Prediction of Full Field Residual Stress in Arbitrary Bodies Using ERS-toolbox®

AFGROW User Workshop

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Predict. Test. Perform.

Abstract

Engineered residual stress (ERS) is increasingly being applied as a way to extend the durability and damage tolerance performance of primary structure in various industries including aerospace and power generation. To reduce development costs, reduce the development time, and increase the effectiveness of the final design, methods that accurately predict residual stress for surface treatments are being developed. ERS-toolbox® is a software suite which predicts full field residual stress for a variety of processes including conventional shot peening (SP), laser shock peening (LSP), and cold hole expansion (CX). An overview of ERS-toolbox® will be presented along with example applications.

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Overview

An overview of eigenstrain theory

- What eigenstrain is
- Why ERS-toolbox® uses eigenstrain

ERS-toolbox® introduction

- What ERS-toolbox® is used for
- How ERS-toolbox® integrates into the engineering workflow
- Current and future development

Example Applications

- LSP repair design for an F-22 wing-attach lug
- LSP repair design for a A-10 wing forging
- Residual stress predictions for CX Holes

Eigenstrain Theory

An Overview of Eigenstrain Theory

What is eigenstrain?

- Strain produced without external forces
  - Plastic deformation, temperature changes, etc.

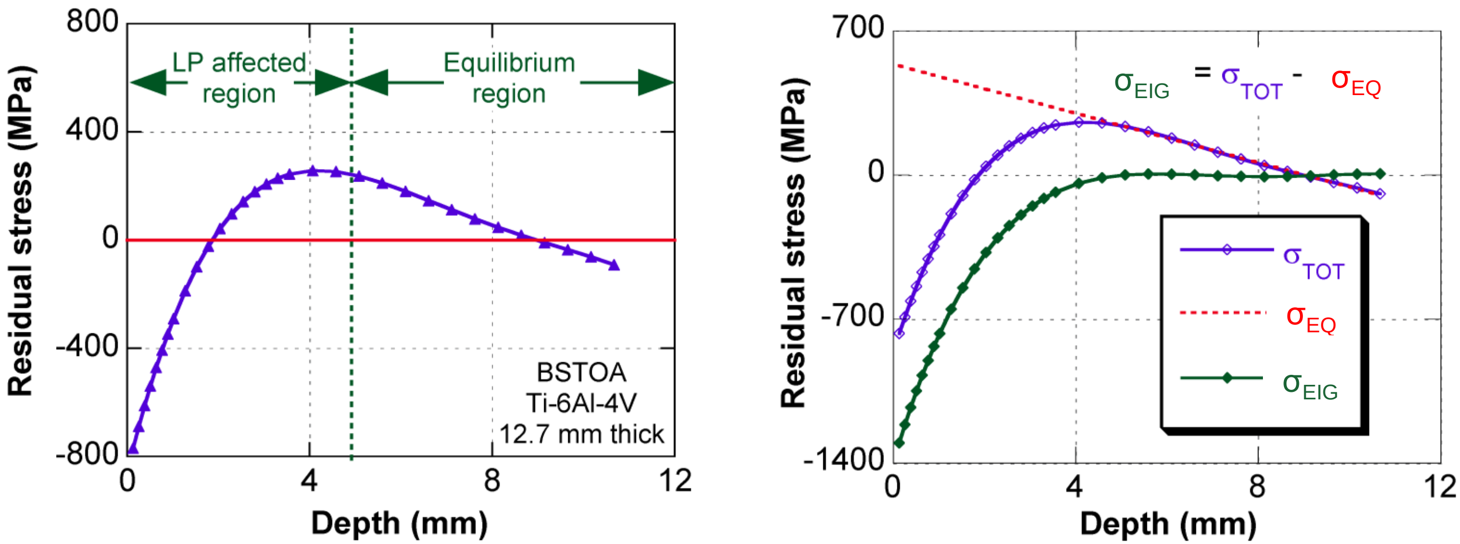
In particular, we are interested in incompatible eigenstrain

- An incompatible strain field is one which cannot exist within a body without stress
- For example, think of a block of material in two different situations
  - In one case the block is heated uniformly throughout. The temperature change (and eigenstrain) is uniform. The block will expand uniformly and the stress will be zero everywhere.
  - In the second case, the block is heated only on the exposed surfaces. The temperature change throughout the body is not uniform and neither is the eigenstrain. In this case the resulting stress field is nonzero and a strong function of distance from the heated surfaces.

An Overview of Eigenstrain Theory (cont.)

Surface processes which create residual stress induce incompatible eigenstrain in the processed material

- The resulting total stress state can be broken down into two components: the eigenstress σ_{EIG} (geometry independent), and the equilibrating stress σ_{EQ} (geometry dependent). The total stress field is then $\sigma_{TOT} = \sigma_{EIG} + \sigma_{EQ}$.



(a) Example of typical laser peening residual stress profile showing the laser peening affected depth and
(b) plot showing the laser peening induced residual stress and the equilibrium residual stress

DeWald. A. T., and Hill, M. R., 2009 "Eigenstrain based model for prediction of laser peening residual stresses in arbitrary 3D bodies: Part 1 model description", The Journal of Strain Analysis for Engineering Design, 44(1), pp. 1-11

An Overview of Eigenstrain Theory (cont.)

Why ERS-toolbox uses eigenstrain

- Eigenstrain is assumed to be geometry invariant
  - The eigenstrain distribution for a given process depends on the process itself and the material but not the geometry
  - If you know the eigenstrain distribution for the process you can use it to predict the resulting residual stress for any geometry
    - Contrast this ability with residual stress which is valid only for one geometry

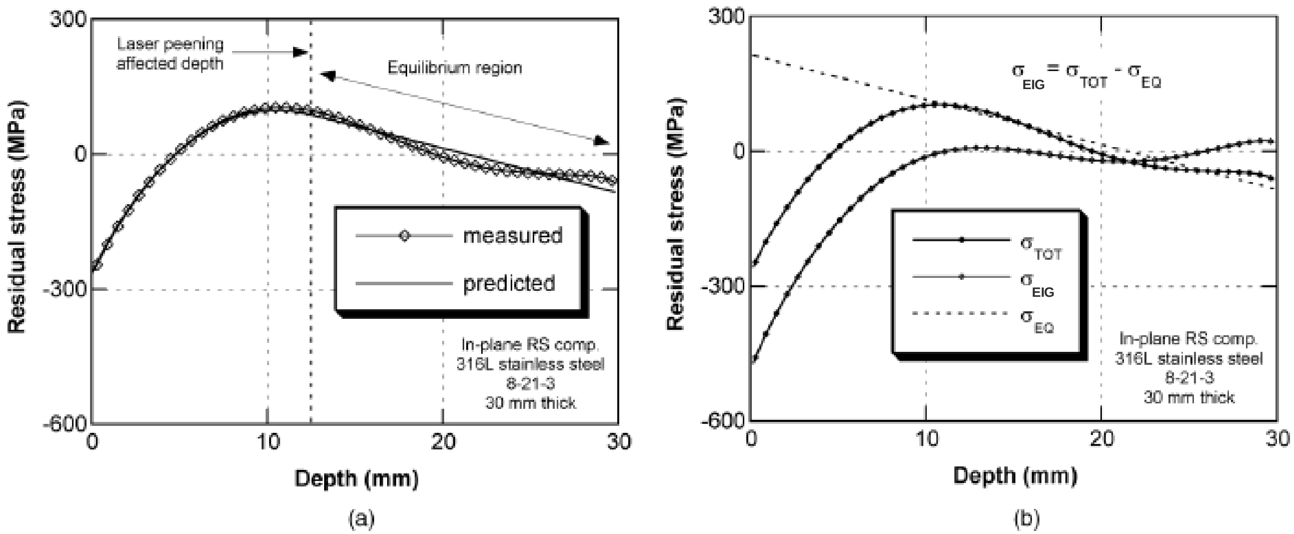
Note that while eigenstrain is a geometry invariant, the measurement of eigenstrain is not

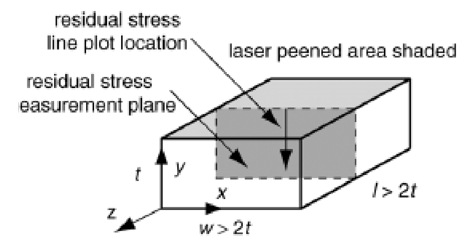
- For SP and LSP one must design the measurement block such that the resulting eigenstrain data is truly the underlying geometry invariant eigenstrain
- The CX holes the processes of extracting the eigenstrain is much more involved as it is not possible to separate the CX hole process from the hole geometry
  - An inverse finite element method must be used with an appropriate optimizer

An Overview of Eigenstrain Theory (cont.)

Example of using eigenstrain to predict residual stress in a 3D body

- The example process is on 316L stainless steel using LSP
- The block used to fined the process eigenstrain is 30 mm thick and the in-plane dimensions are 60 x 60 mm





(a) Plot showing measured and predicted total residual stress along the line through the middle of a 30 mm thick block of annealed 316L treated with laser peening and (b) plot showing the measured total residual stress decomposed into the laser peening induced residual stress and the equilibrium residual stress

DeWald. A. T., and Hill, M. R., 2009 “Eigenstrain based model for prediction of laser peening residual stresses in arbitrary 3D bodies: Part 1 model description”, The Journal of Strain Analysis for Engineering Design, 44(1), pp. 13-27

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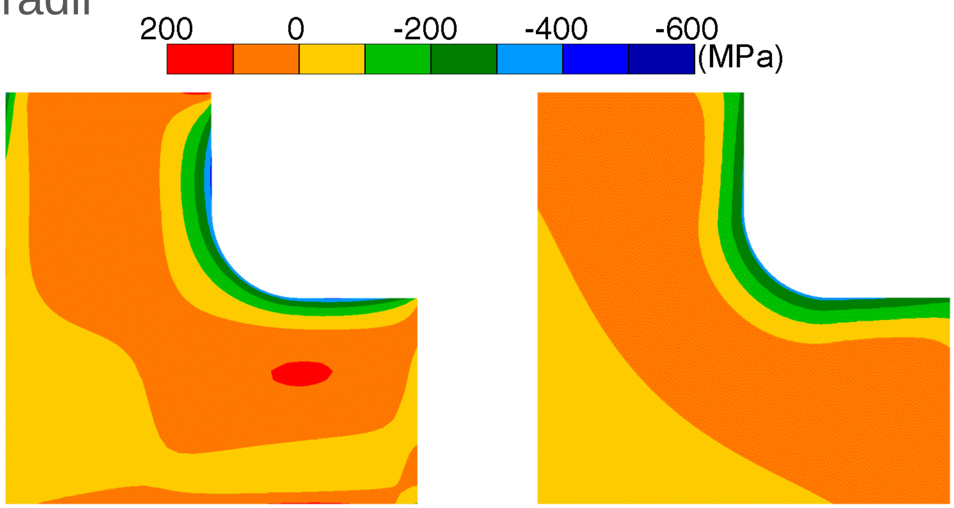
An Overview of Eigenstrain Theory (cont.)

