Structural Vessel Repairs Using Automated Weld Overlays

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Introduction

- Automated welding technology
- Structural versus non-structural repairs
- Choice of Inconel for structural repairs
- Importance of as-welded properties

Quality Assurance Program

- Test Program
  - Obtain key properties of as-welded Inconel 625 overlay.
  - Examine the bond between overlay and base metal.
  - Compare fatigue strength of unrepaired and repaired plates.
- Finite element analysis
  - Improve the ability to model the overlay and predict consequences

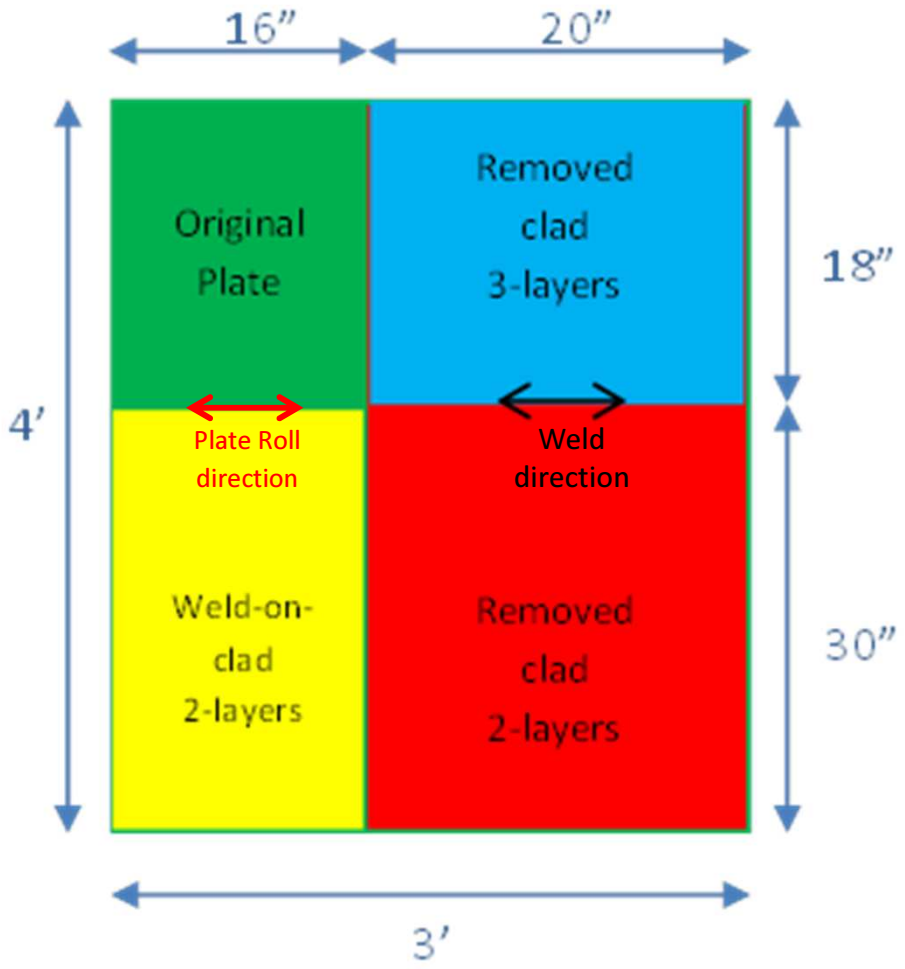
Test Plate

Clad carbon steel plate:

