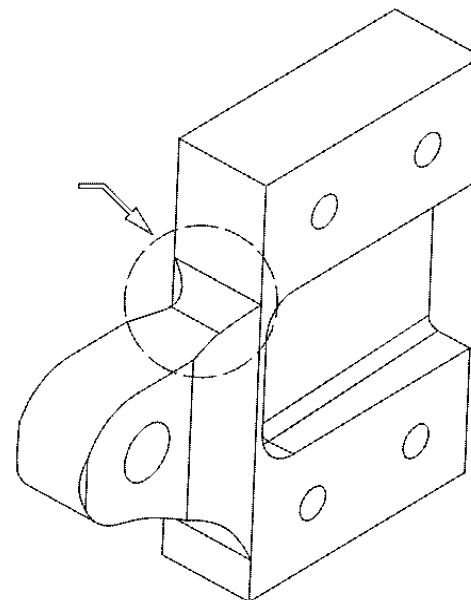


- **Developed Residual Stress Modeling Techniques Appropriate for frame geometries**

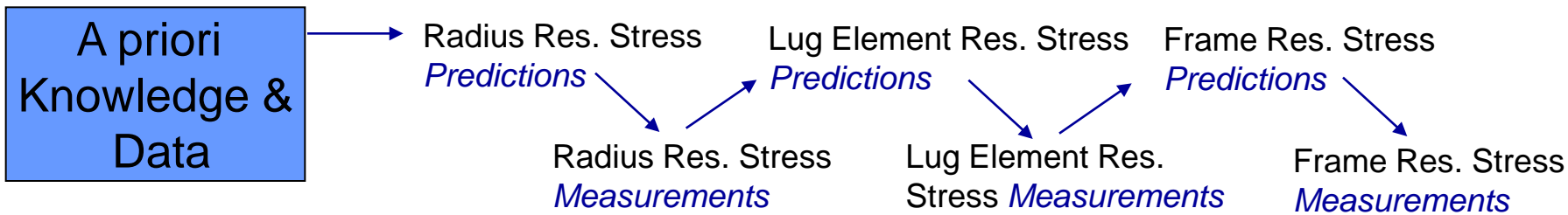
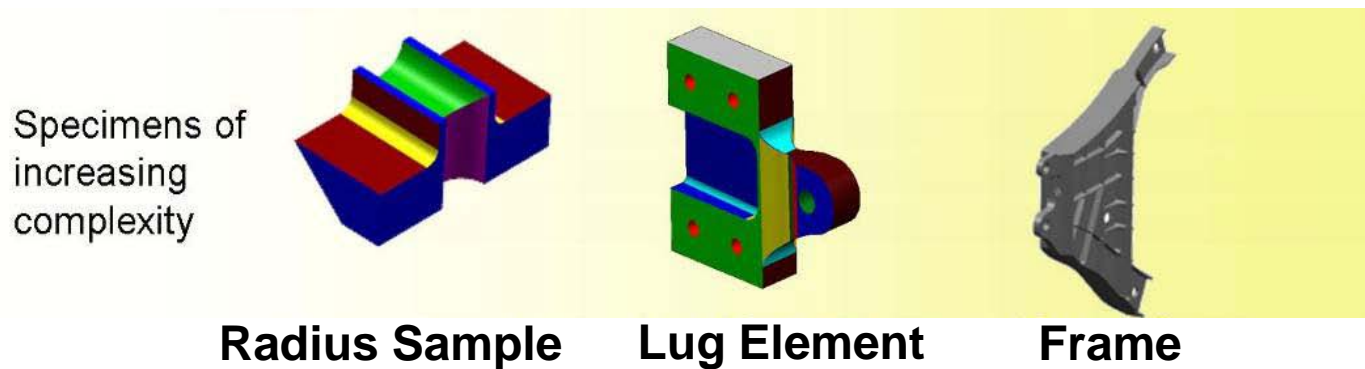
- **Perform Fatigue Tests**

