Understanding the Residual Stress Effect in Damage Tolerance Evaluation of Integral-Stiffened and Friction Stir Welded Panels

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Abstract

Virtually all future air-vehicles have challenging design goals to reduce cost and weight of structure. Structural unitization is receiving intense study to reduce parts count, which in turn leads to simpler assemblies and further cost-saving potential via buy-to fly cost reductions from innovative use of material form and advanced joining methods. Design for lower weight generally translates to higher operating stresses, and for unitized structure this means damage tolerance becomes a key design driver owing to the loss of structural redundancy representing classical built-up design.

Alcoa is responding to these challenges and addressing this shift in design philosophy through ongoing experimental and analytical work to evaluate advanced design/ manufacturing concepts as well as advanced materials. This presentation describes results from one current program investigating integral-stiffened wing and fuselage cover applications for large transport-type aircraft. The primary experimental work focuses on fatigue crack growth and residual strength measurements from large, integral stiffened panels containing a central crack and severed middle stiffener. The test panel dimensions and loadings were selected to be structurally representative of high acreage lower wing skin applications. Several of the concept variants employed integral stiffened extrusions that were friction stir weld joined to form an ultra wide advanced concept panel. These latter tests were particularly enlightening in two important regards: 1) the tests demonstrated advance concept weight saving potential in excess of 20% over current state-of-the-art structure sized by damage tolerance, and 2) the proper accounting of residual stress effects in both test interpretation and predictive modeling is essential to understanding and capturing full benefit of the advanced design approaches. The presentation concludes with a summary of lessons learned.

Outline

- Introduction and Background
  - Brief overview of Alcoa R&D program
  - Alcoa Trade Study Tools
  - Advanced-concepts test panel design and construction
  - Key program test results
- Finite element estimate of friction stir weld residual stress
- Sectioning of panels before residual stress measurements
- Separating and recombining welding effects and extrusion effects
- Implications for stress-intensity factor
- Summary and Conclusions

Long Term Initiative for Lower Wing Skin Panels

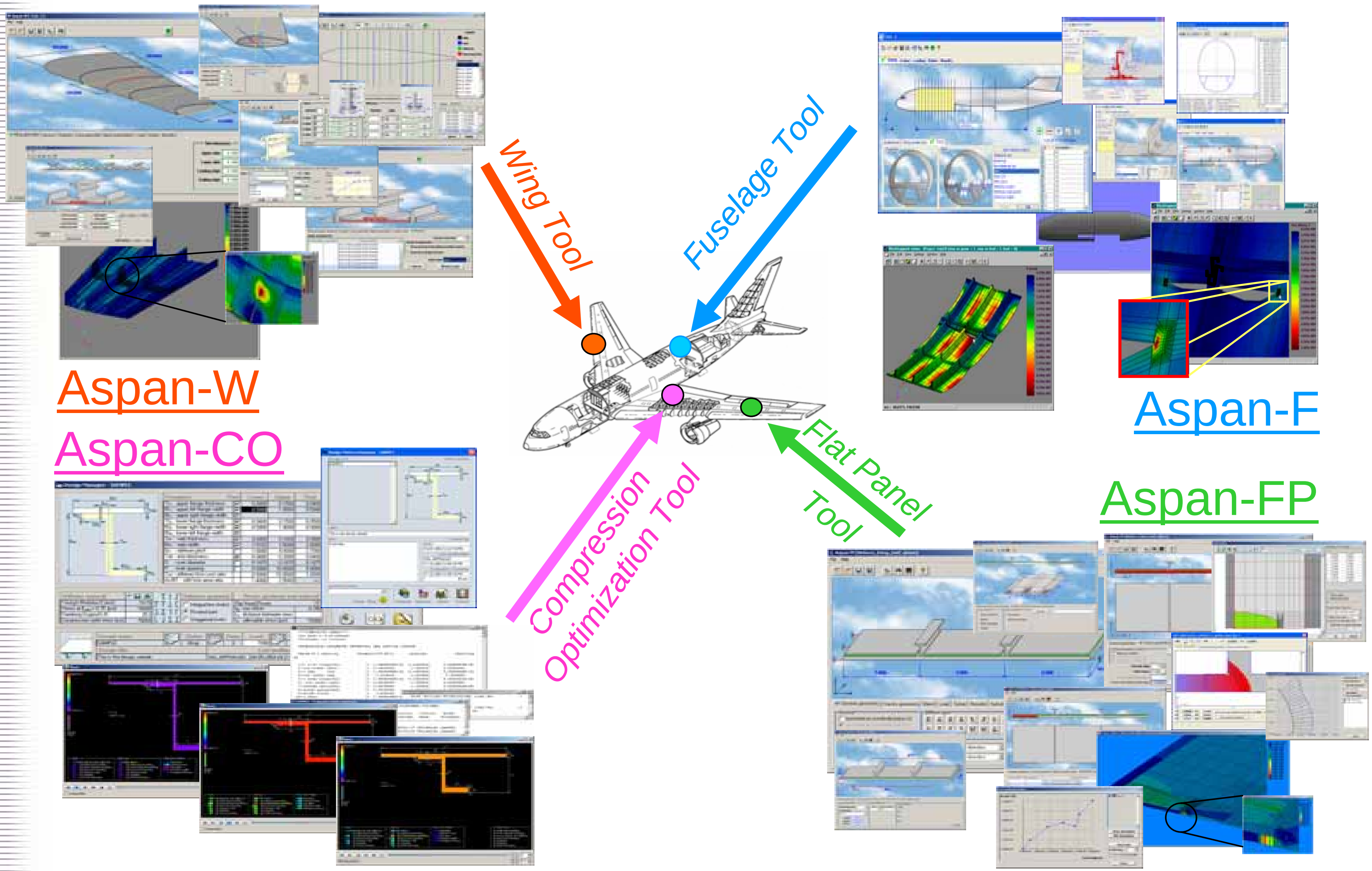
Future metallic aircraft lower wing structure will operate at higher stress to save significant weight over today's structure

- Advanced alloys can meet the static load requirement for these future weight/performance targets
- Advanced alloys alone will likely not meet DA/DT requirements
- Solutions are under development to address these DA/DT deficits

Alcoa has focused it's aerospace R&D to meet these performance requirements for tomorrow's aircraft

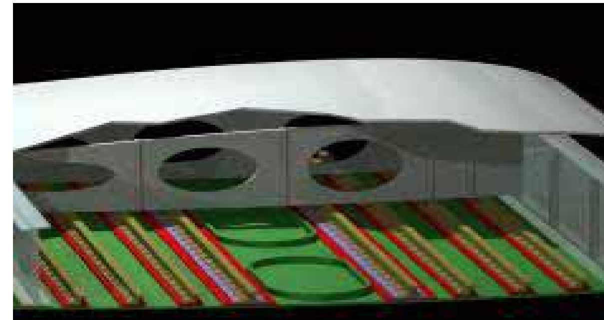
- Strategy goes well beyond incremental alloy/product development improvements
- Strategic focus redefines the performance, cost and value of metallic and hybrid aerostructures

Alcoa Rapid Trade Study Tools Help Identify Benefits of New Materials and New Design Concepts

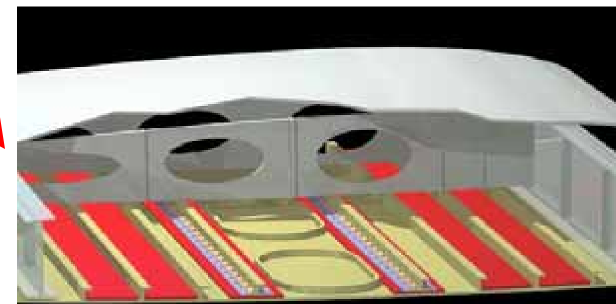


Advanced Materials and Manufacturing Technologies Enable Significant Weight Savings Opportunities for Lower Wing

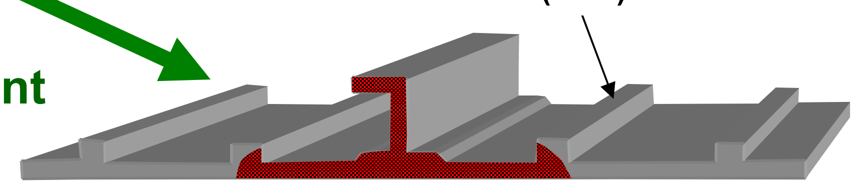
- Selective reinforcement (built-up or integral)
  - Improve fatigue crack growth performance
  - Improve residual strength
  - Improve static strength
- Integrally Stiffened Panels
  - FSW wide extrusions
  - Thick machined plate
- Damage containment features
  - For built-up panels
  - For integral panels
  - With and without reinforcement straps