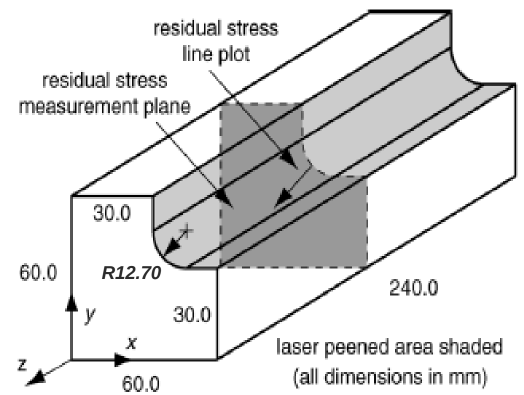
Example of using eigenstrain to predict residual stress in a 3D body

- With the eigenstrain distribution known and verified using basic sanity checks, it can be used in arbitrary 3D bodies processed with the same LSP parameters and the made of the same material
- The example shown below was for a 316L stainless steel block with a corner radii



(a) (b)

Contour plots of residual stress (σ_{zz}) for (a) measured and (b) predicted



DeWald. A. T., and Hill, M. R., 2009 “Eigenstrain based model for prediction of laser peening residual stresses in arbitrary 3D bodies: Part 2 model verification”, The Journal of Strain Analysis for Engineering Design, 44(1), pp. 1-11

ERS-toolbox® Introduction

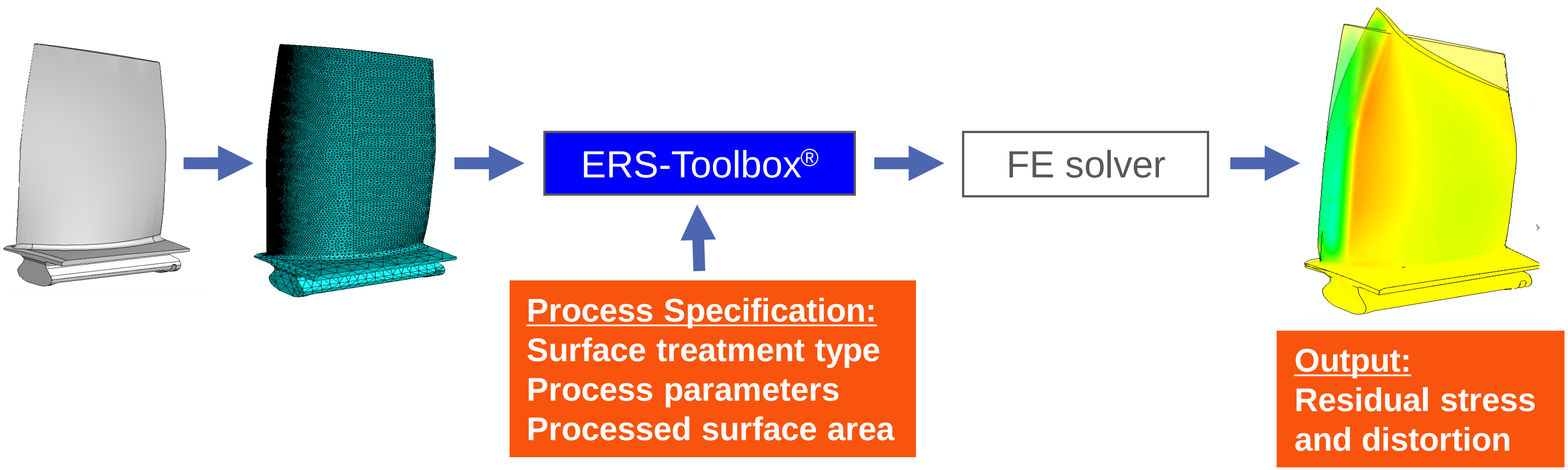
ERS-toolbox® Introduction

What ERS-toolbox® is

- ERS-toolbox® is a software tool that uses eigenstrain to predict full field residual stress in arbitrary 3D bodies
- The currently supported processes are shot peening, laser shock peening, and cold hole expansion (in development)
- ERS-toolbox® provides methods for interpolating between known processes

ERS-toolbox® integrates into the existing engineering workflow

- Supports existing FEA suites such as ABAQUS and ANSYS



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ERS-toolbox® Introduction (cont.)

Past Development

- ERS-toolbox® has been in use by Hill Engineering since 2005 as an internal research code
  - Written in a combination of FORTRAN and MATLAB
  - Was limited to LSP and SP residual stress predictions

Current Development

- ERS-toolbox® is being developed into a software tool which can be externally released externally and used by engineers
  - New code base written in modern, multithreaded C++
  - Enhanced support for LSP and SP
- Support for CX holes is being developed with sponsorship from the Air Force
- Support for probabilistic variability is being developed via a SBIR contract with the Navy

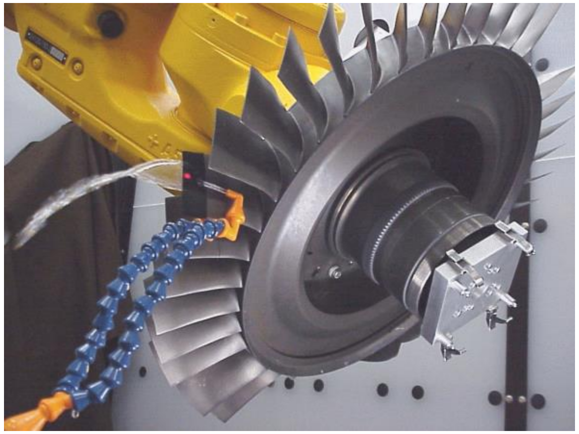
ERS-toolbox® Introduction (cont.)

The residual stress process design workflow is currently iterative

- High cost due to number of tests and fabricated parts needed
- Large program time frames due to manufacturing, processing, and testing lead times on each iteration

ERS-toolbox® can reduce the time and monetary cost of designing a residual stress process compared to the iterative approach

- The process can be designed and iterated using standard FEA tools



F119 engine IBR being laser shock peened.
Source: http://www.lsptechnologies.com/production-uses/