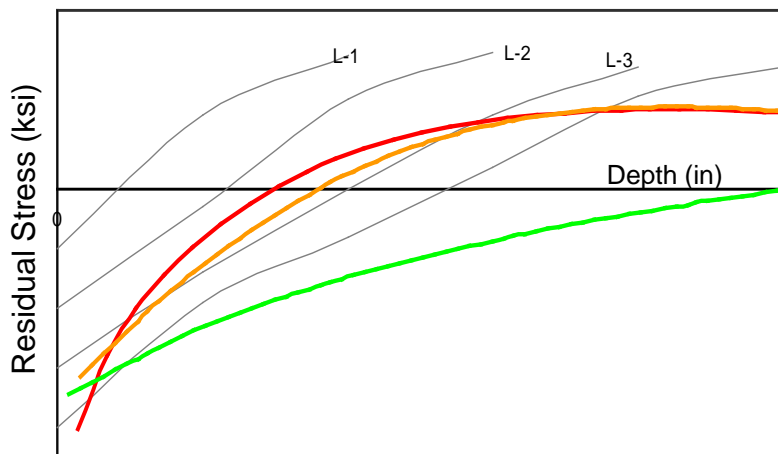
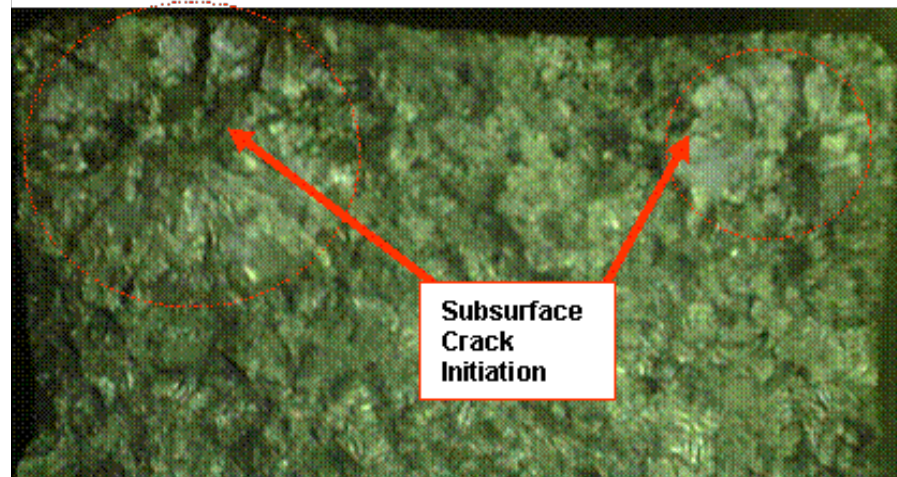
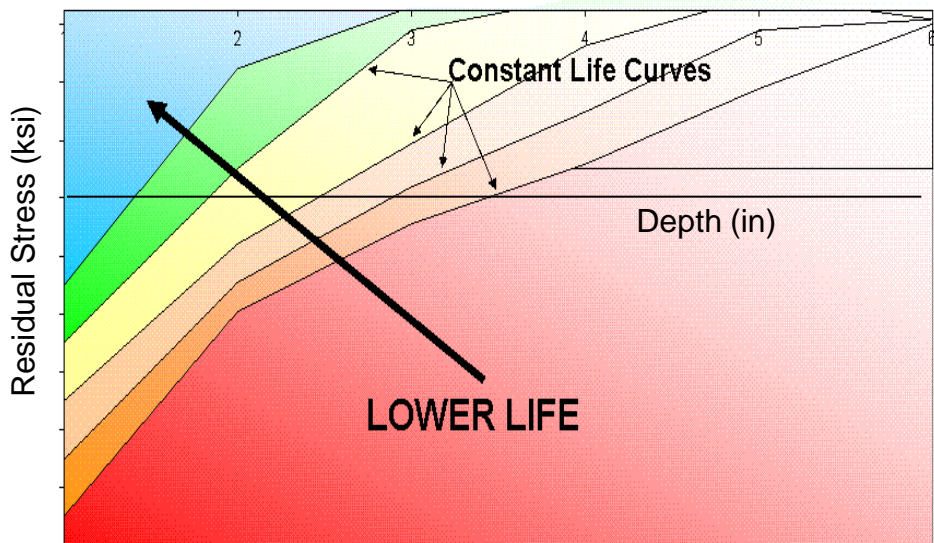
- Use representative structure

- **Define Benefit with Weibull Analysis**

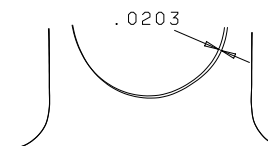
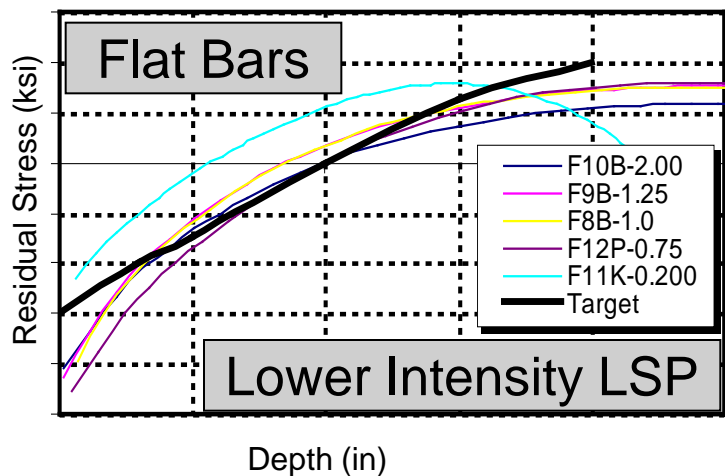
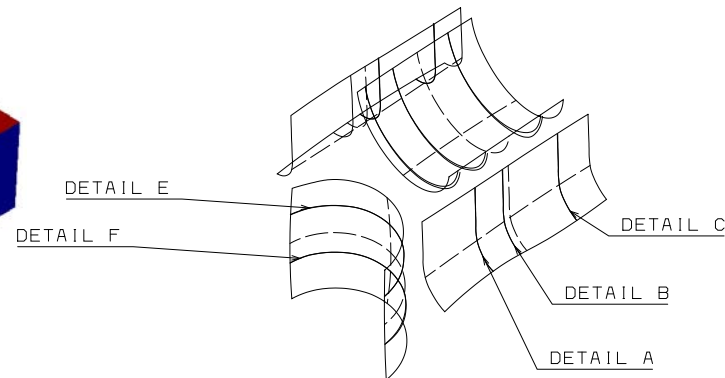
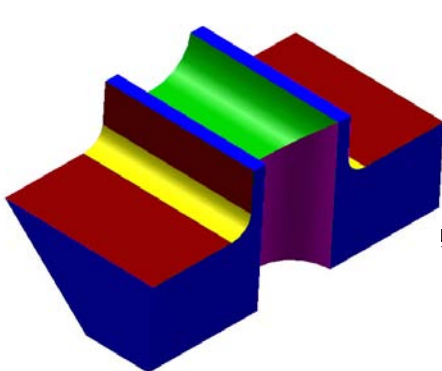
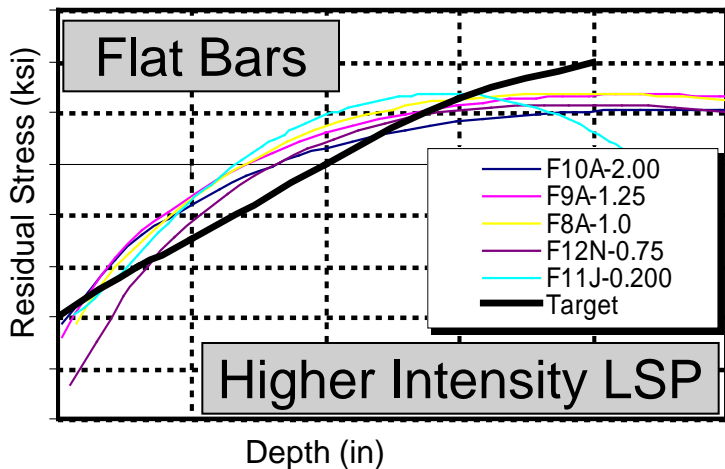