Built-up Structure with Reinforcement



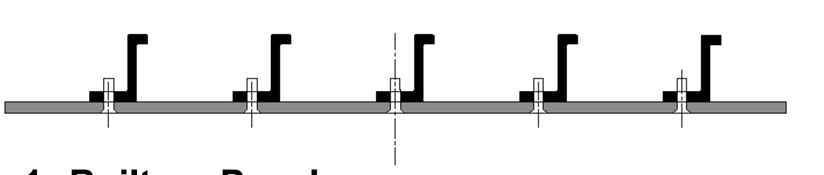
Integral Structure with Reinforcement



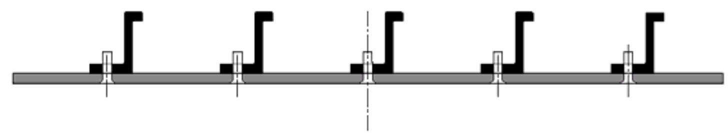
Each feature slows crack growth

Selected Lower Wing Concepts

Baseline Concepts

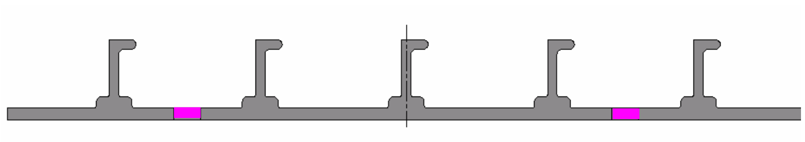


1. **Built-up Panel**
   Plate: C433-T351
   Extruded stringer: 2026-T3511



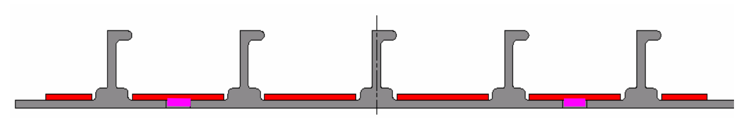
2. **Built-up Panel**
   Plate: C433-T39
   Extruded stringer: 2224-T3511

Advanced Integral and Hybrid Concepts



7. **Extruded Panel**
   Friction Stir Welded Two Places

   Extruded Material: 2XXX Al-Li Alloy



8. **Extruded Panel**
   Friction Stir Welded Two Places
   With Reinforcement Straps
   Extruded Material: 2XXX Al-Li Alloy

Large Panel Concept Validation Program

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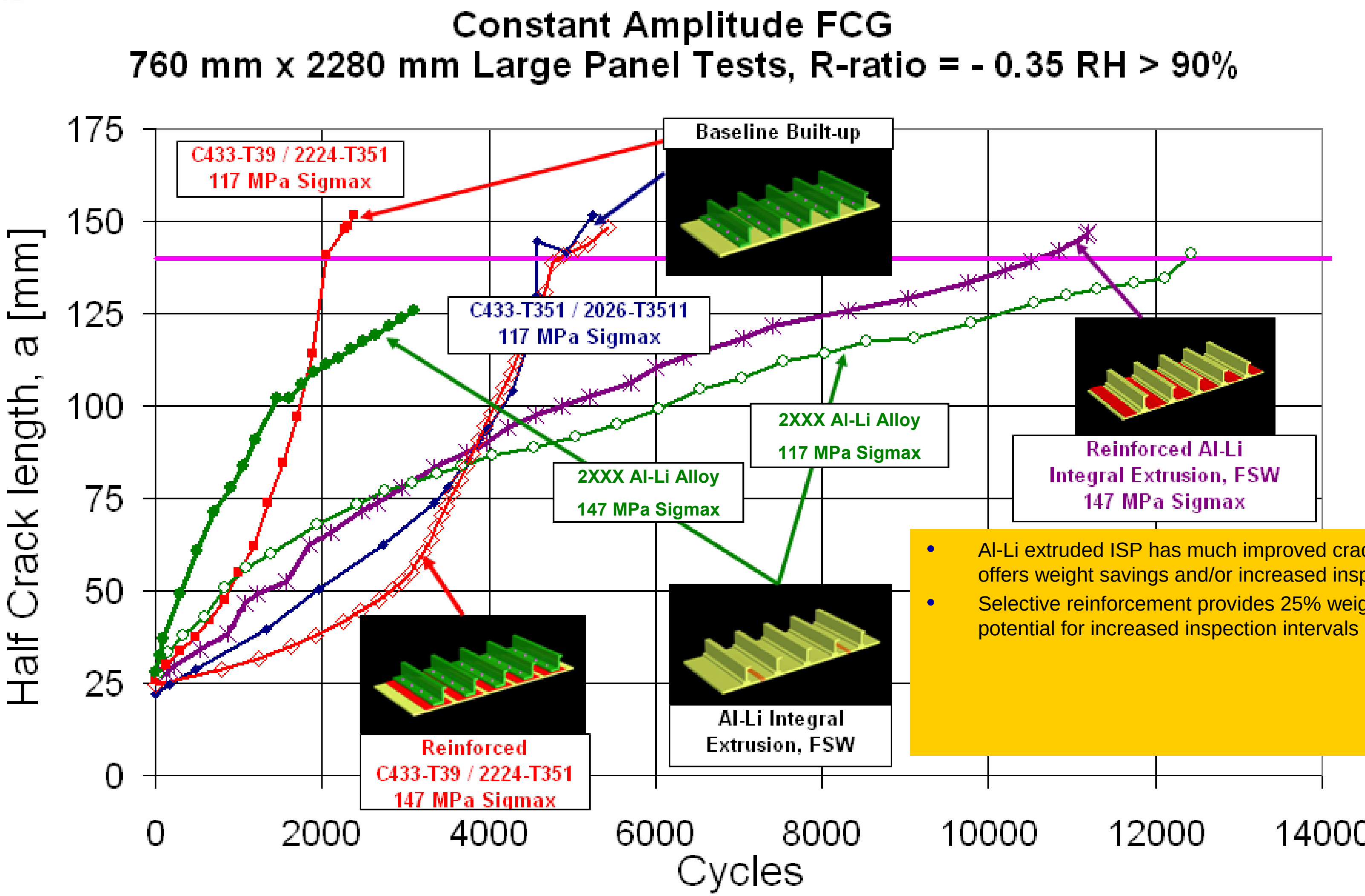
Test Conditions and Loading

- Large stiffened panels (762 mm x 2286 mm).
  - 5 stringers (5.5 inch spacing)
  - Representative of wing lower covers
  - 2a initial = 2.0 inches
  - broken stiffener
- Constant amplitude loading
  - Baseline stress
  - +25% stress
- Mini-twist wing spectrum loading
  - Baseline stress
  - +25% stress
- High humidity air
- Panels also tested for residual strength

Vought Aircraft selected as testing vendor
Prototype Panel being Loaded into the Testing Frame

Large 30" x 90" Panel Constant Amplitude Test Results

Baseline σ_{max}=17ksi, σ_{mean}=12ksi, σ_{min}=-6ksi

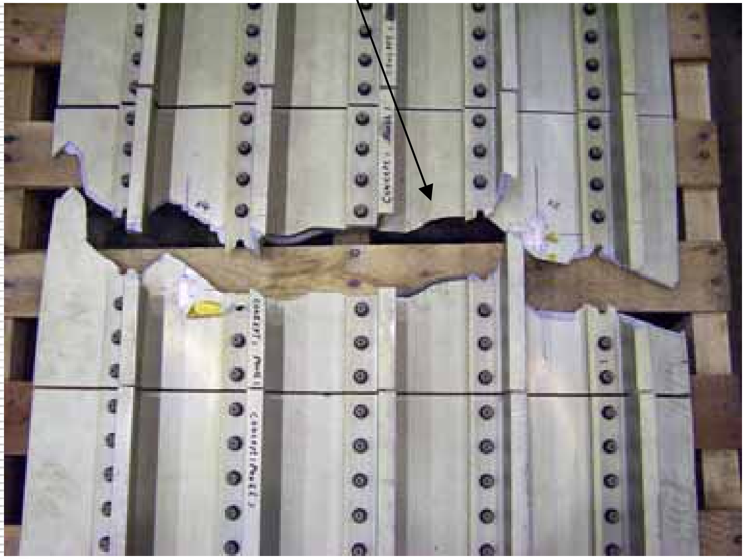


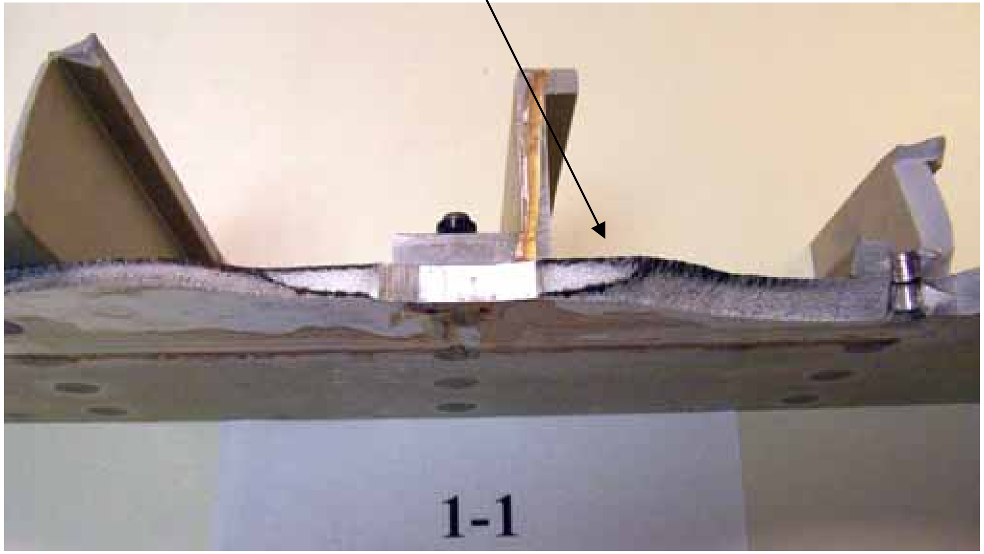
- Al-Li extruded ISP has much improved crack growth life – offers weight savings and/or increased inspection interval
- Selective reinforcement provides 25% weight savings plus potential for increased inspection intervals