LSP Repair Design for an F-22 Wing-Attach Lug

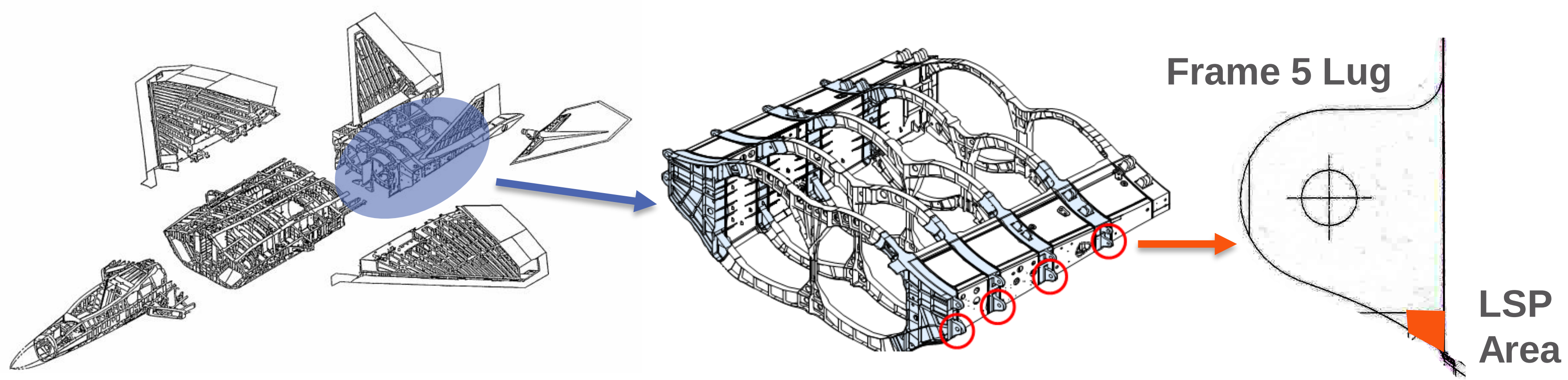
Background

USAF F-22 aircraft

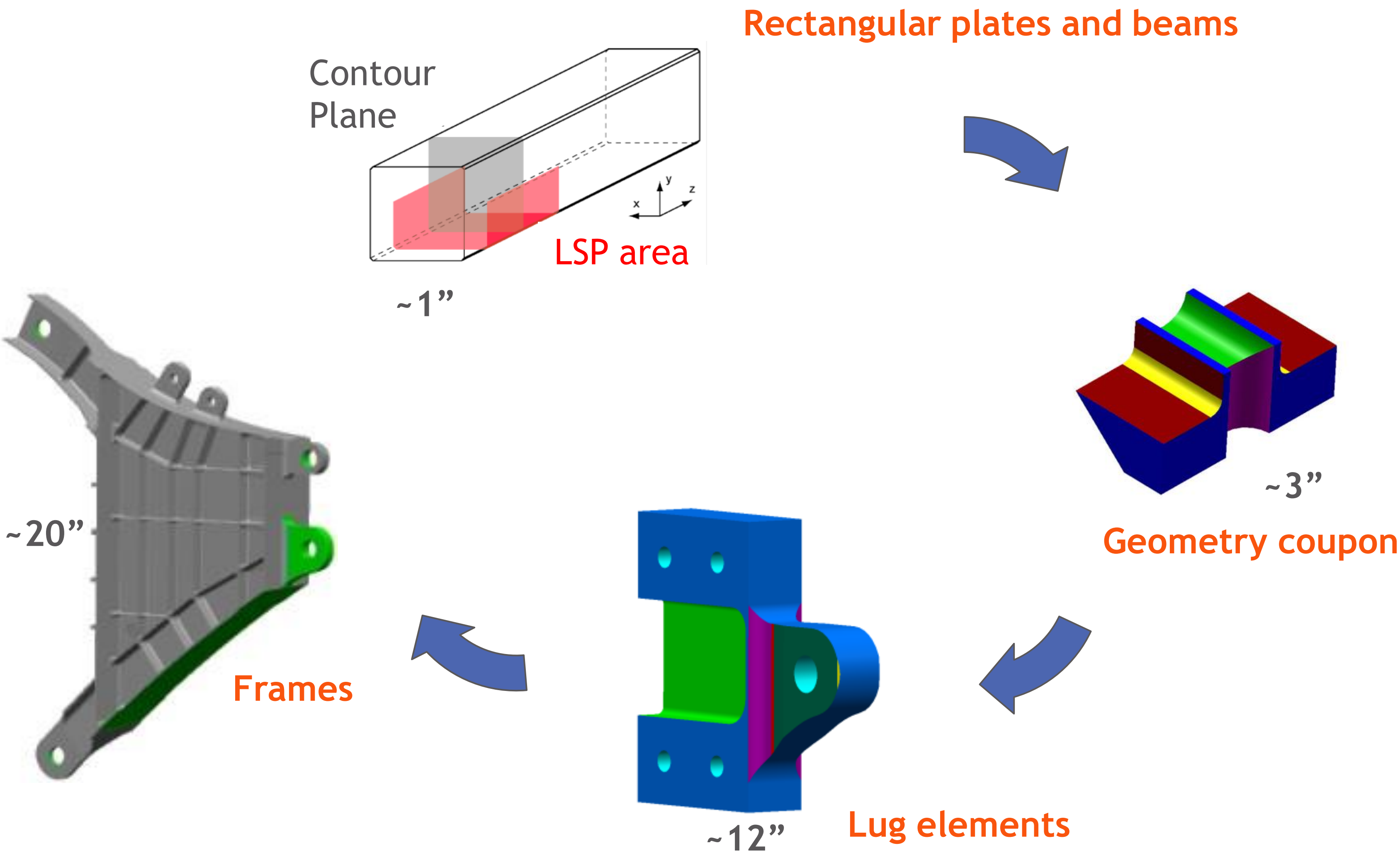
- Significant portion of F-22 fleet “at-risk” of structural failure
- Costly unplanned inspections
- Likely early retirement of aircraft

Developed residual stress treatment to extend lifetime of airframe

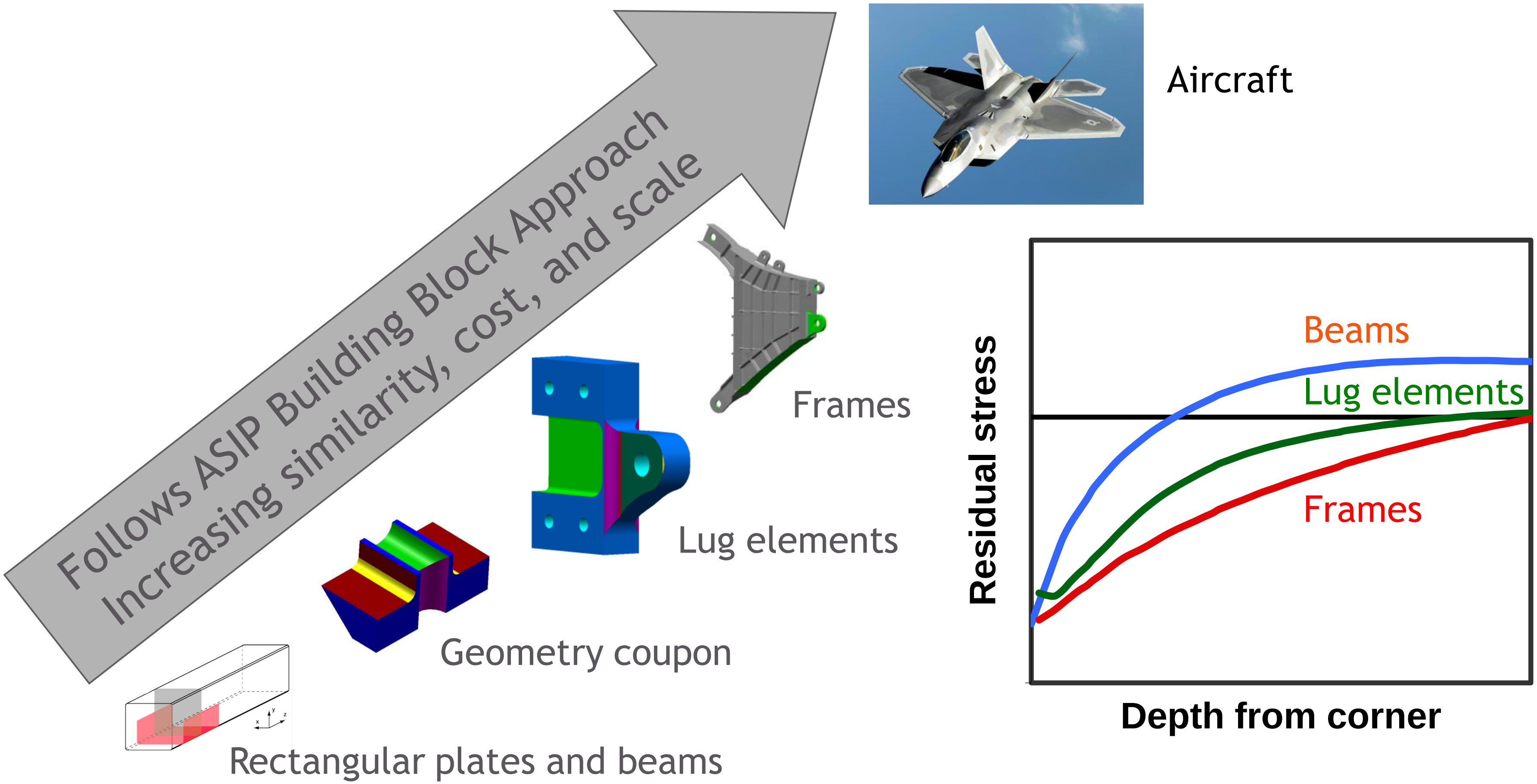
- Cracks grow more slowly in presence of residual stress



Program approach



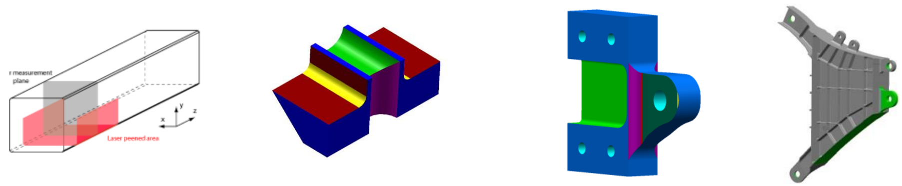
Residual stress changes with geometry

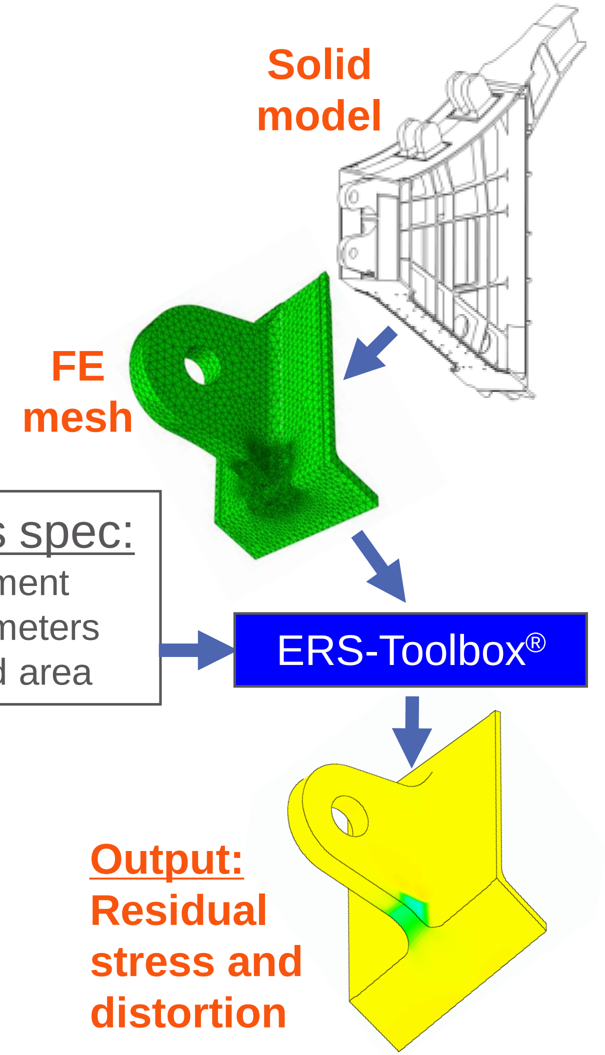


Residual stress engineering requires transferability with geometric scale

Use of ERS-Toolbox® on F-22 LSP program

Predicted residual stress in range of test articles





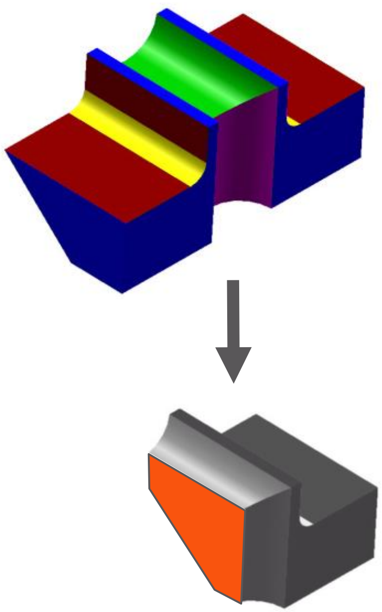
Process spec:
LSP treatment
LSP parameters
Processed area