- Only minimal a priori LSP knowledge existed for frame configurations
 - Material: Ti-6Al-4V Beta Anneal
- Utilized a scale-up approach

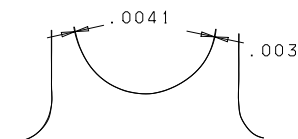




- **RED RS Curve**
 - Shows Lowest life **SUBSURFACE**
- **ORANGE RS Curve**
 - Follows L3 Life Line; constant life near surface
- **GREEN RS Curve**
 - Life increases subsurface
- Select **ORANGE/GREEN RS Curves**

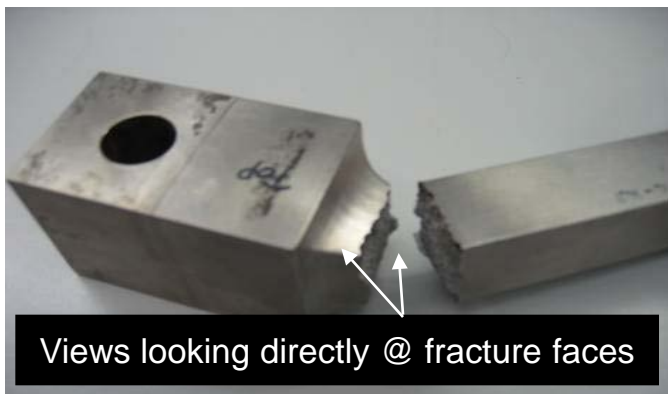


Higher Intensity LSP