C433-T351/2026-T3511 Fractured Test Panel
Constant Amplitude Loading

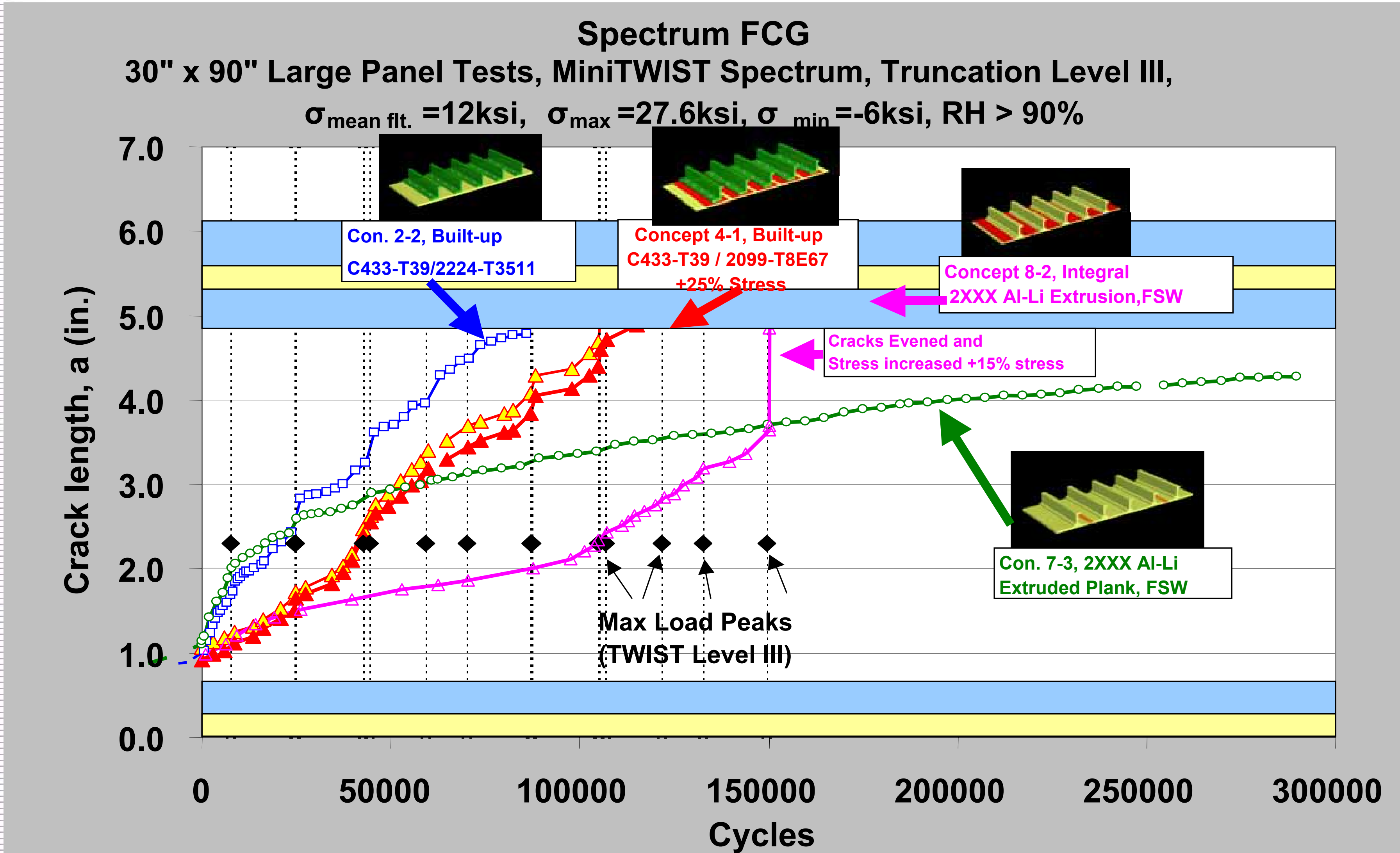
Complex failure characteristics

Crack transitioned to slant fracture early in test





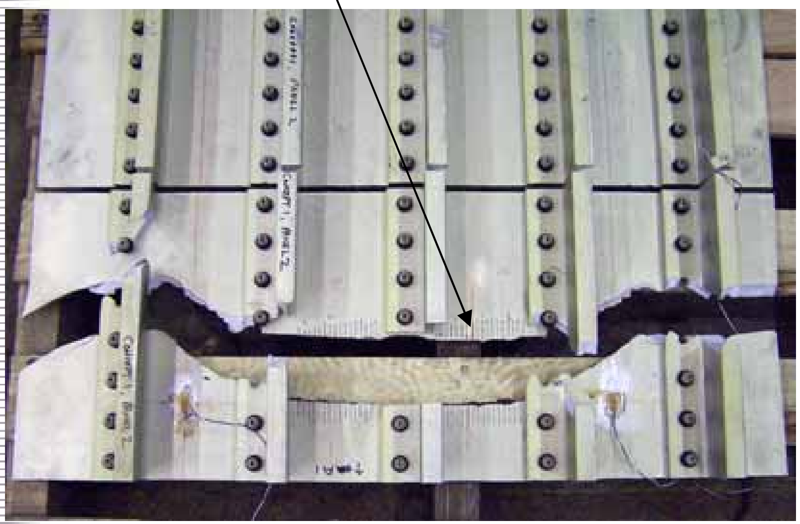
Large 30" x 90" Panel Mini-Twist Test Results