Model outputs support sound engineering decisions

- Manage tradeoffs between more compressive stress (generally good) versus more tensile stress and distortion (generally bad)
  - High vs low intensity
  - Large vs small processed area
- Manage locations and magnitude of tensile stress

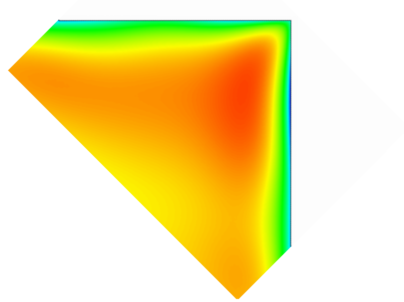
Example residual stress prediction

Geometry coupon

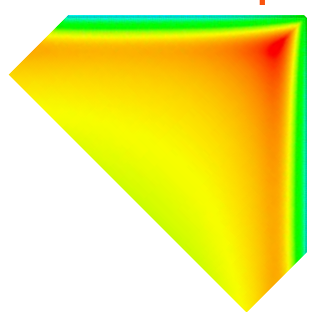


Comparison of results on single plane

Measured

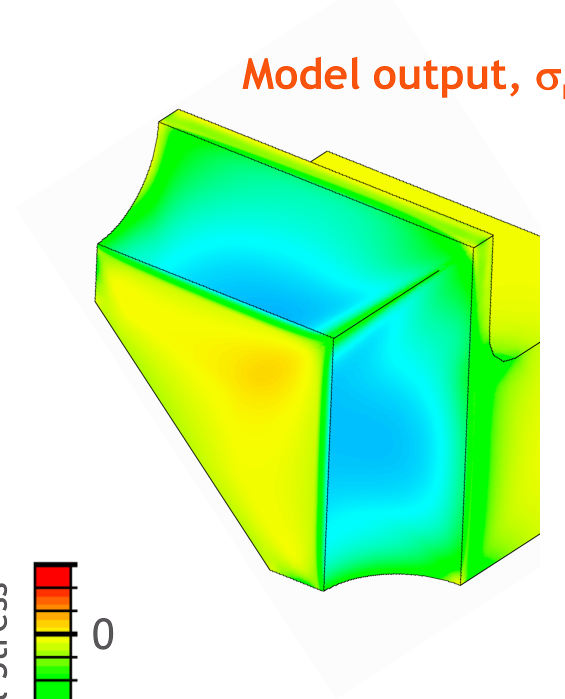


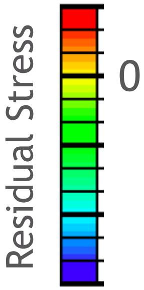
Model output



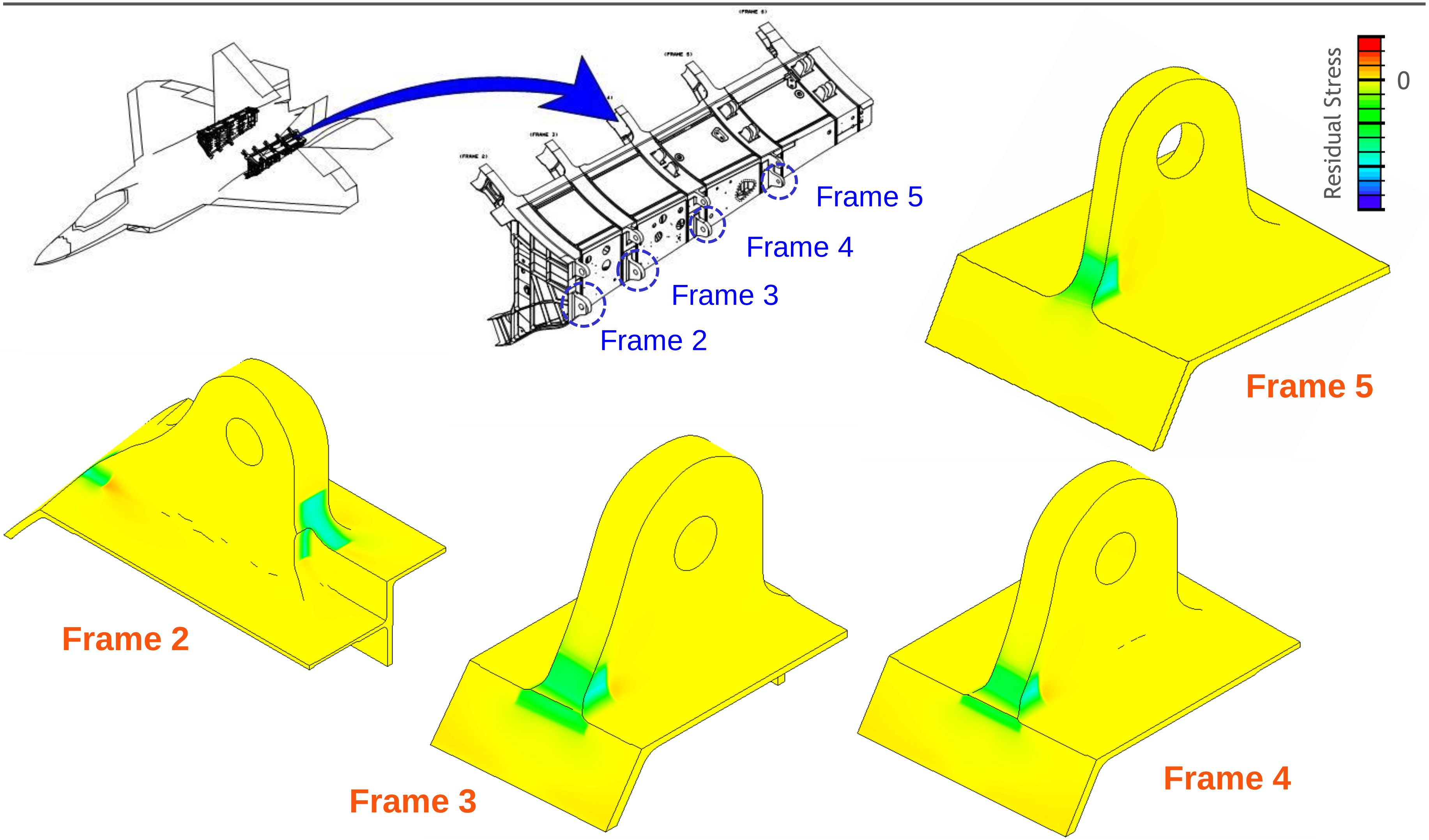
Model result is full field

Model output, σ_{min}





Residual stress predictions, all LSP frames



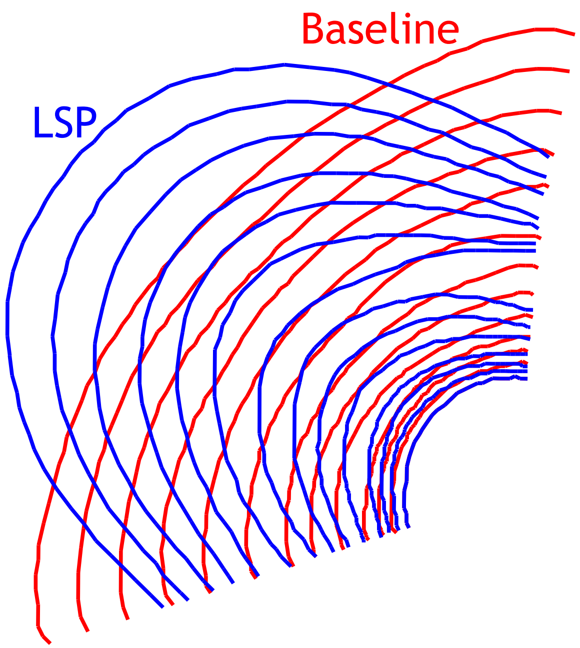
Predicted crack growth behavior in frames

Growth occurs on same plane in Baseline and LSP models

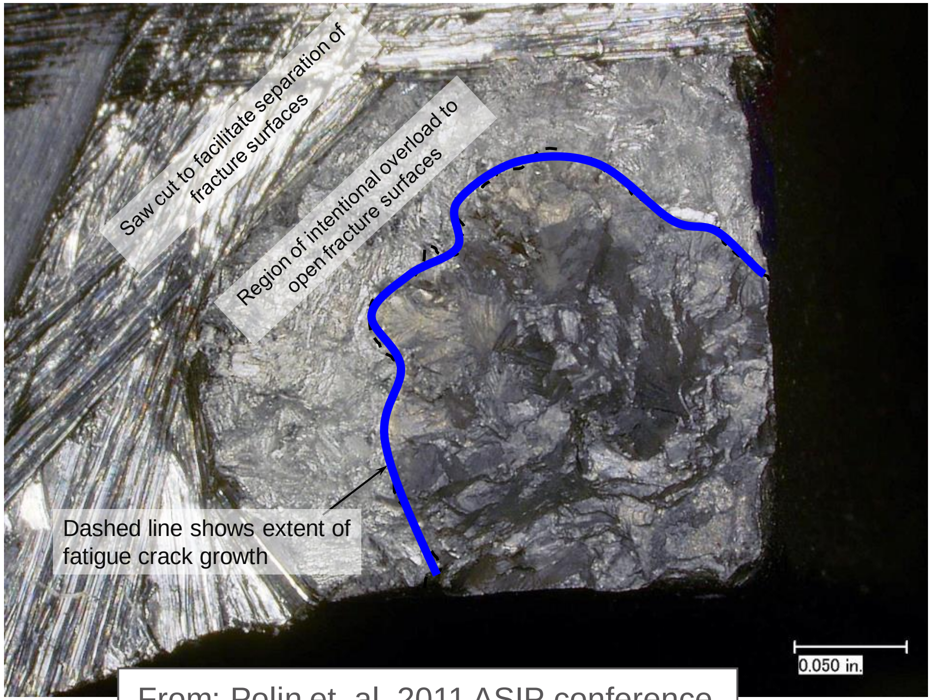
- Baseline prediction: planar, roughly quarter-elliptical shape
- LSP prediction: planar, bulging shape

Similar behavior for all Frames

Predicted crack shape evolution



Observed crack shape for LSP
(Frame 2 test article)