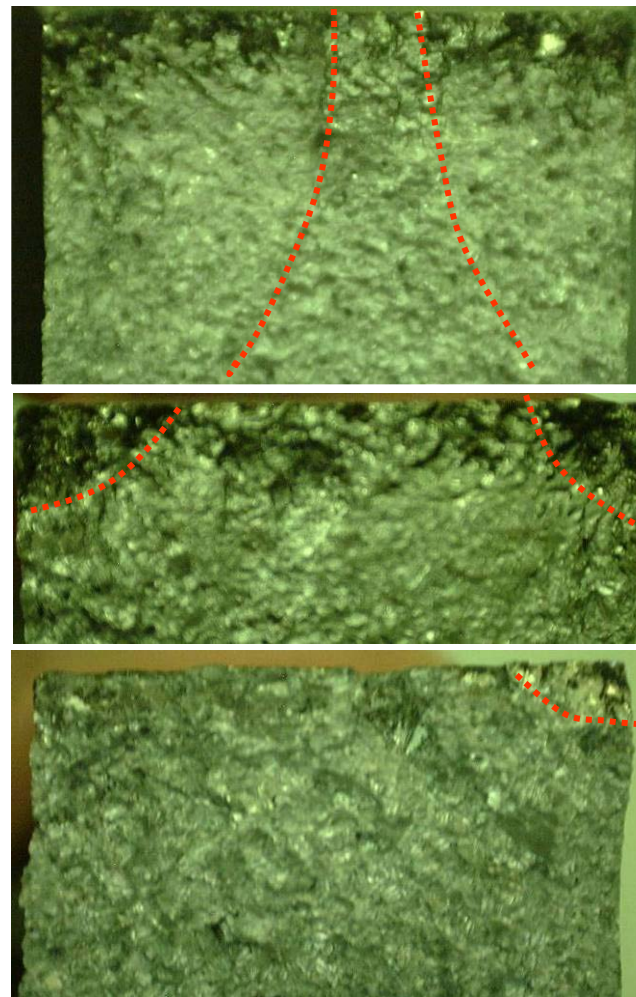
Lower Intensity LSP

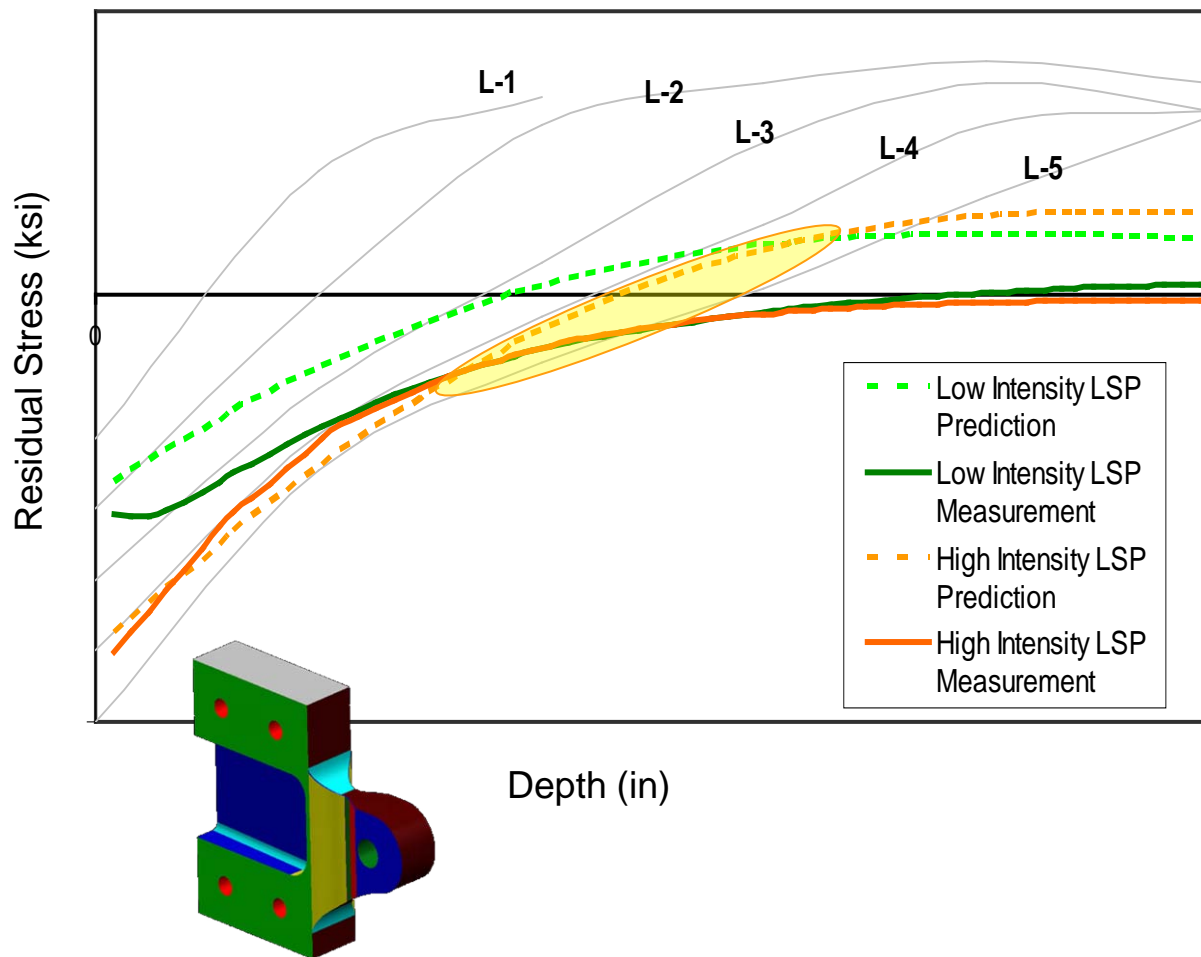
- **Lower Intensity LSP Selected to match the target life curves and minimize distortion**



- **Lower Intensity LSP**
 - Initiations examined at 3 different times in fatigue life
 - **No Subsurface Initiations Found**

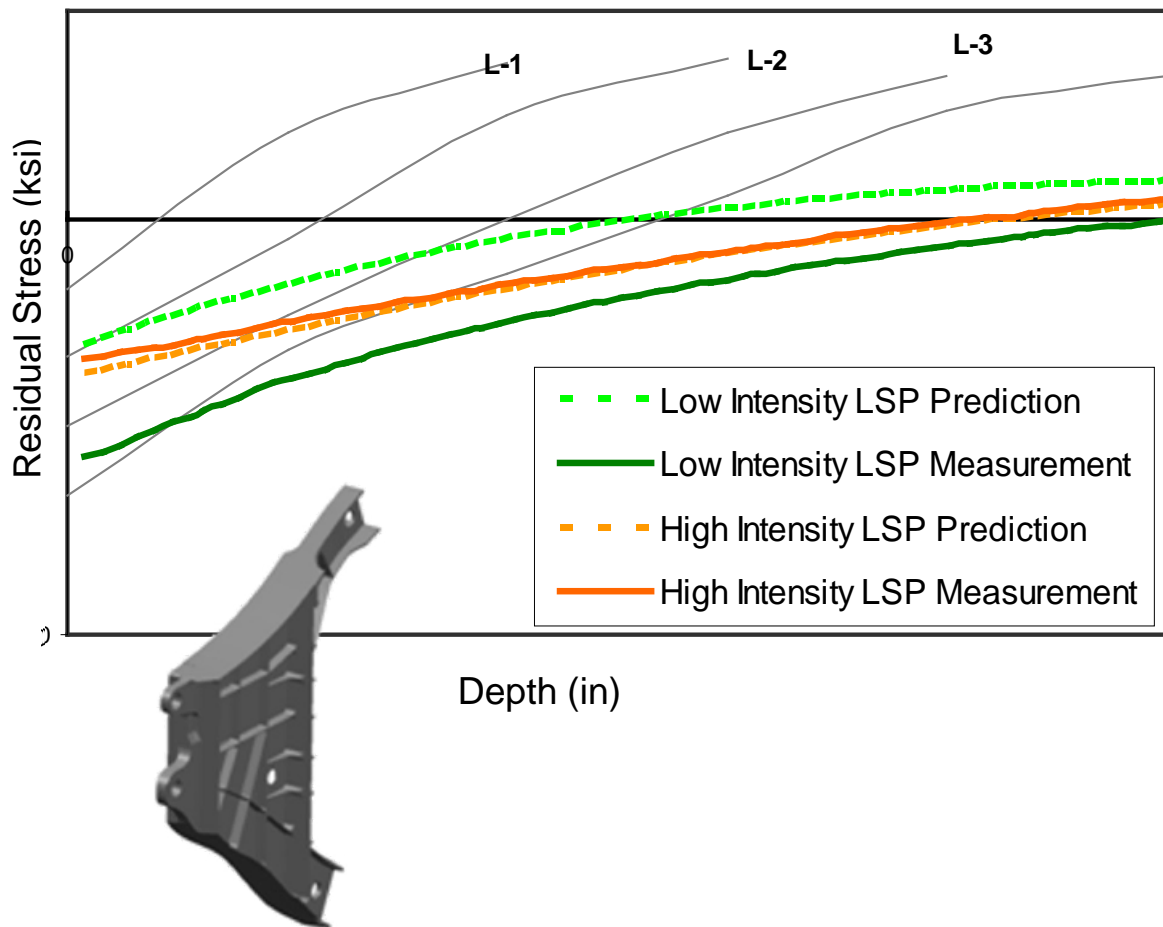
- **Next Steps:**
 - Proceed with Scale-up
 - Predict RS for Lug and Frame