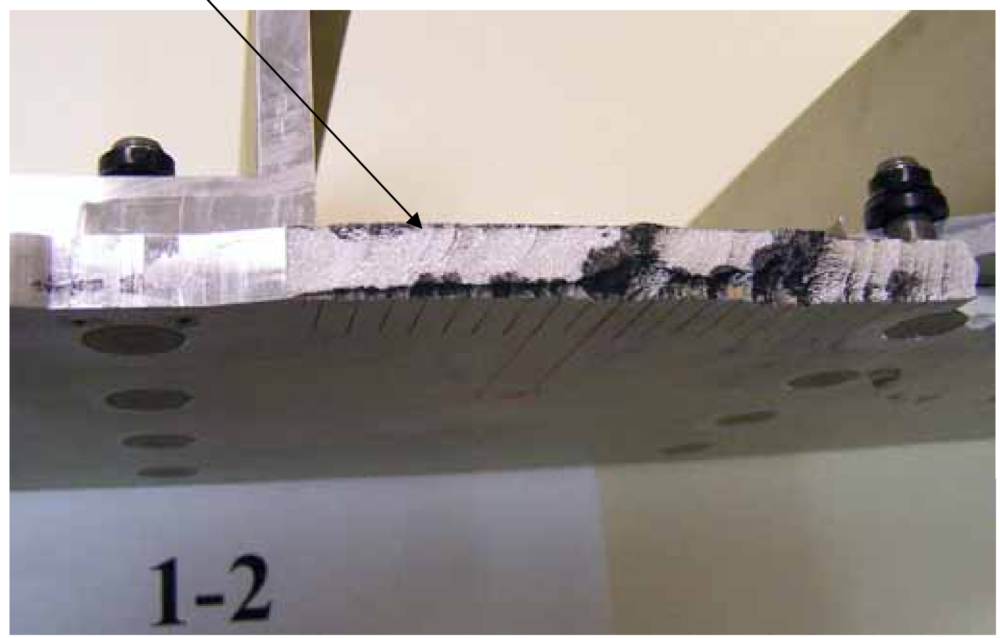


C433-T351/2026-T3511 Fractured Test Panel – Mini-Twist Loading

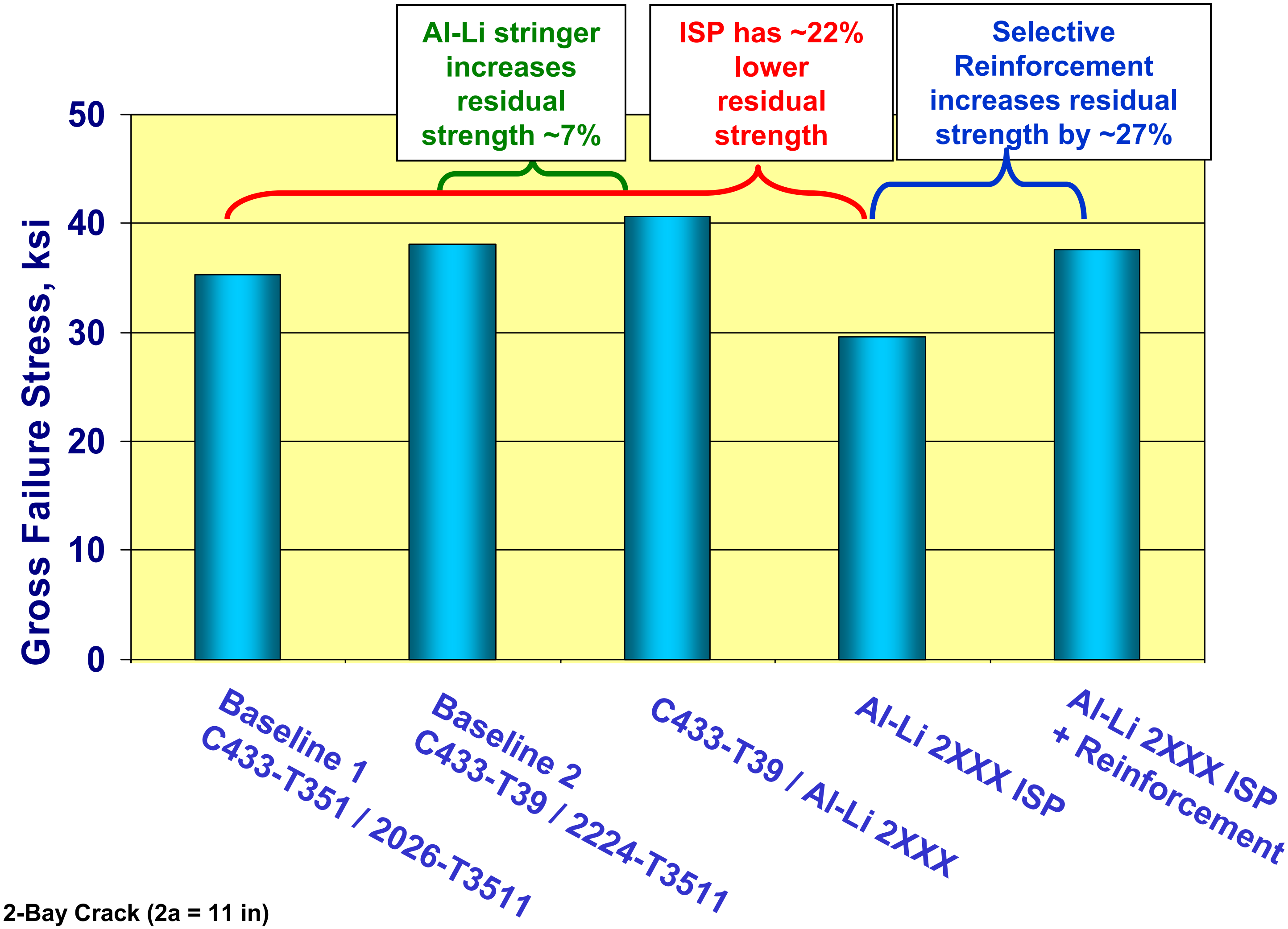
- Crack remained in plane
- Curved crack growth front indicative of bending in panel

- Crack remained straight





Residual Strength Test Results: Selective Reinforcement Restores Residual Strength to Baseline Levels



Note: 2-Bay Crack (2a = 11 in)
finite width
20% FML

Brief Summary before Continuing

- Baseline ISP has fantastic performance relative to state of the art built-up solutions (greater than 6x CA improvement, much greater than 3x spectrum improvement)
- Advanced stress level ISP (+25%) had 1.5x life improvement over built-up
- Selective reinforcement restores residual strength for ISP (residual strength loss for integral panels is well known)

⇒Reduced weight and/or longer inspection intervals

Residual Stress Modeling and Measurements

Eigen Strain Approach to Estimate Residual Stress due to Friction Stir Welds

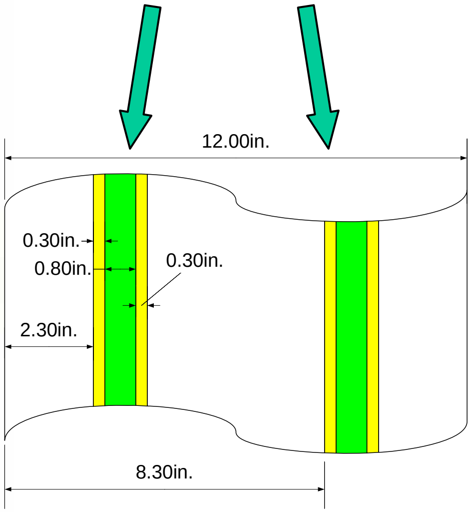
- **Calibrate the model:**
  - Use measured residual stress levels from a 12in wide FSW panel containing two longitudinal welds
  - Assume strains around the welds can be approximated by temperature change and coefficient of thermal expansion ($\alpha \bullet \Delta T$)
  - Apply temperature gradient (eigen strain) to weld regions and solve for equilibrium
  - Scale the results to match the measured residual stress field

- **Apply the model:**
  - Use the same temperature gradient and material properties to predict Concept 7 panel FEM results

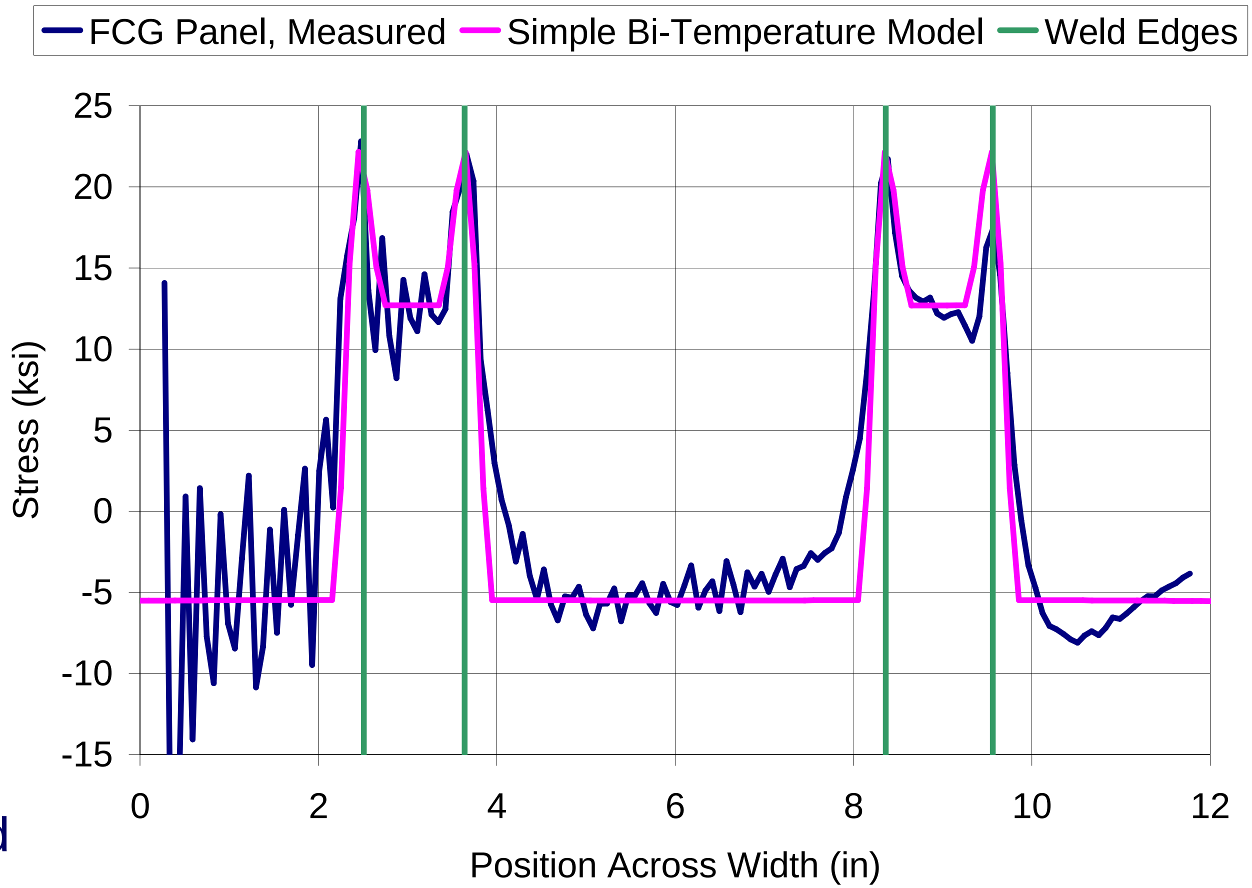
- **Limitations:**
  - Does not include local strength variations from extrusion process