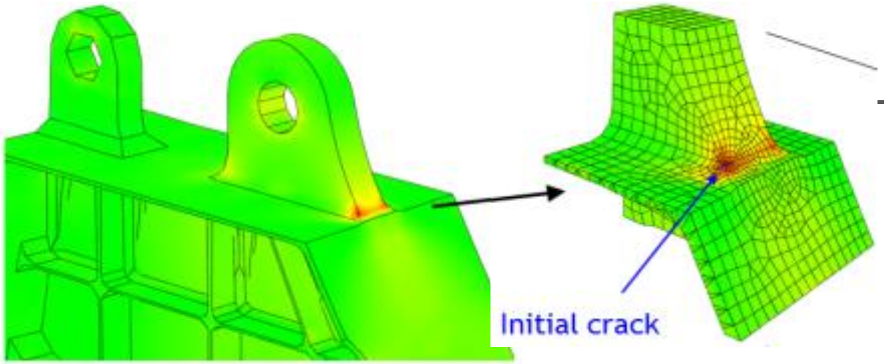


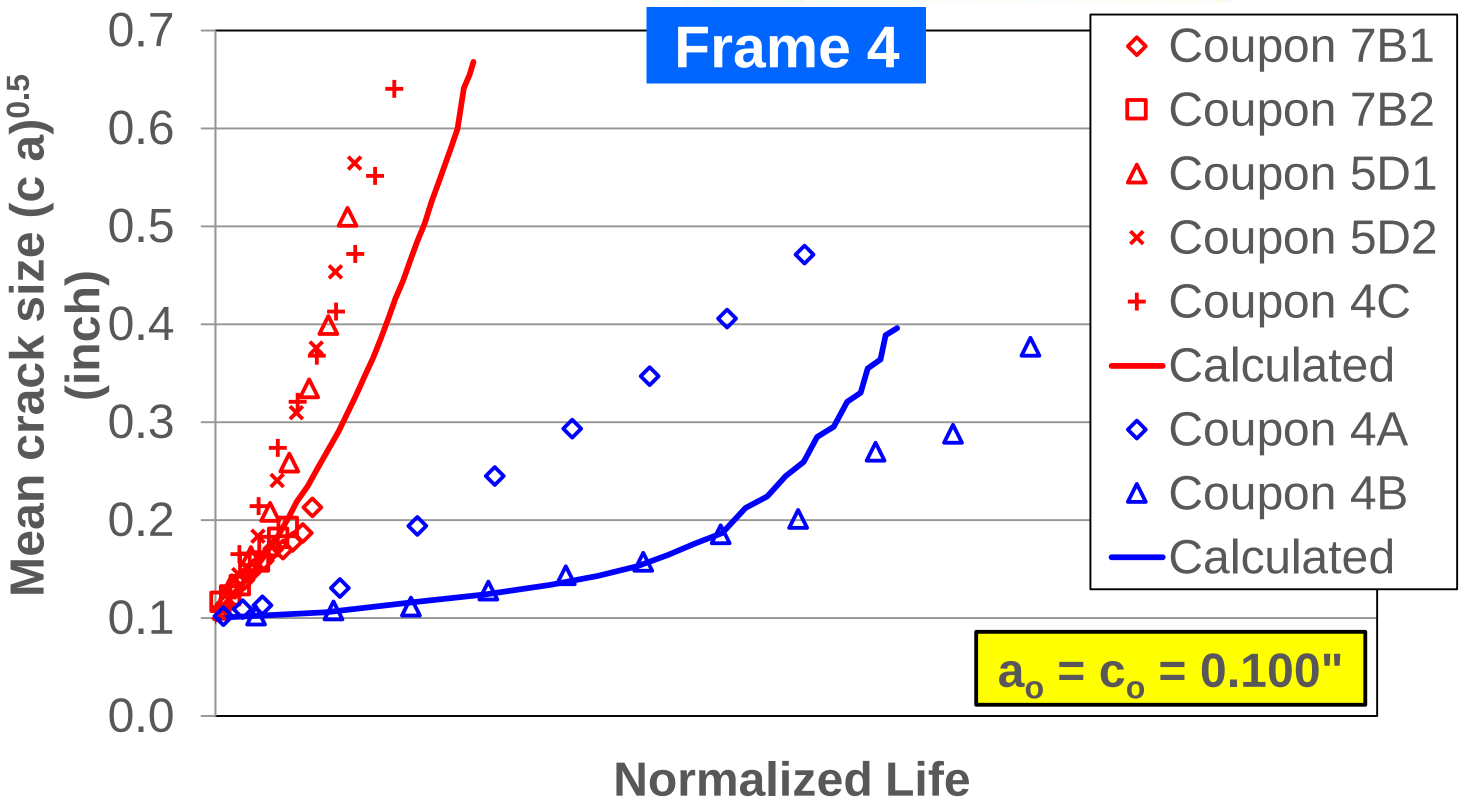
From: Polin et. al, 2011 ASIP conference

Test correlation

RED = Baseline

BLUE = LSP over crack





Program success: inspection relief

Significant inspection relief was achieved using the engineered residual stress repair on the F-22

- Unplanned inspections at location of repair were eliminated

Inspection Burden Relief for F22 at the Frame Lug Fillets

BOEING

DT Life (II)	Previous Inspection Interval w/o residual stress	New Inspection Interval w/o residual stress	New Inspection Interval with residual stress
Frm2 Upr	1,150	4,700	26,400
Frm2 Lwr	1,050	8,250	very large
Frm3 Lwr	600	5,150	31,600
Frm4 Lwr	850	4,150	52,900
Frm5 Lwr	1,200	20,100	111,600

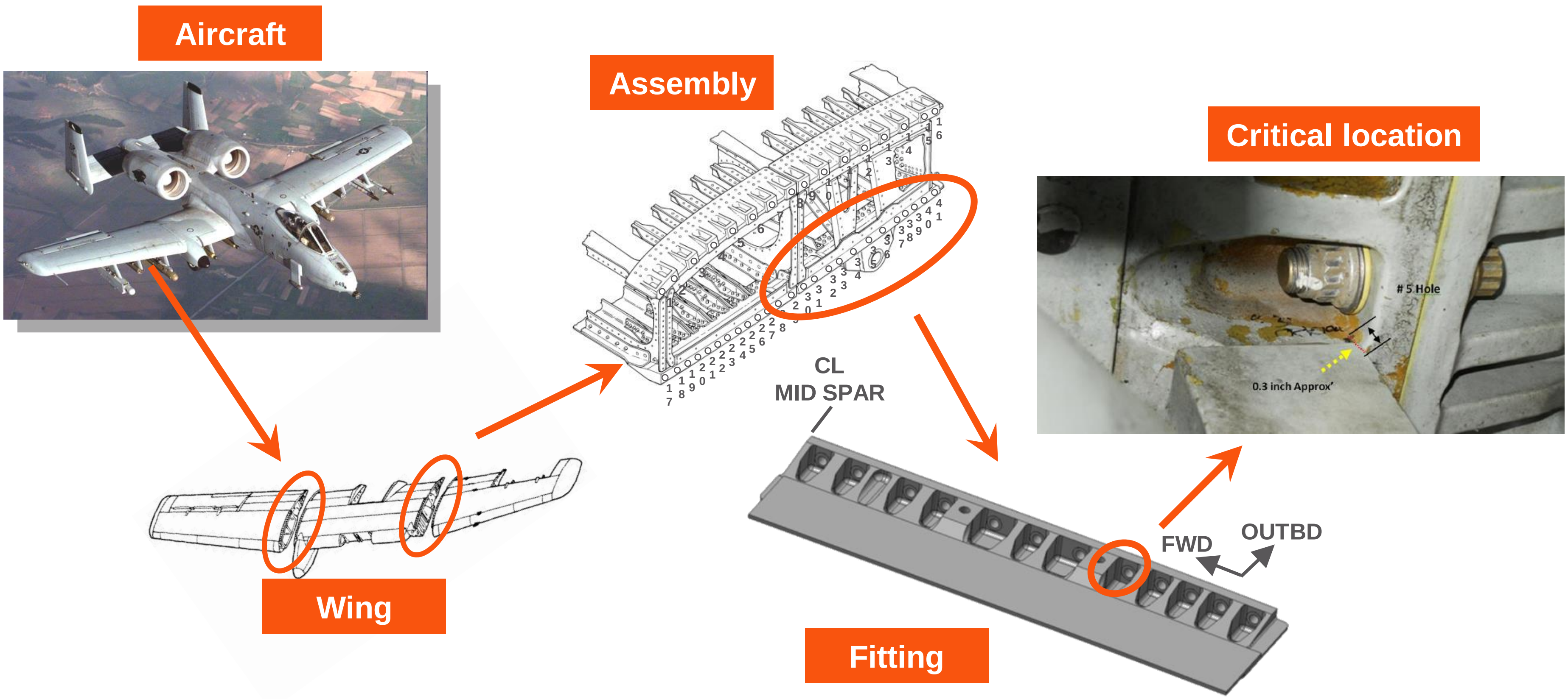
ASIP Conference December 3-5, 2013 The Boeing Company Export Controlled ECCN: EAR-99 NLR 19

LSP repair design for an A-10 wing forging

Background

A-10 WS-110 fitting exhibits fatigue cracking

- Critical structure: lower splice between outer and center wing panels
- Significant (nearly fleet wide) fatigue cracking issue