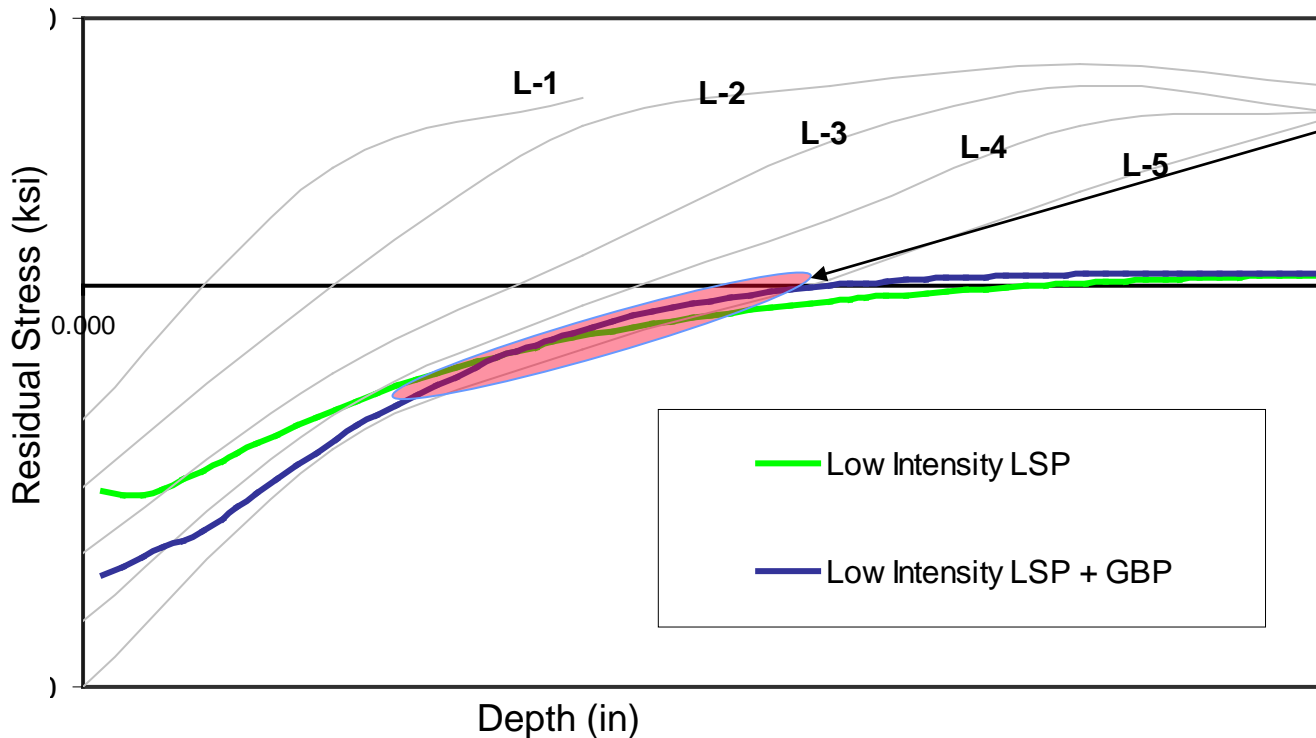
- **Low Intensity LSP**
 - Prediction shows no subsurface potential
 - Measurement shows no subsurface potential