Calibrated Model Matches Measured Results for 12in Wide FSW Panel

FSW Locations

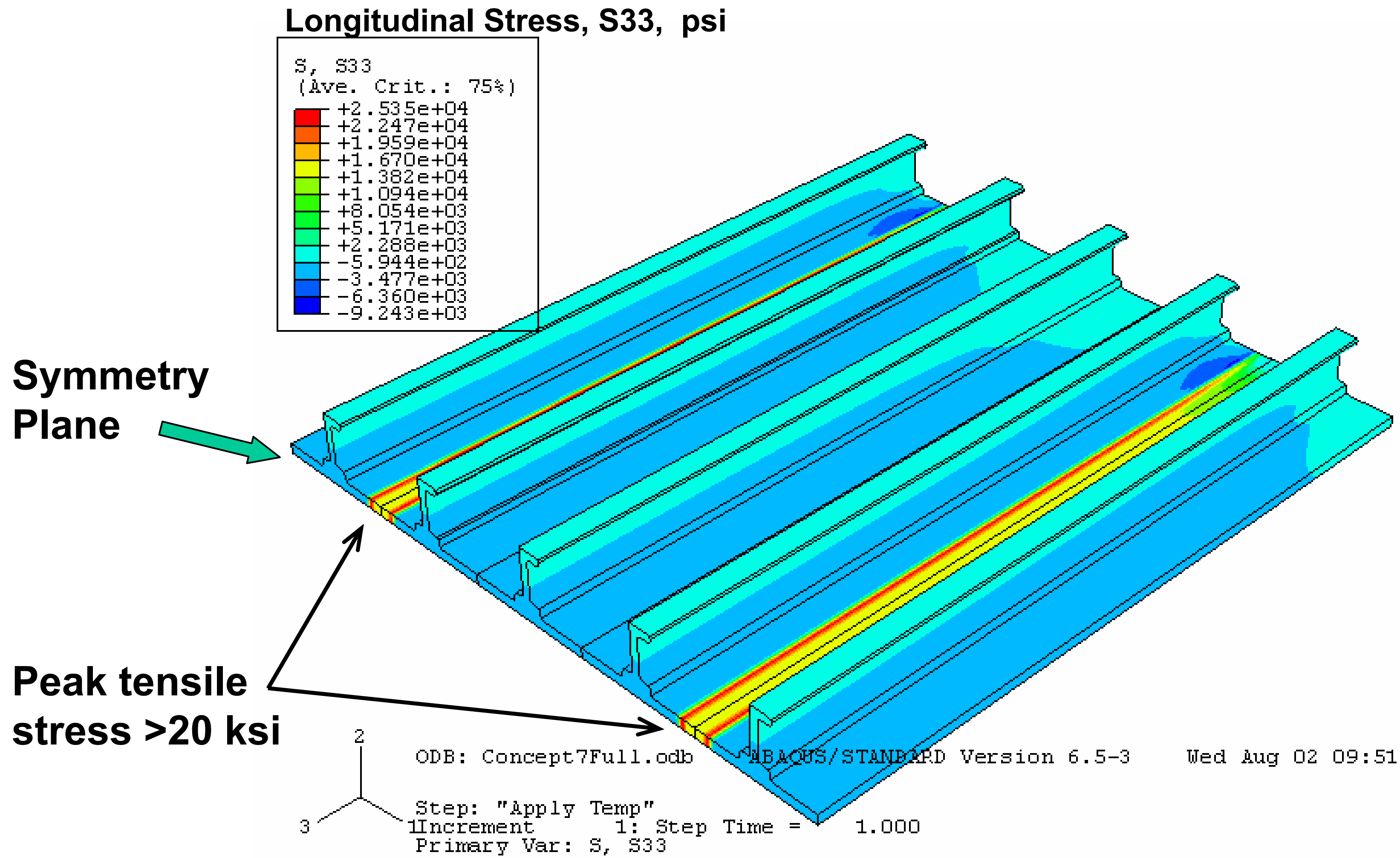


Bi-Temperature Eigenstrain Model (Yellow regions cooled to -190F, Green regions cooled to -125F)



Measured vs. Predicted Residual Stress

Calibrated Thermal Model Applied to Concept 7 Welded ISP Panel Indicates Similar Response to Small Panel



Line Plots of Predicted Residual Stresses for Small and Large Panels

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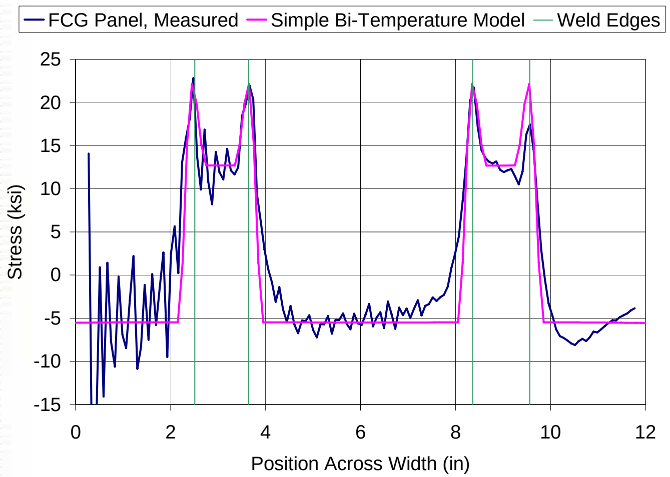
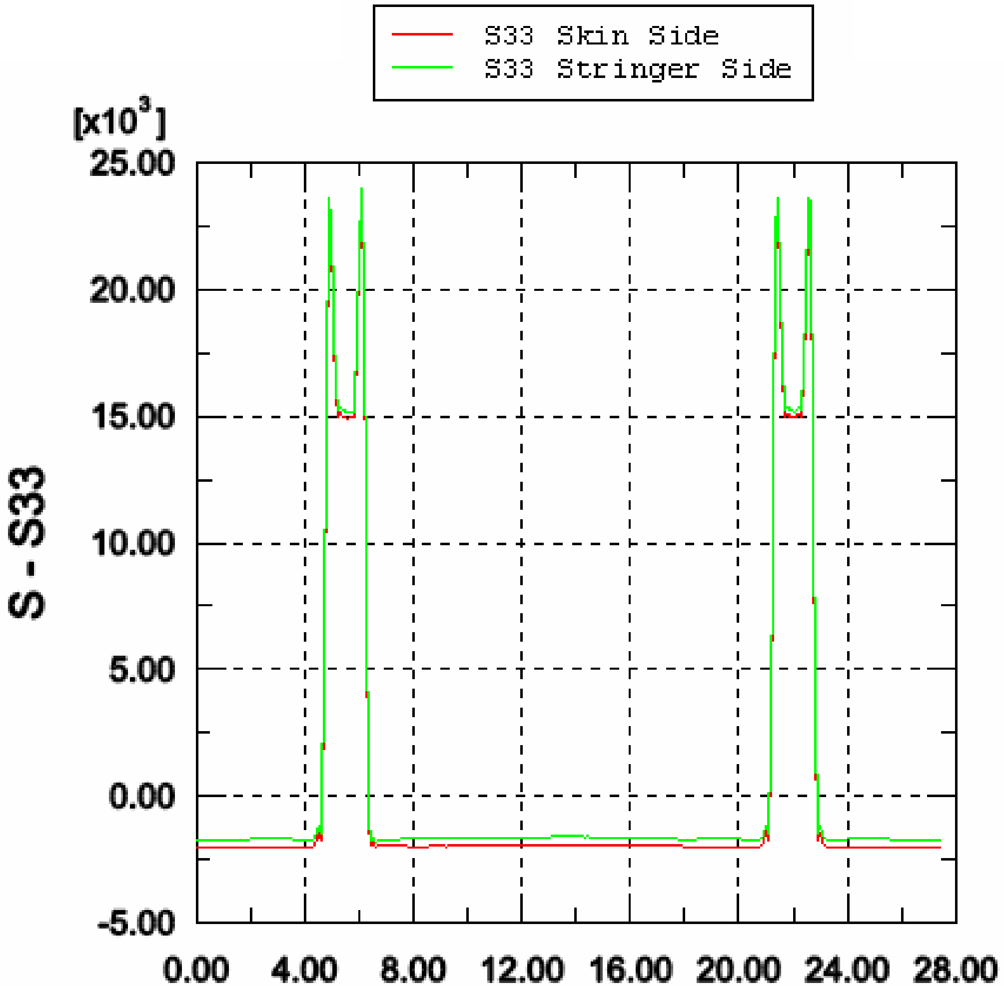
Small Panel Results