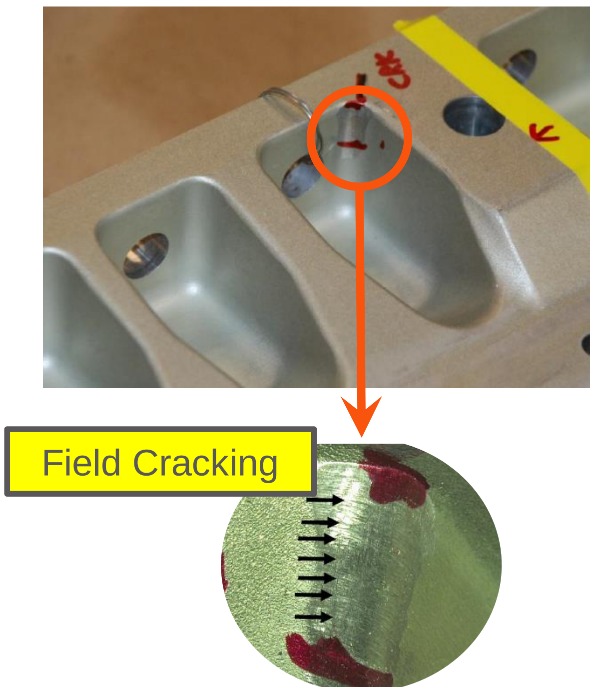


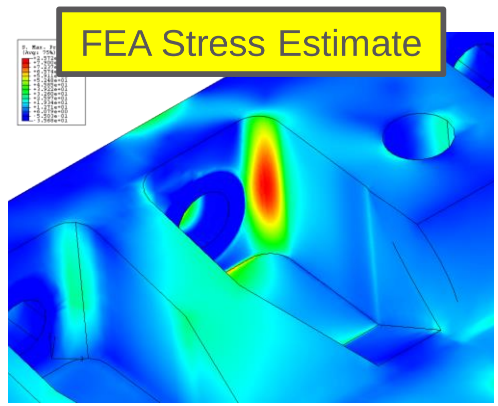
Program opportunity

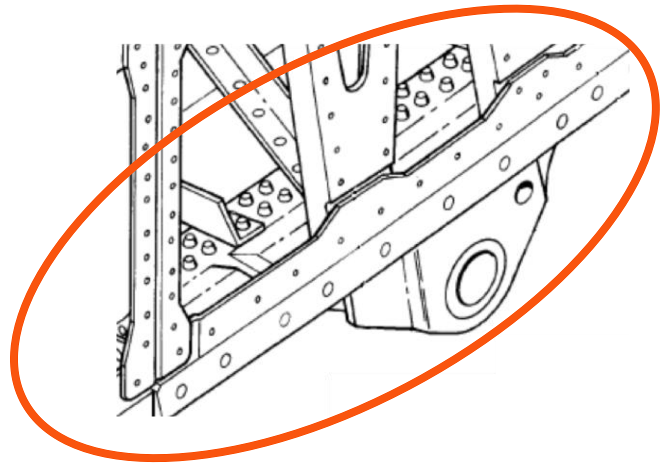
Cracking driven by localized area of high stress

Repair is expensive because the fitting is integral to the wing panel

Opportunity: use compressive residual stress to improve performance



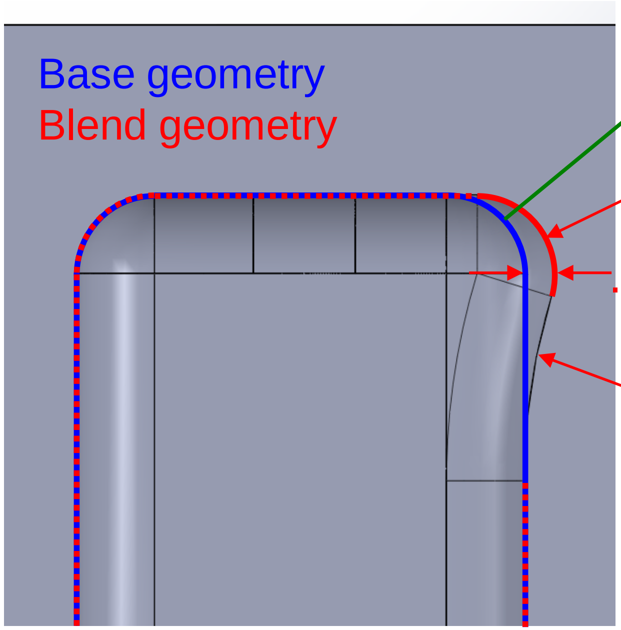




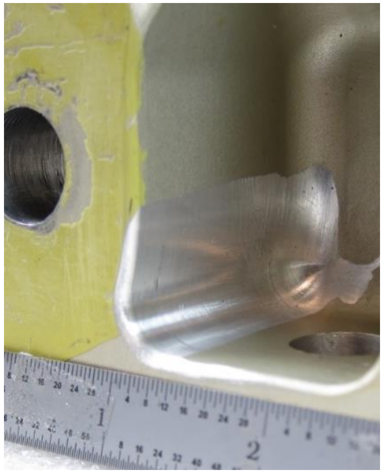
Repair approach

Repair for existing cracks has two components

- A blend with the same nominal radius
  - Removes existing cracks up to 0.1 inches deep
  - Leaves good surface for RS processing
- Application of LSP
  - Imparts compressive residual stress to improve FCI and FCG life



Demonstration Blend



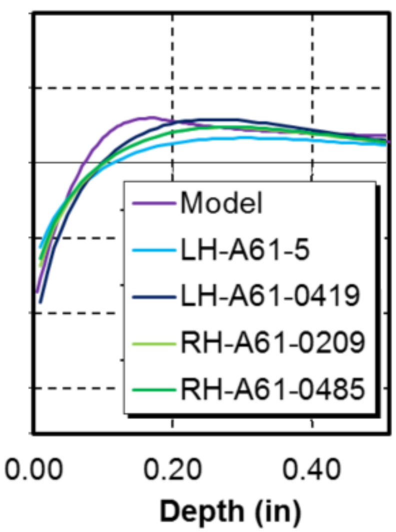
Comparing ERS-toolbox to measurements (cont.)

Measure residual stress in WS-110 fittings with LSP

- Four replicate parts
- Contour method

Measurements in reasonable agreement ERS-toolbox® output

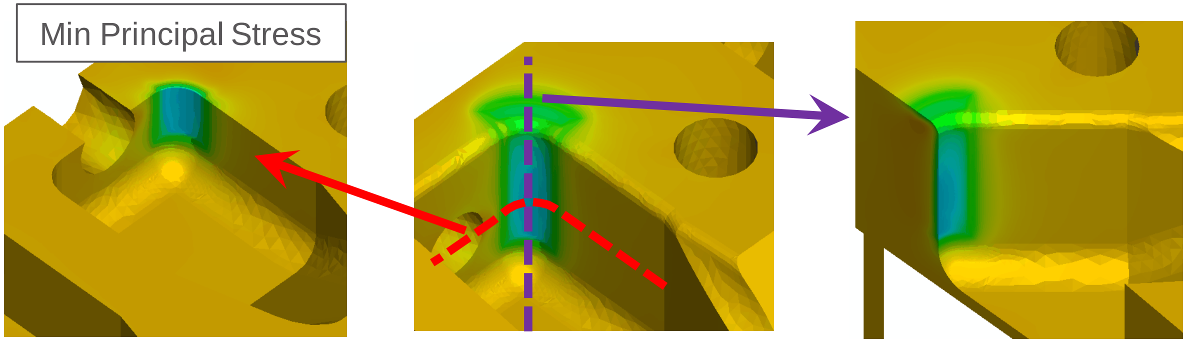
- Similar near surface residual stress
- Similar, but conservative, depth of compression

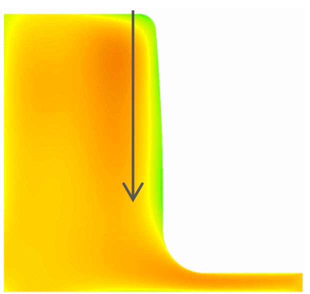


ERS-toolbox® Output

Contour Measurement

Min Principal Stress



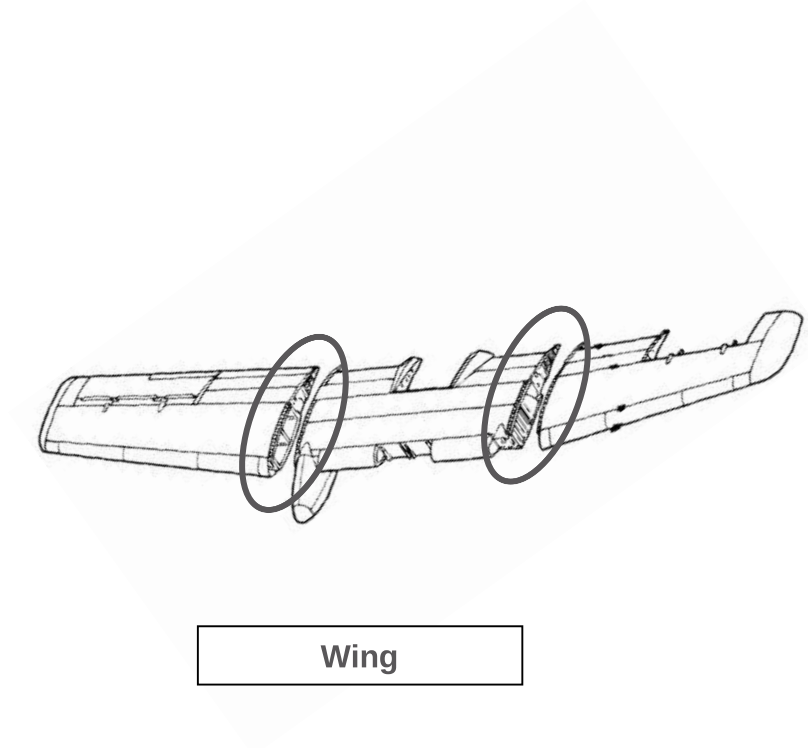


LSP Process Distortion Requirements

Machined mounting face bulges out slightly from LSP

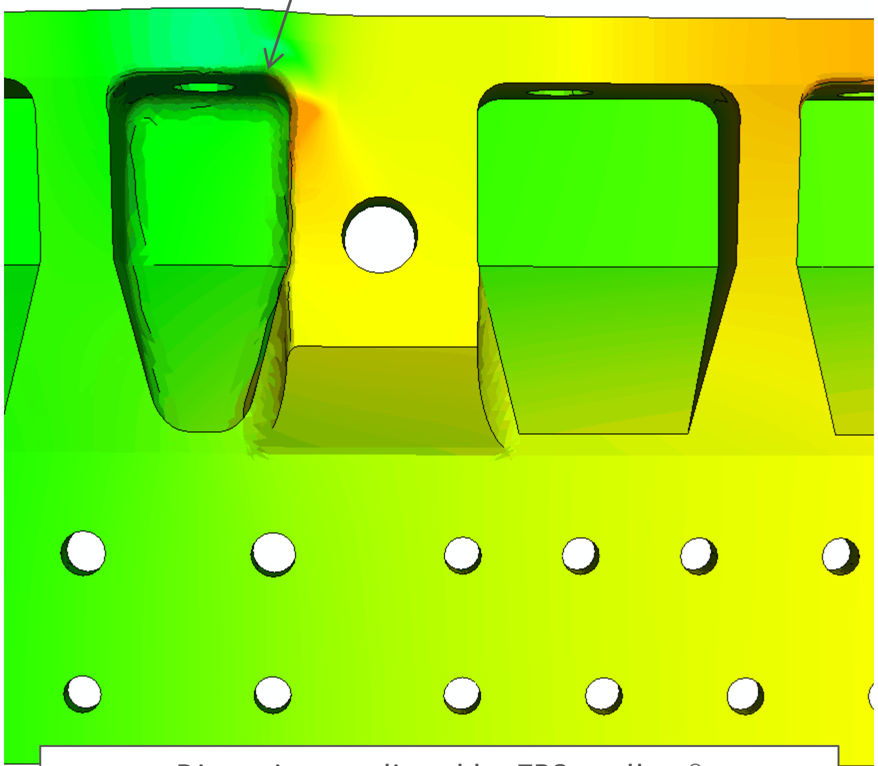
- Problematic because there are very tight tolerances on the mating face