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



- 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

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



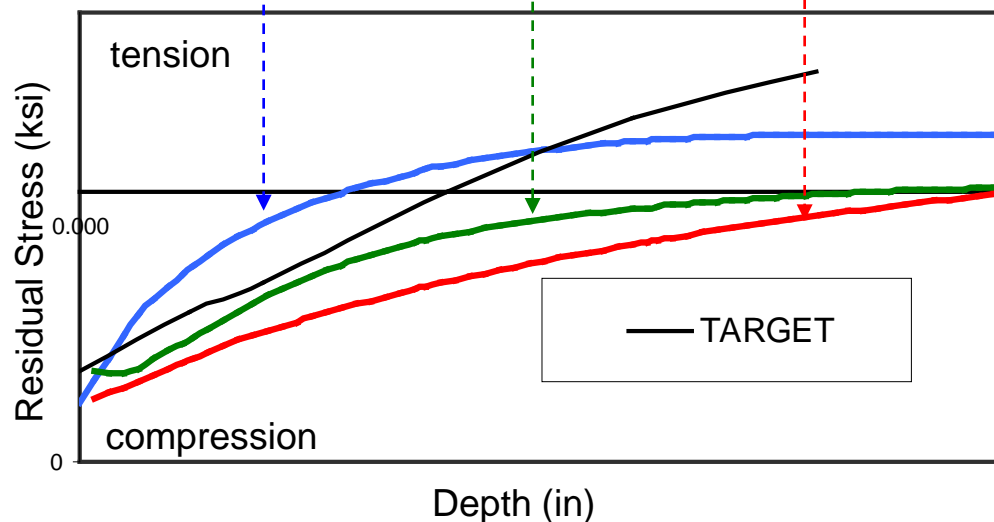
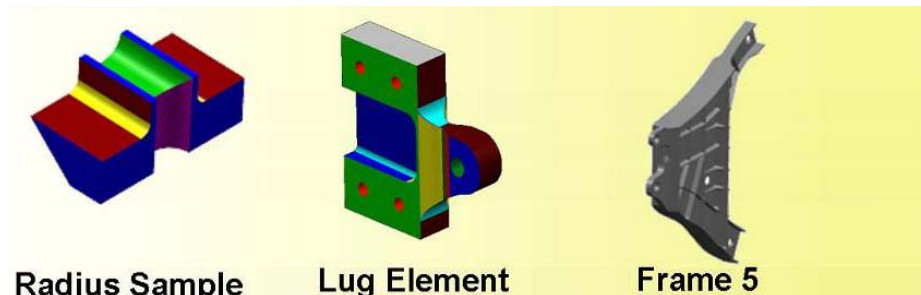
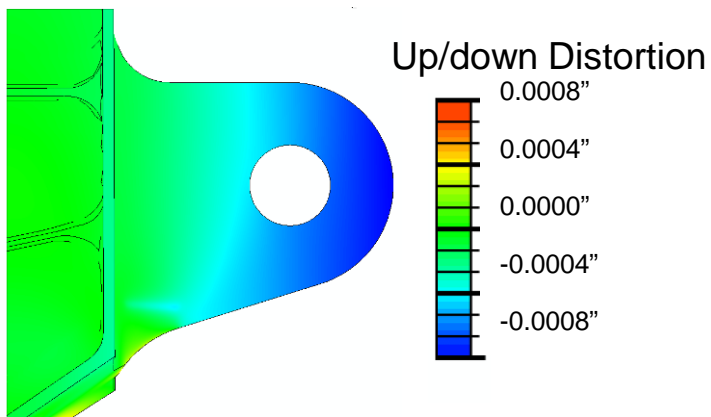
- LSP + GBP has a small subsurface cracking vulnerability

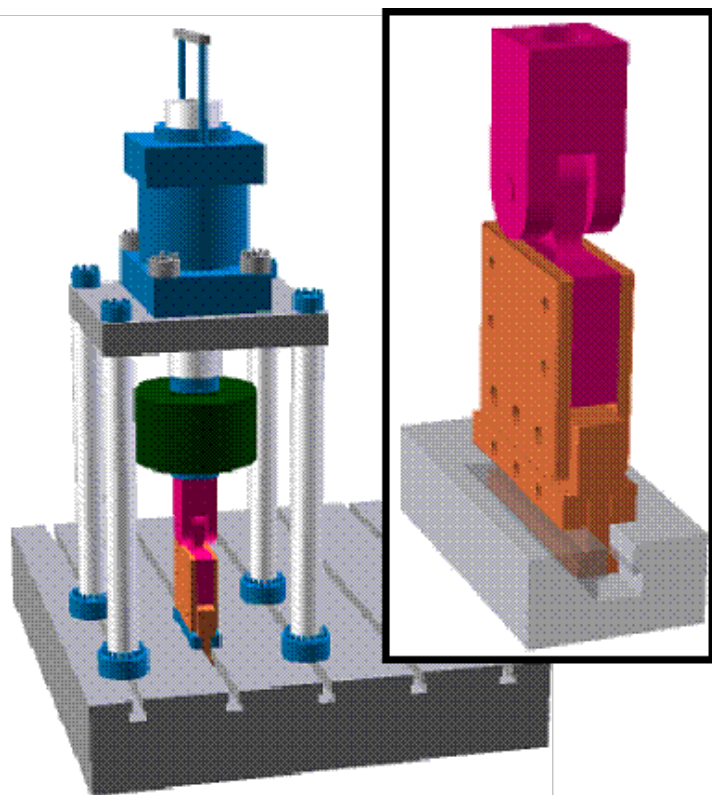
- Low intensity chosen to minimize vulnerability

- Fatigue Tests showed no subsurface cracks

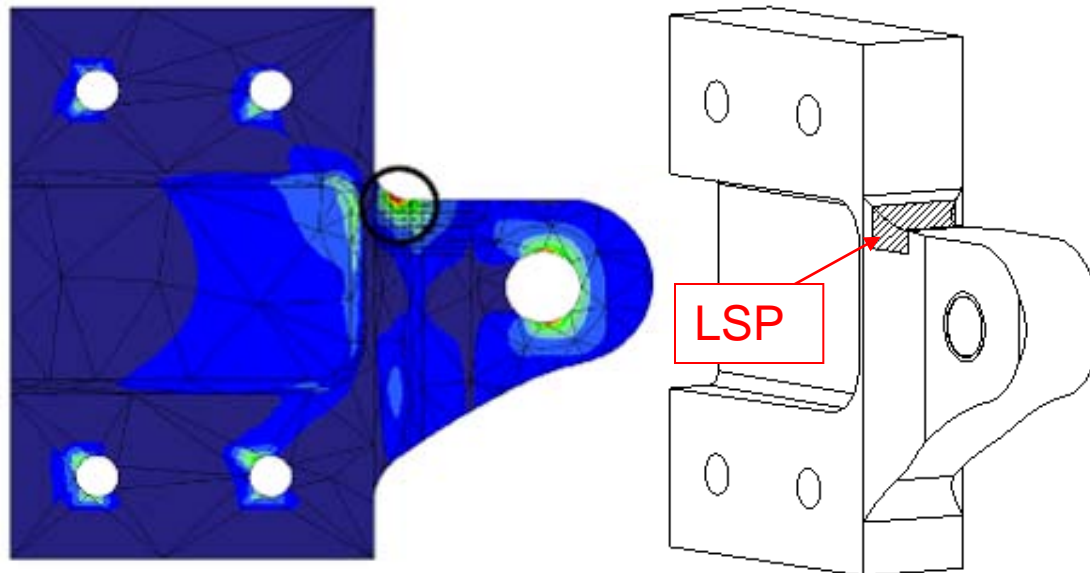
- Increasing geometries (mass & configuration):