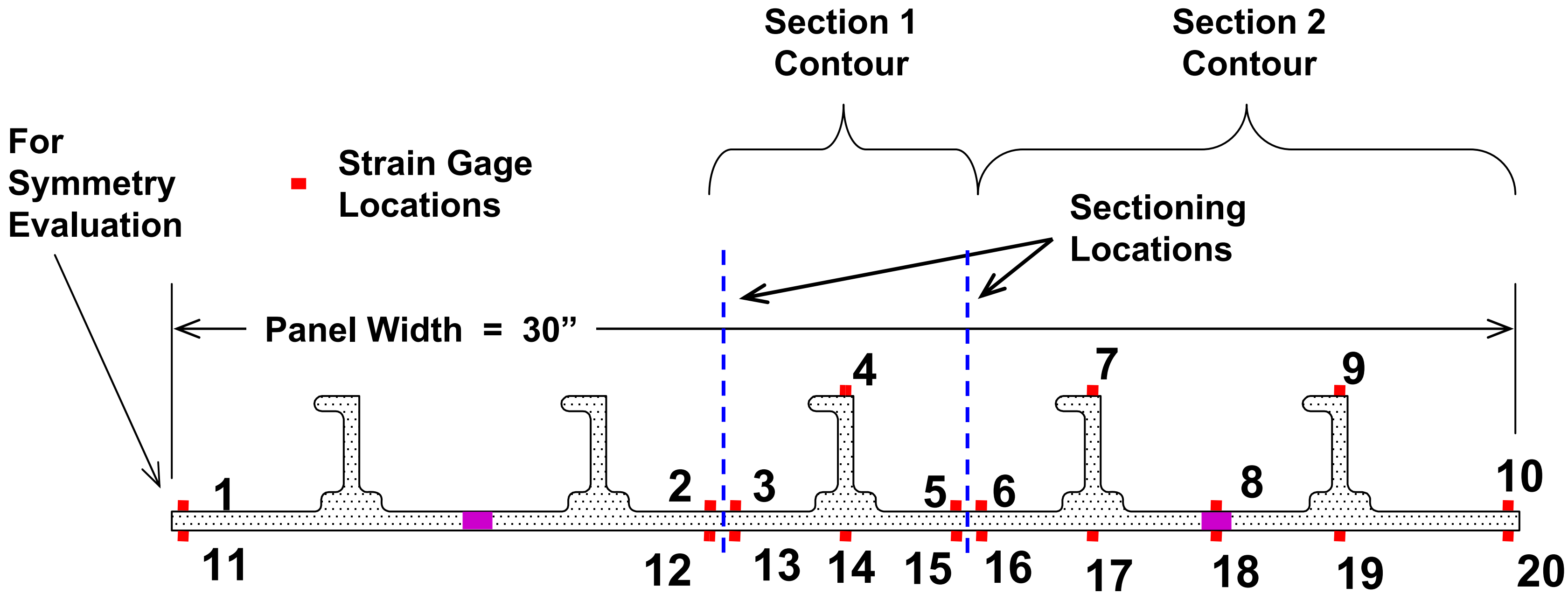
- Peak tensile stresses are similar in both panels
- Compressive stresses are lower (magnitude) in wider panel
- Slightly higher compressive stress on skin side

Concept 7 Large Panel Results

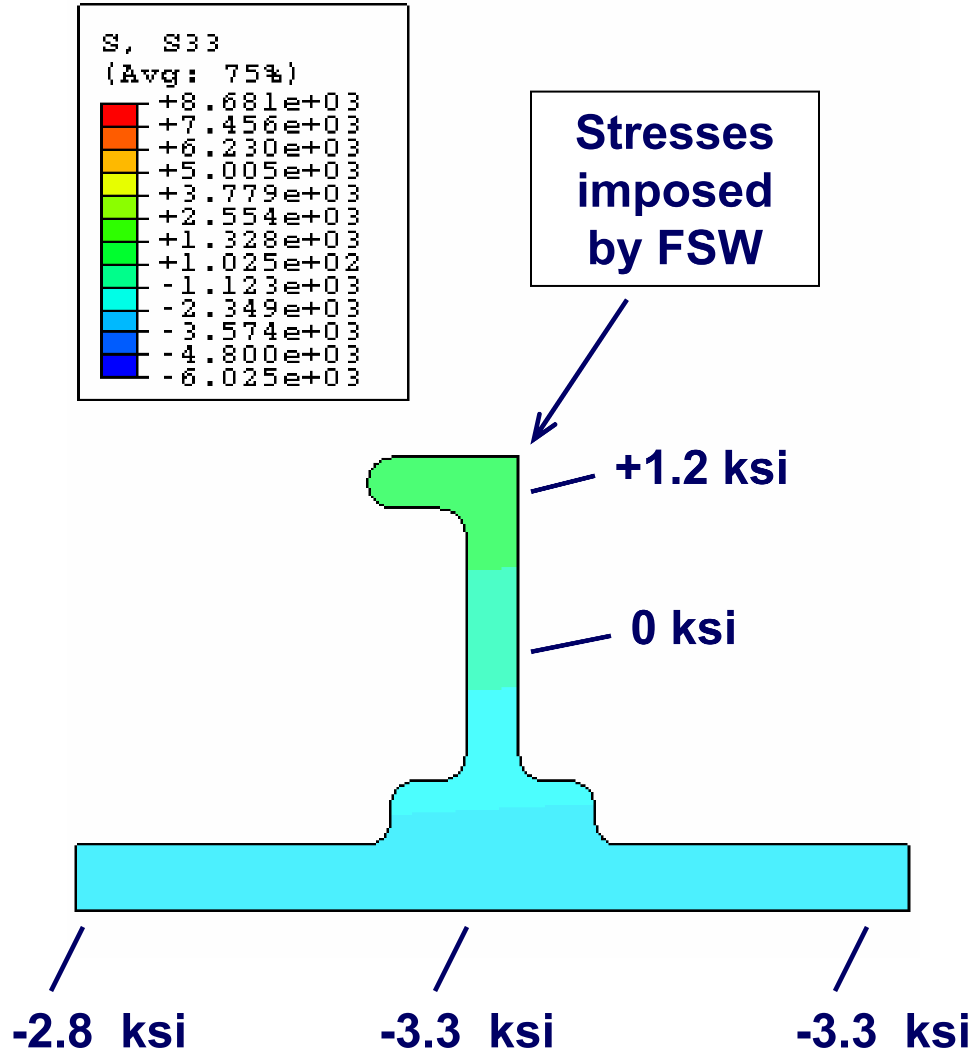


Sectioning Approach for Residual Stress Measurements

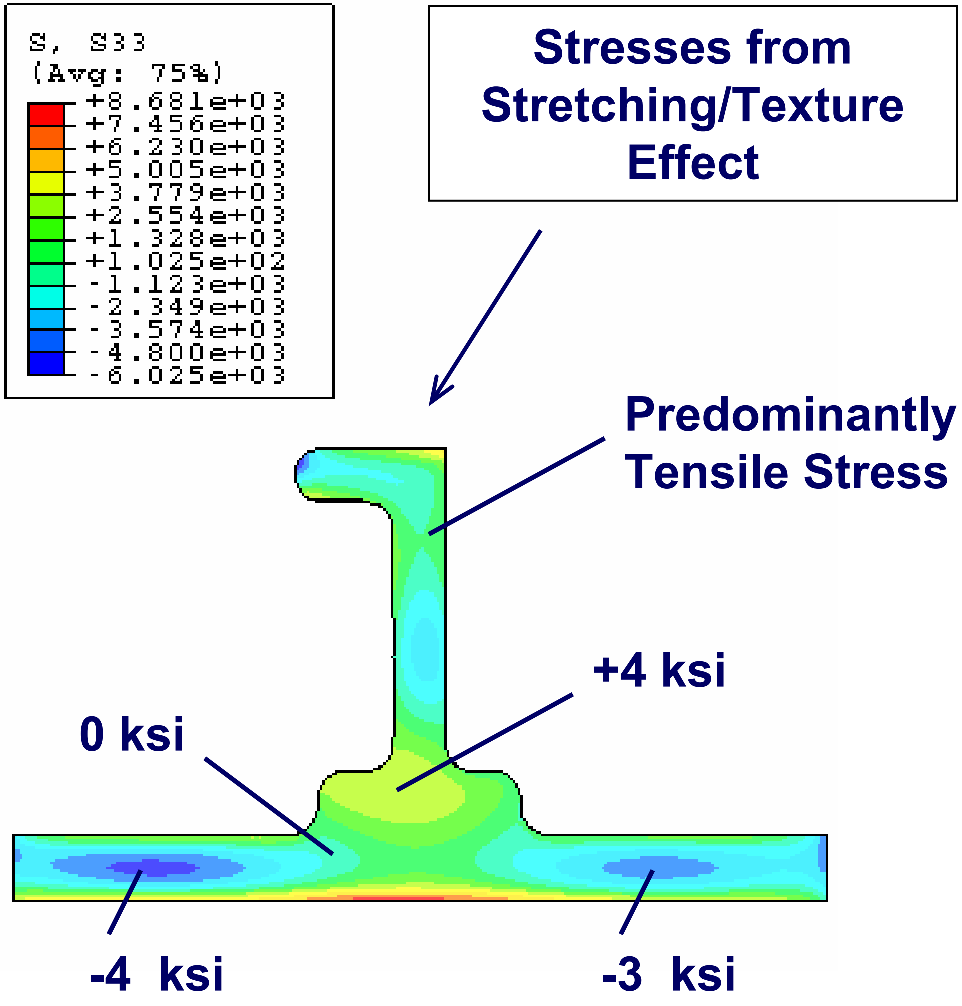
- Sectioning necessary to characterize full panel width (unable to measure residual stress for full width panel)
- Mount strain gages and section the panel into three longitudinal strips
- Measure the change in strain due to sectioning
- Calculate the stress change due to sectioning
- Conduct contour method residual stress measurement on sectioned strips
- Reconstruct total residual stress state using strain gage data and contour method results