Use ERS-toolbox® to asses distortion issues



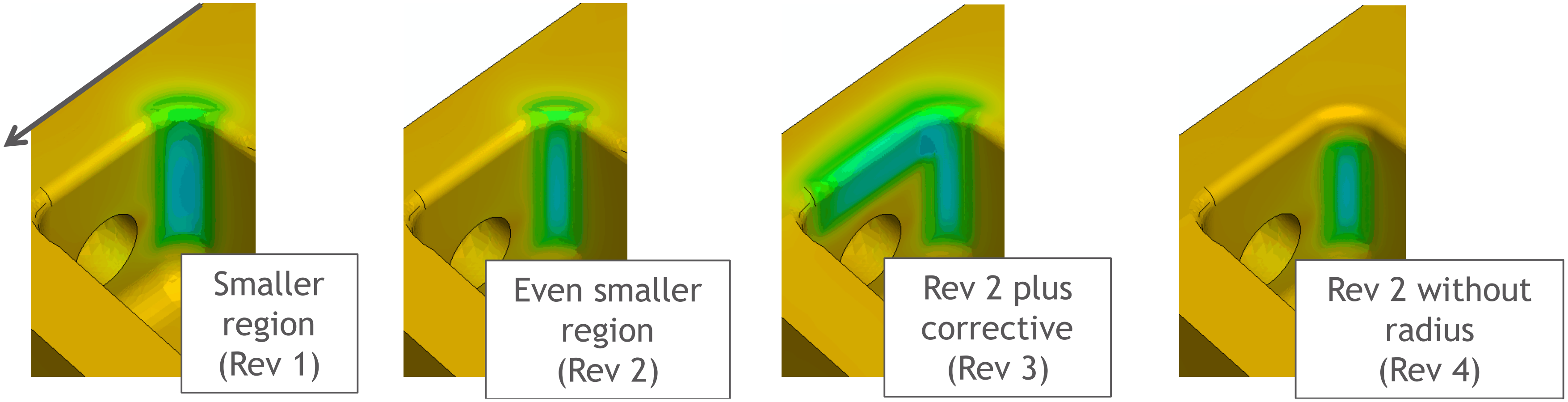
Wing

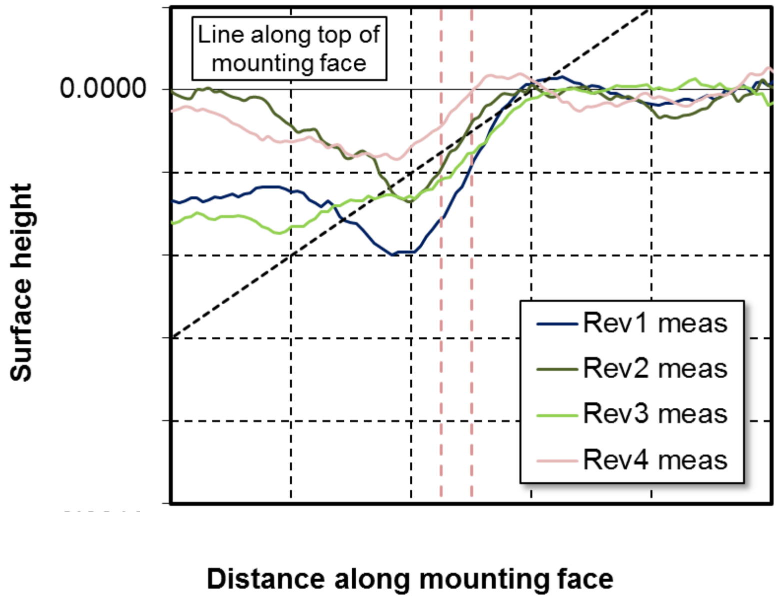
LSP process

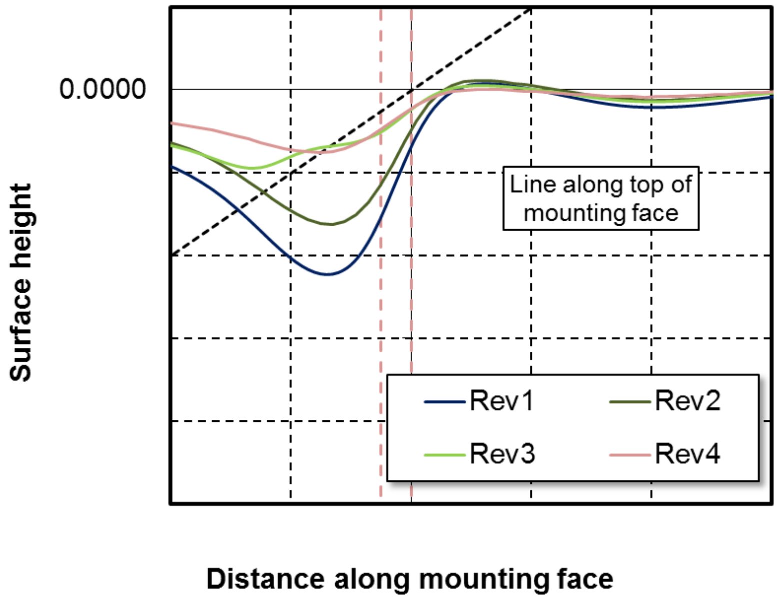


Distortion predicted by ERS-toolbox®
Displacement component normal to face

LSP Pattern Size Variation







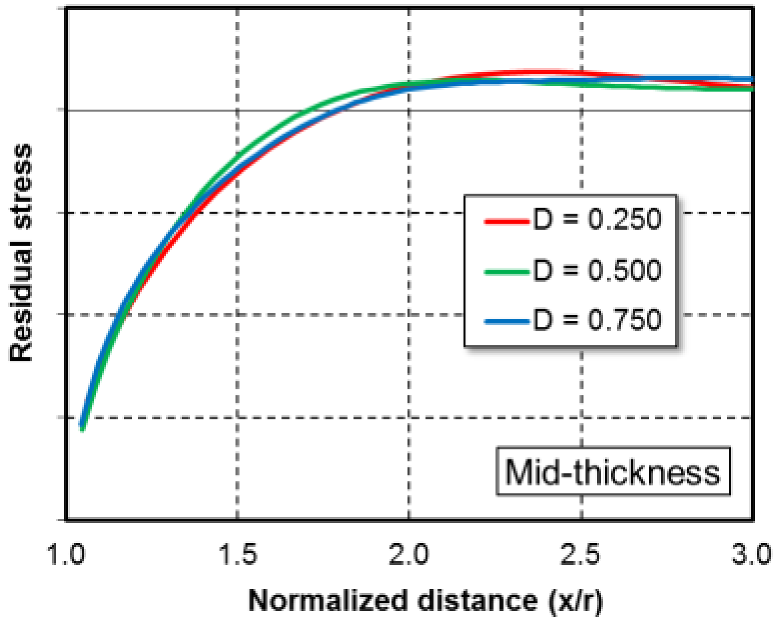
Residual stress predictions for CX Holes

ERS-toolbox® and CX Holes

ERS-toolbox® support for cold-expanded holes is in active development

Benefits of using eigenstrain for residual stress predications in cold-expanded holes

- The geometry independence assumption of eigenstrain eliminates several variables
  - Edge margin
  - Thickness
  - Hole radius



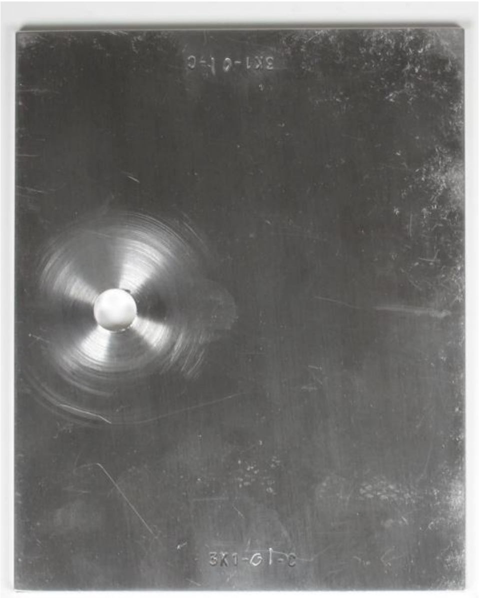
Edge Margin Example

Model source

- Material: 7075-T7651
- Hole Diameter: 0.375 inches
- Thickness: 0.313 inches
- CW Percent: 4%
- Edge Margin: 8.27