- Decreased distortion
- Similar surface compression RS
- Deeper compression RS layer











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



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

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



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

$$\ln(L) = \Lambda = \sum_{i=1}^{F_e} N_i \ln \left[\frac{\beta}{\eta} \left(\frac{T_i}{\eta} \right)^{\beta-1} e^{-\left(\frac{T_i}{\eta} \right)^\beta} \right] - \sum_{i=1}^S N'_i \left(\frac{T'_i}{\eta} \right)^\beta$$

Weibull Maximum Likelihood Function

- Set $\beta=3$ 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 i th time-to-failure data group

β is the Weibull shape parameter

η is the Weibull scale parameter

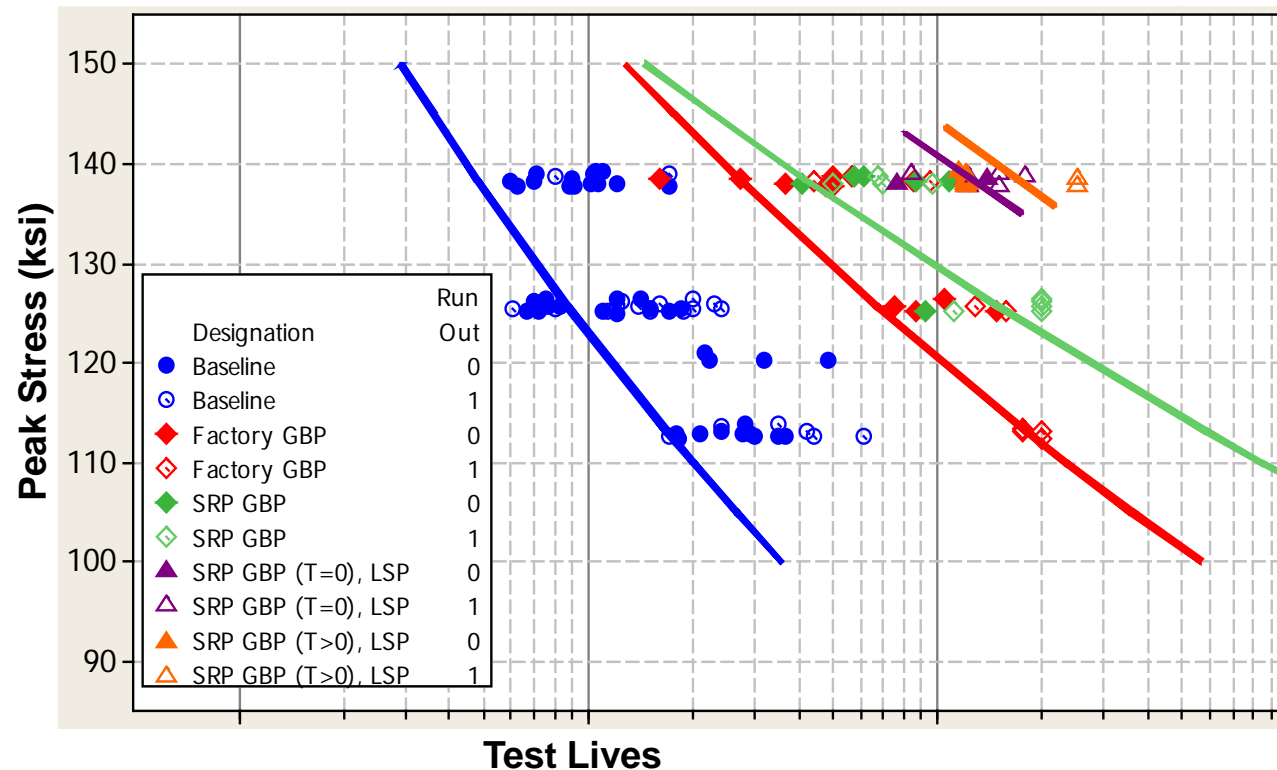
T_i is the time of the i th group of time-to-failure data