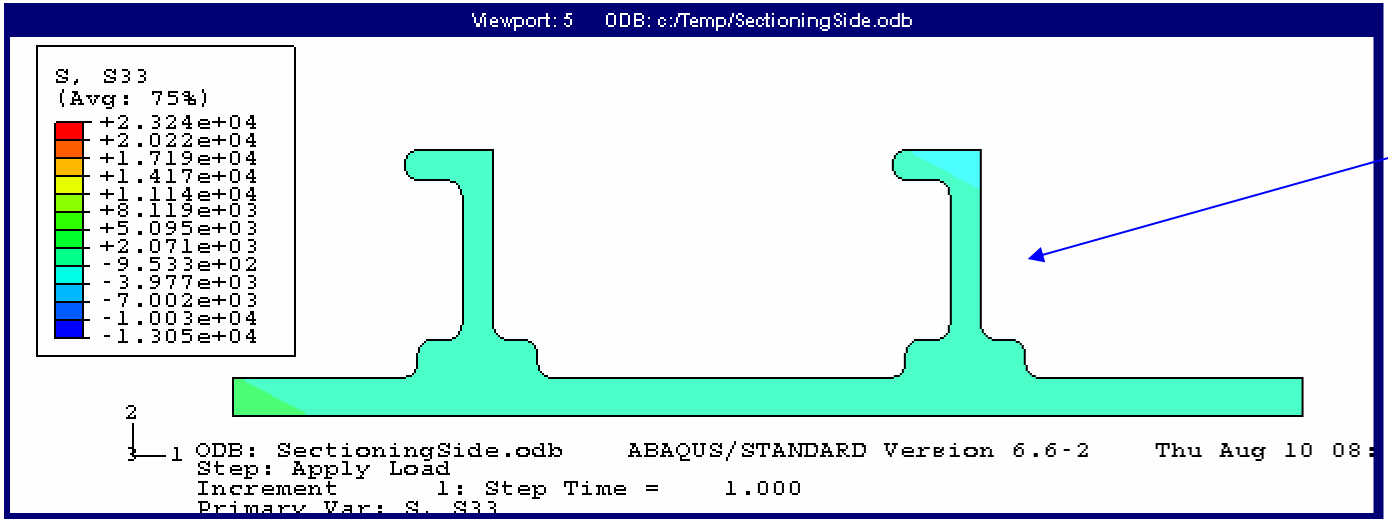
Stress Determined by Sectioning (from strain gages) agree with FEA Eigen Strain Model of FSW



Contour Method Results on Section 1 Agree with Expected Results from Previous Strength Measurements

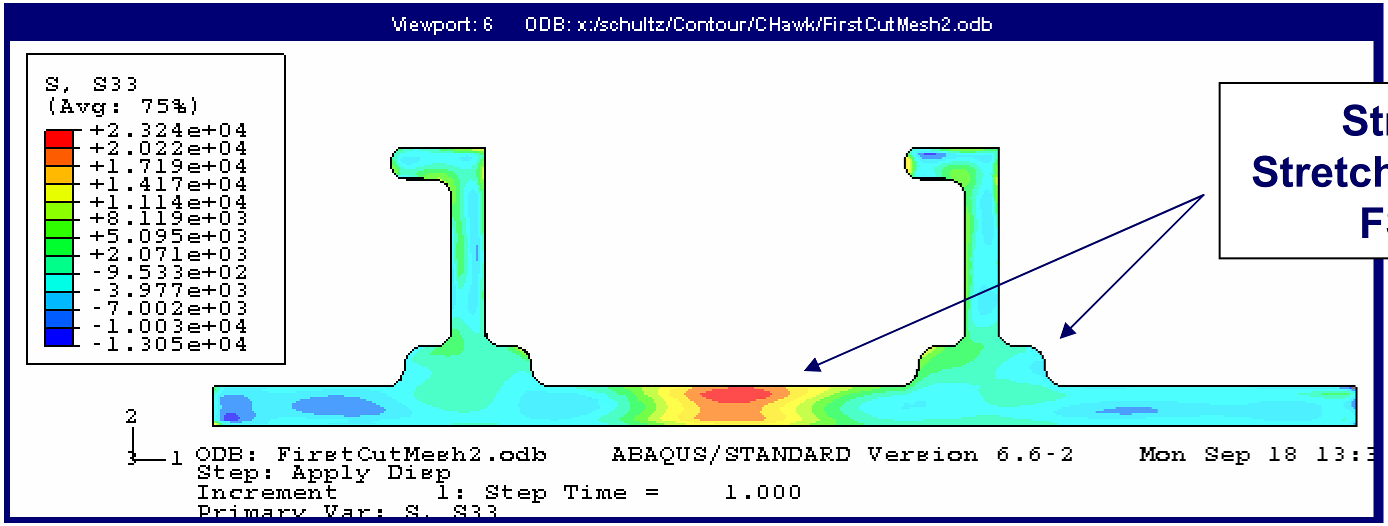


Stress Determined (on Section 2) by Sectioning (top) and Post Sectioning Contour (bottom)



Stresses imposed by middle section

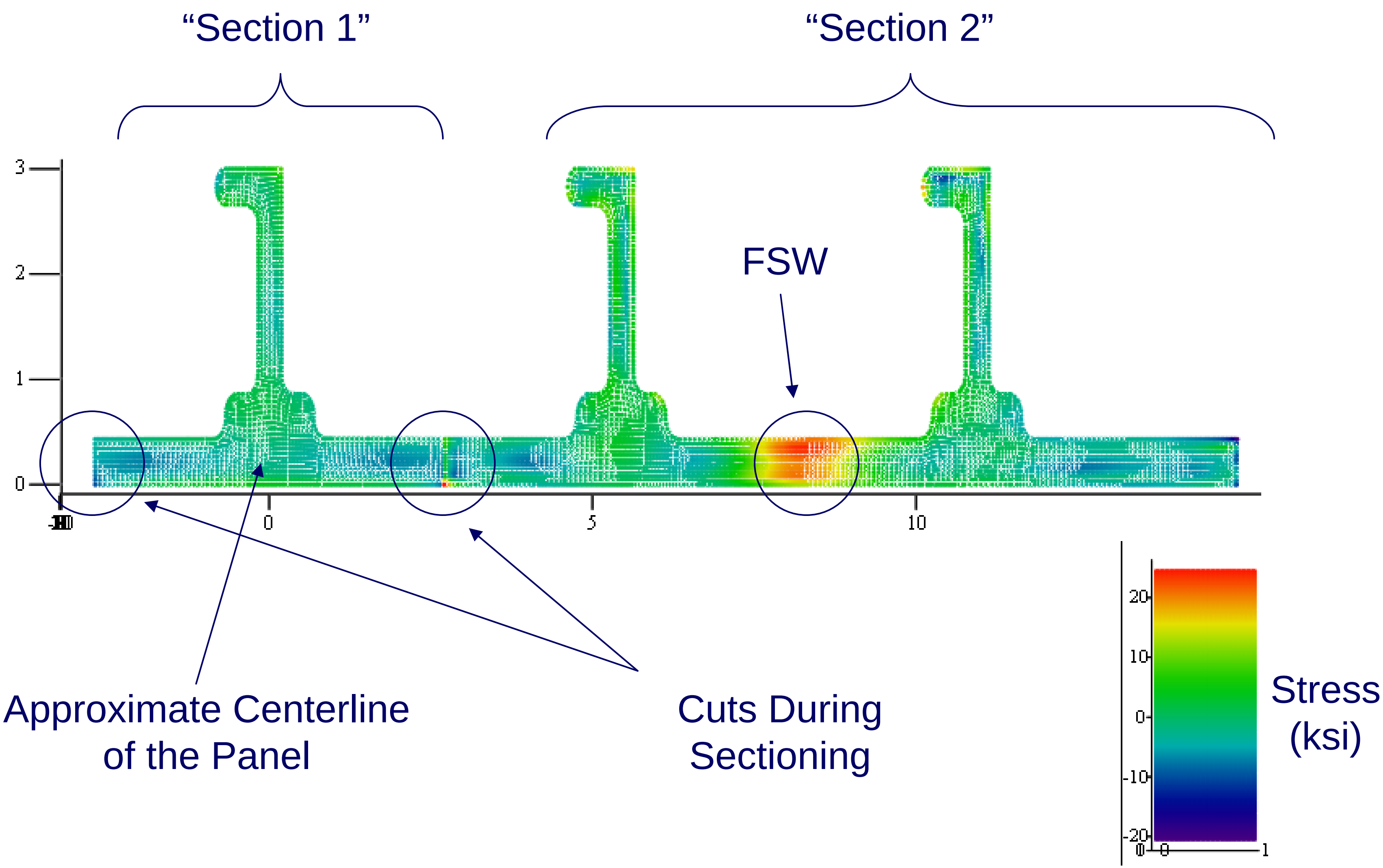
Contour Method Results on Section 2 Agree with Expected Results from FEA Eigen Strain Analysis