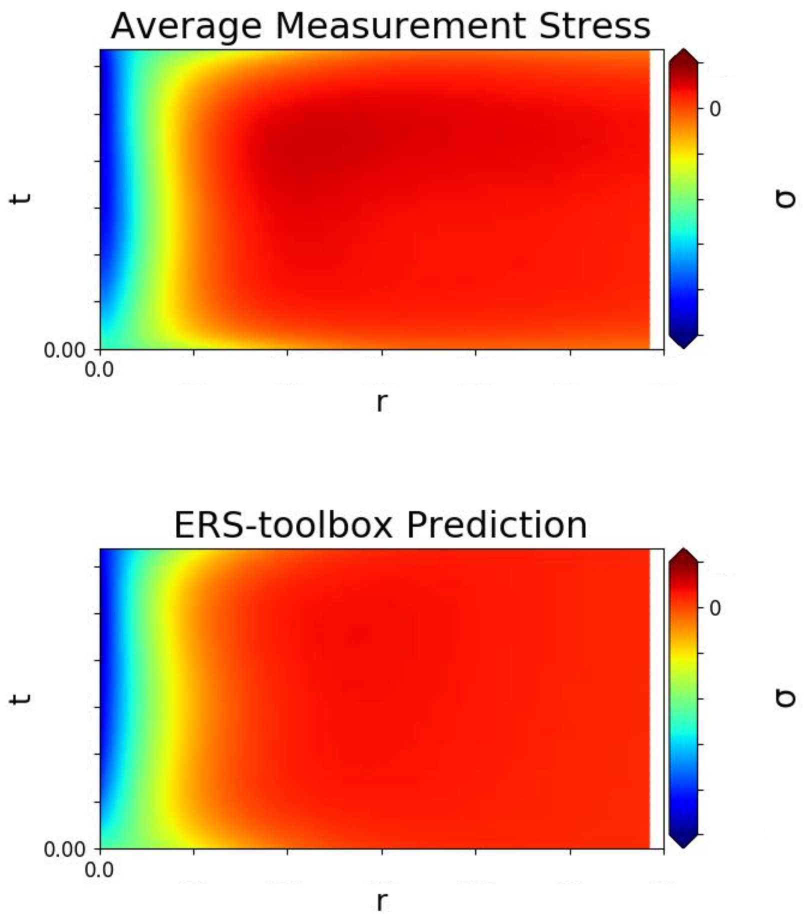
Prediction

- Material: 7075-T7651
- Hole Diameter: 0.375 inches
- Thickness: 0.313 inches
- CW Percent: 4%
- Edge Margin: 2.40

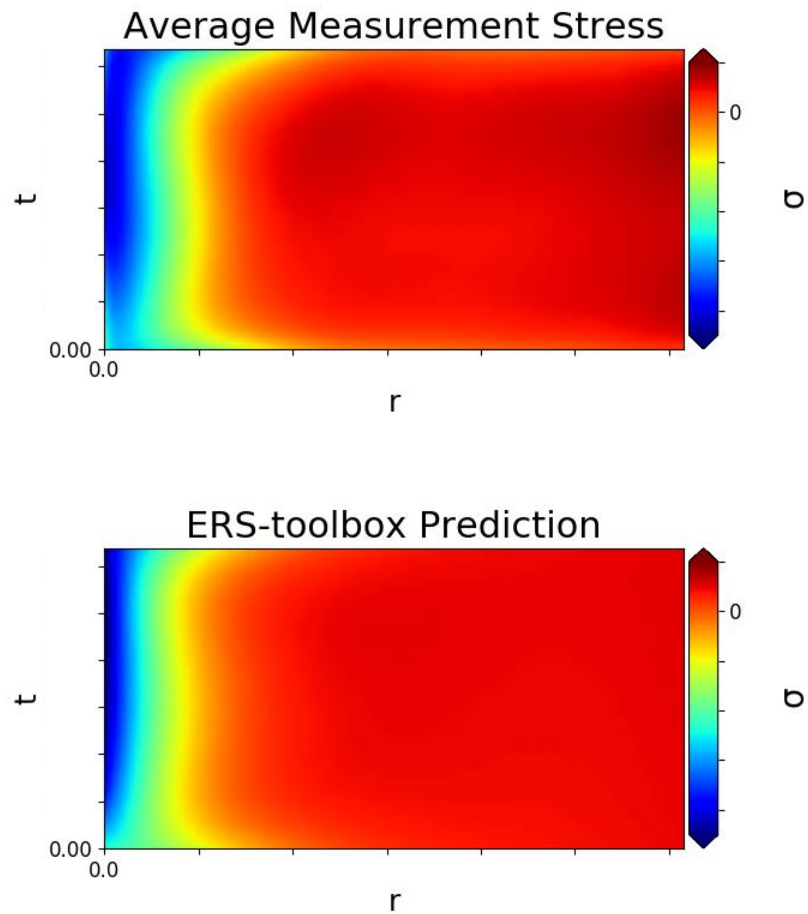


Nominal coupon geometry (hole position varies)

Prediction Results

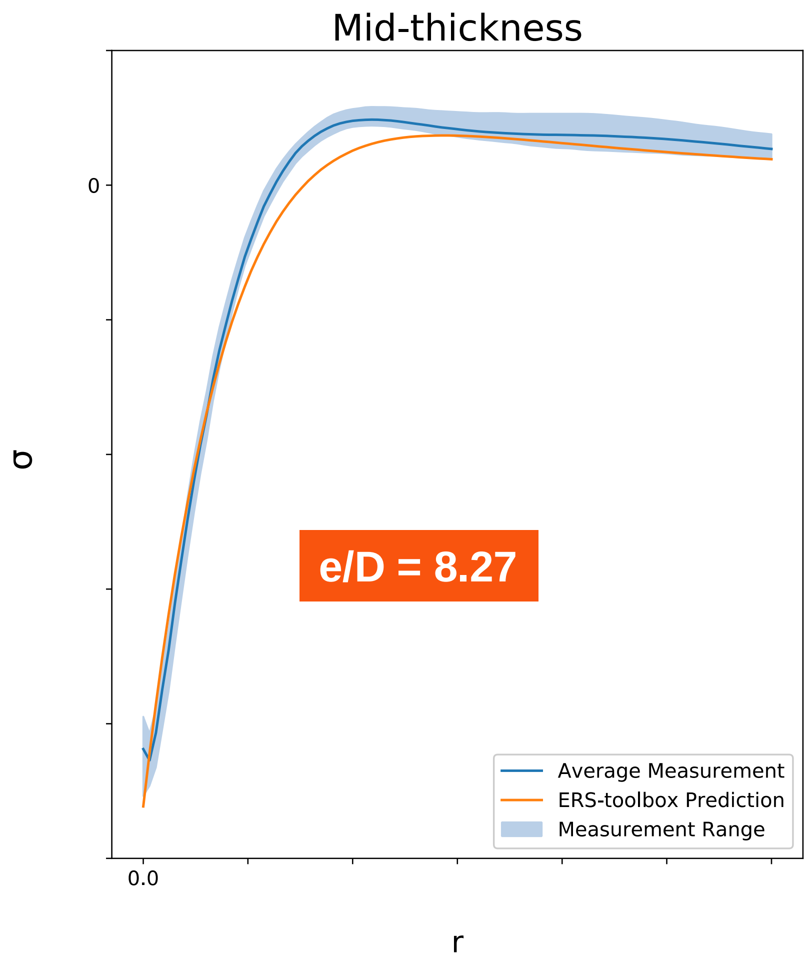


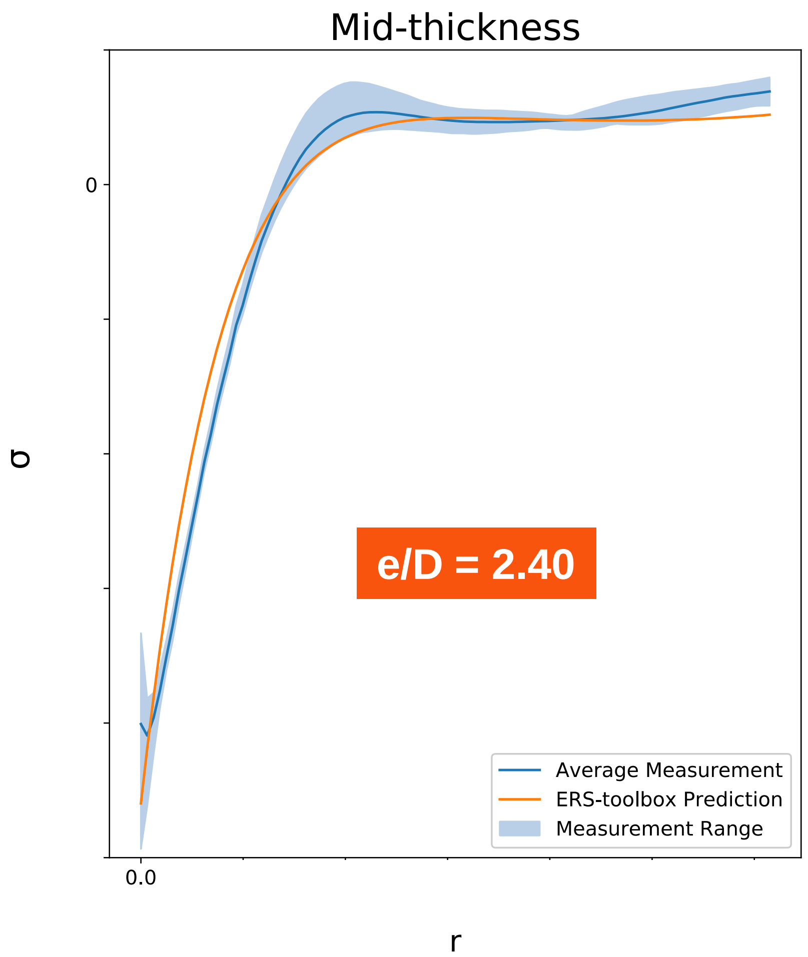
e/D = 8.27



e/D = 2.40

Prediction Results (cont.)





Summary

Eigenstrain theory

- Incompatible eigenstrain fields are strain fields that exist in a body without external forces and always induce stress
- Incompatible eigenstrain fields are assumed to be geometry invariant and a single eigenstrain distribution can predict residual stress in numerous geometries

ERS-toolbox®

- The eigenstrain approach is used by ERS-toolbox® to predict full field residual stress in arbitrary bodies
- ERS-toolbox® integrates into the existing engineering workflow by supporting existing FEA suites
- Using software tools like ERS-toolbox® enables the residual stress process design to be more efficient

Example applications

- LSP repair design for an F-22 wing-attach lug
- LSP repair design for a A-10 wing fitting
- Residual stress predictions for cold expanded holes with varying edge margin

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Thank You

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