S is the number of groups of suspension data points

N'_i is the number of suspensions in i th group of suspension data points

T'_i is the time of the i th suspension data group

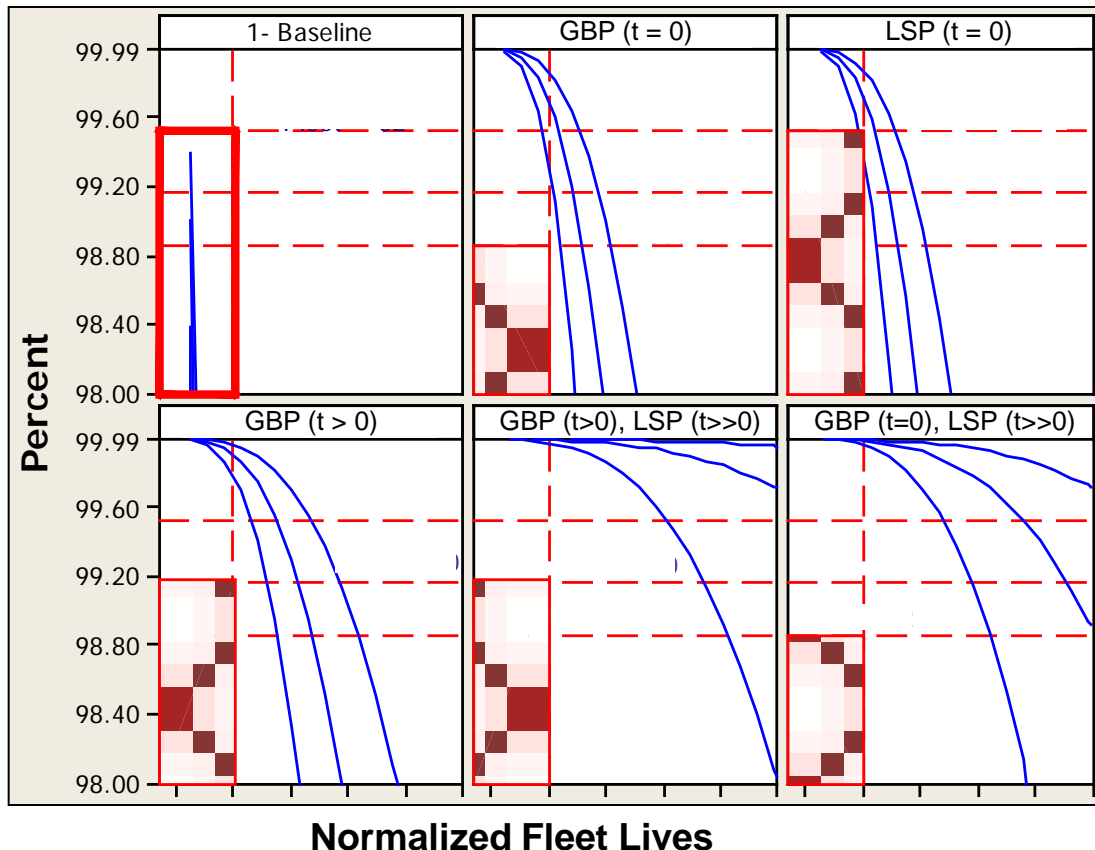
Weibull Analysis Benefit Factors	
GBP (t>0)	9.0
GBP (t=0)	6.1
LSP (t=0)	6.0
LSP over GBP (t>0)	30.2
LSP over GBP (t=0)	19.2



- 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

Parametric Survival Plot



Areas where cracking risk is not met

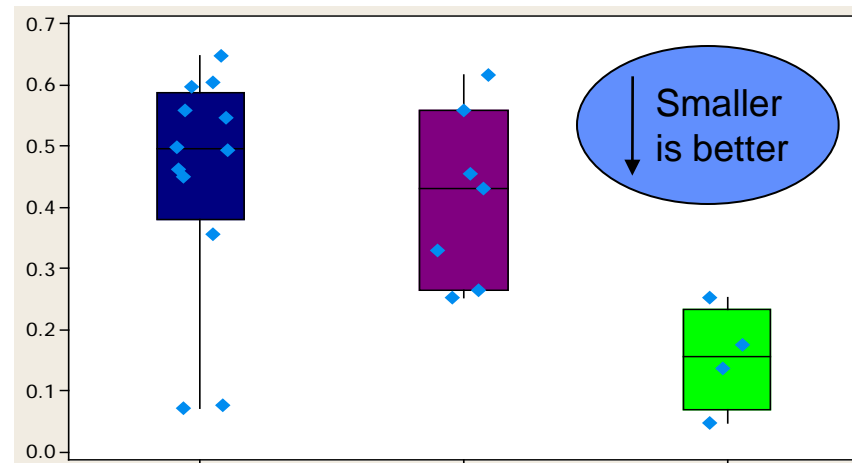
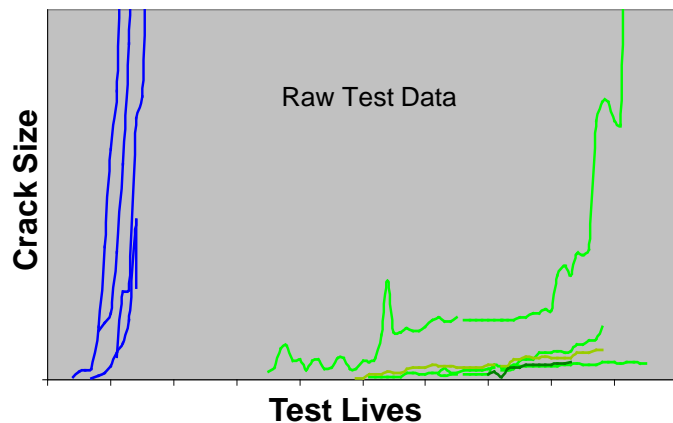
- **Fleet Risk** measures the left tail of a distribution
- **Peening technologies** keep the left tail very small
- **GBP/LSP/GBP+LSP** all improve the fleet reliability by significant factors

Fitted Crack Growth Data



BLUE	–	Basemetal
PURPLE	-	GBP
GREEN	-	LSP

Test Lives



Exponent of Arrhenius Growth Fit (Cracks >0.100")

- **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**

- **478th AESG**



- **Lockheed Martin**



- **Metal Improvement Company**
 - Vernon, CA – Glass Bead Peening
 - Livermore, CA – Laser Shock Peening



- **Hill Engineering, LLC**





F-22
RAPTOR