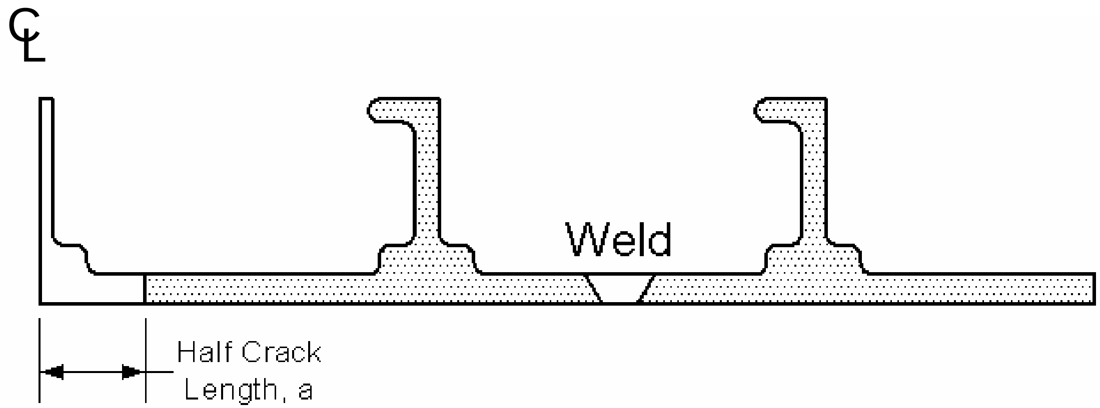
Stresses from Stretching/Texture and FSW Effects

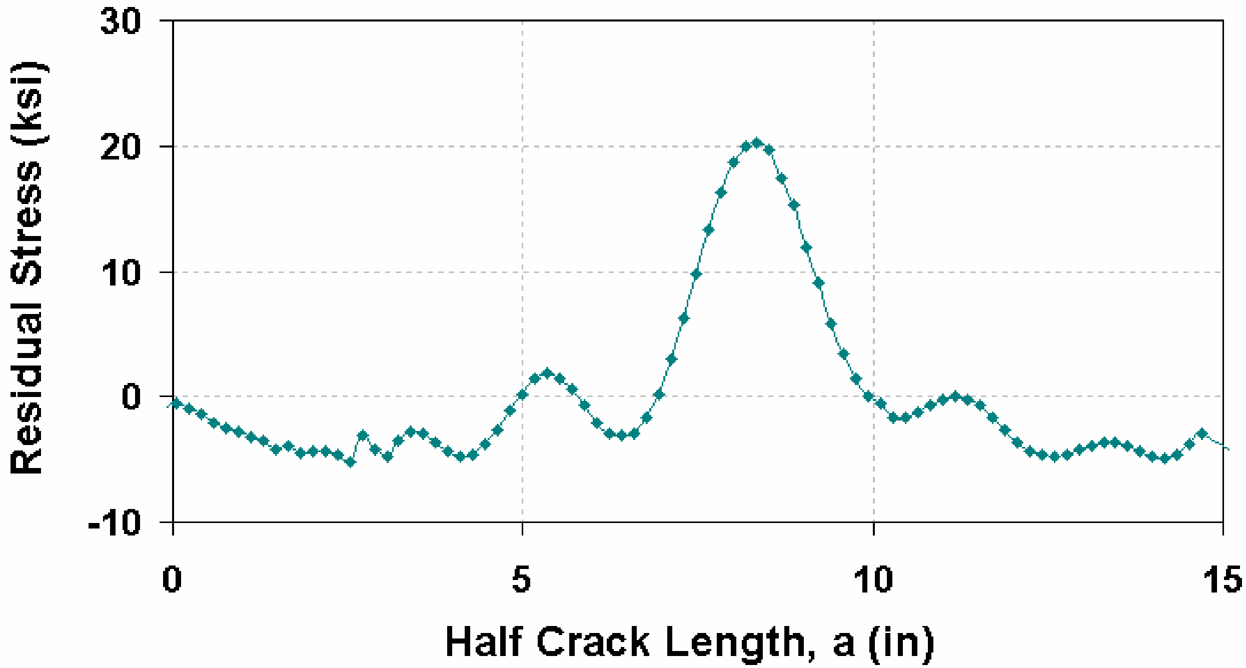
Peak stress is ~20 ksi

Reconstructed Total Residual Stress from Combined Sectioning and Contour Measurements (ksi)

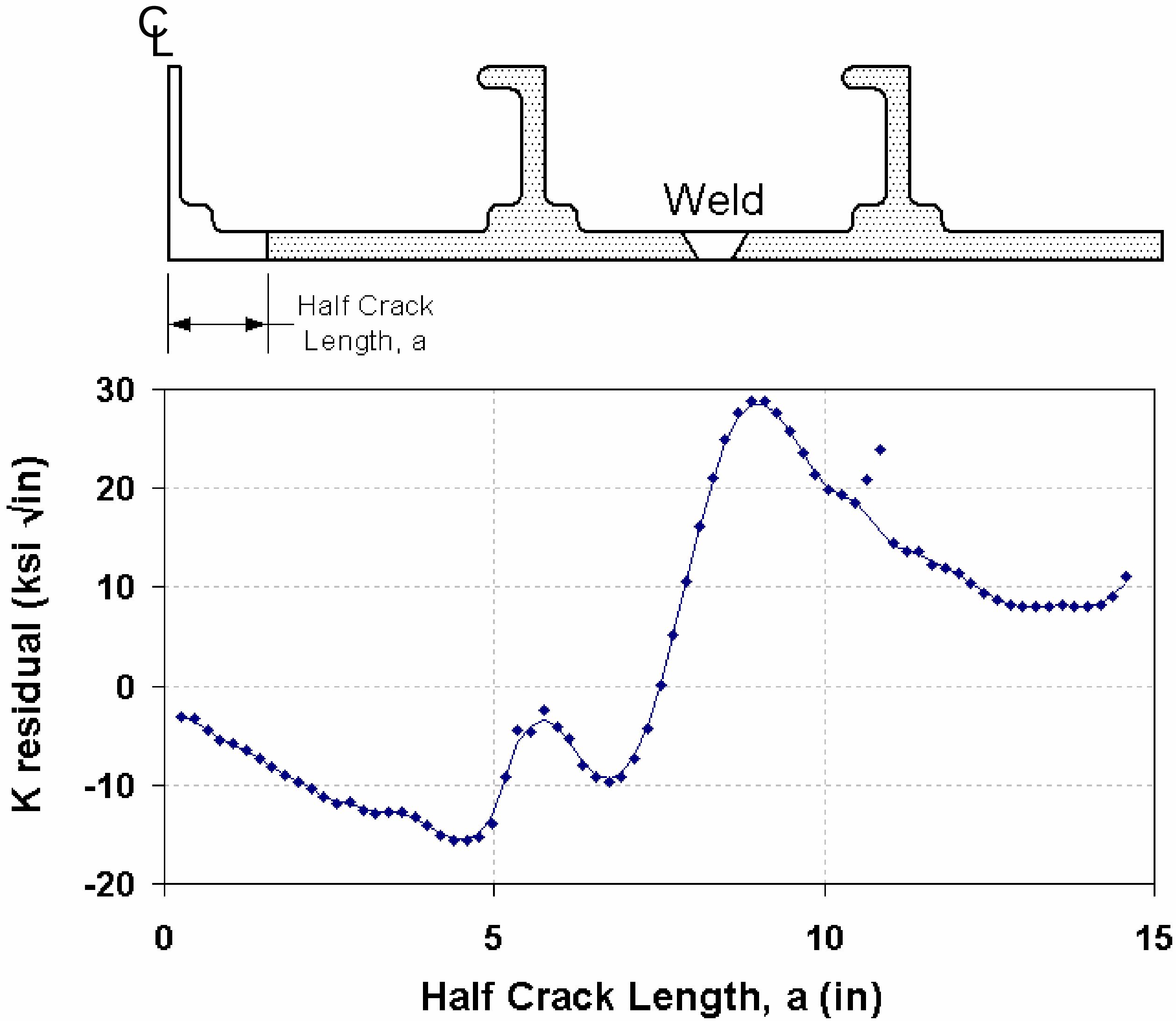


Average Through-thickness Residual Stress Measured from Specimen Centerline have Expected Trends





Residual Stress Converted to $K_{residual}$ Shows Significant Compressive and Tensile Response



Summary and Conclusions

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- Baseline ISP has fantastic performance relative to current built-up solutions (greater than 6x CA improvement, much greater than 3x spectrum improvement)
- Advanced stress level ISP (+25%) had 1.5x life improvement over built-up baseline
- Selective reinforcement restores residual strength for ISP (residual strength loss for integral panels is well known)
  - ⇒ Significant weight reduction and/or much longer inspection intervals
- The eigen strain approach is a simple method of estimating FSW induced stress in large scale components
- Measured values agree well with predicted values
- Compressive residual stresses are widespread and significantly extend the life of the welded panels
- Tensile residual stresses are highly localized
- Residual stresses must be well characterized to be included in a DA/DT analysis