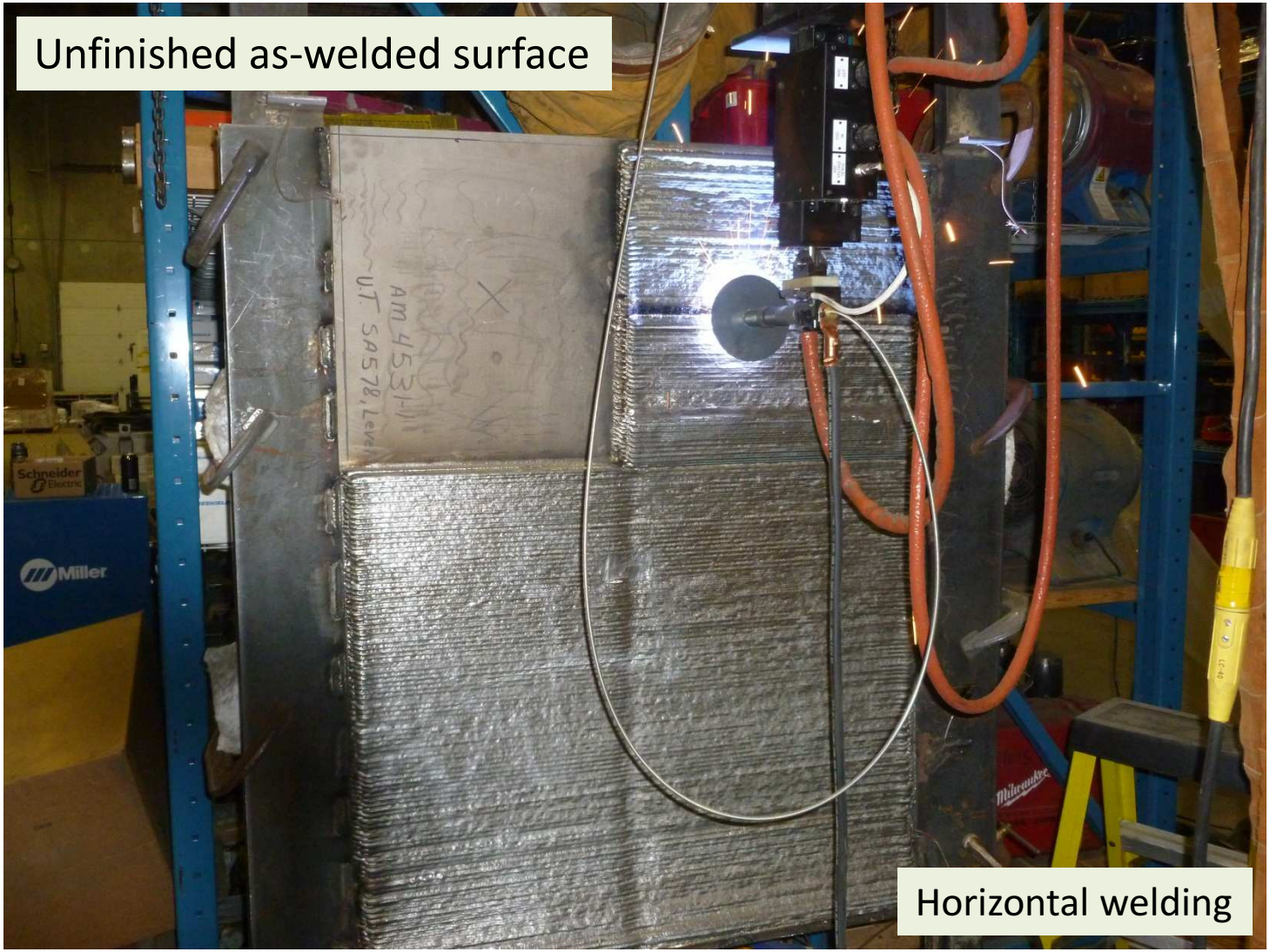
- 3’ x 4’ x 5/8”
- A36 base metal
- 304L SS clad
- Tensile 67.2 ksi, Yield 41.5 ksi, 36% in 2”

Weld overlay:

- Inconel 625
- Two and three 3/16” layers
- Weld on base metal or clad



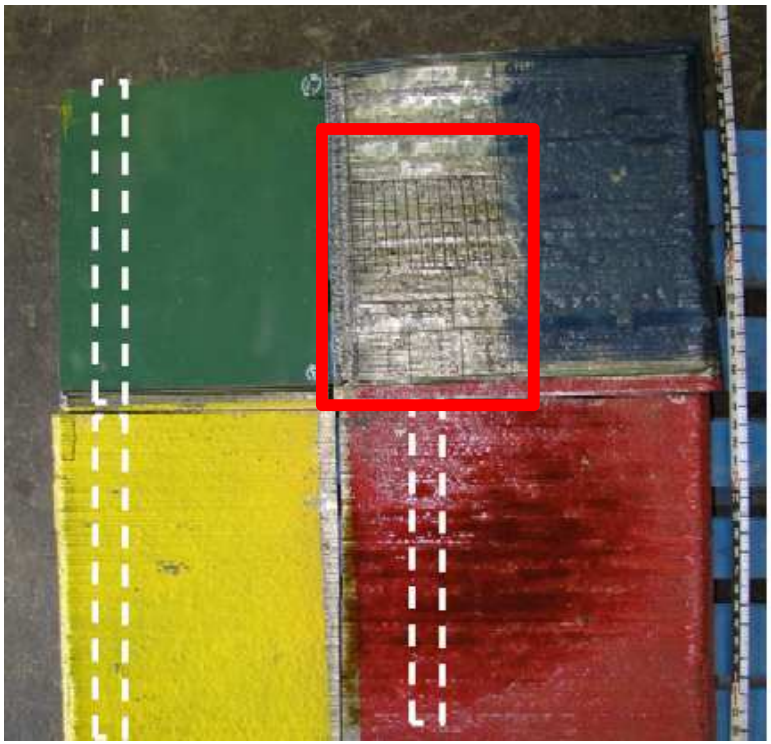
Automated Welding

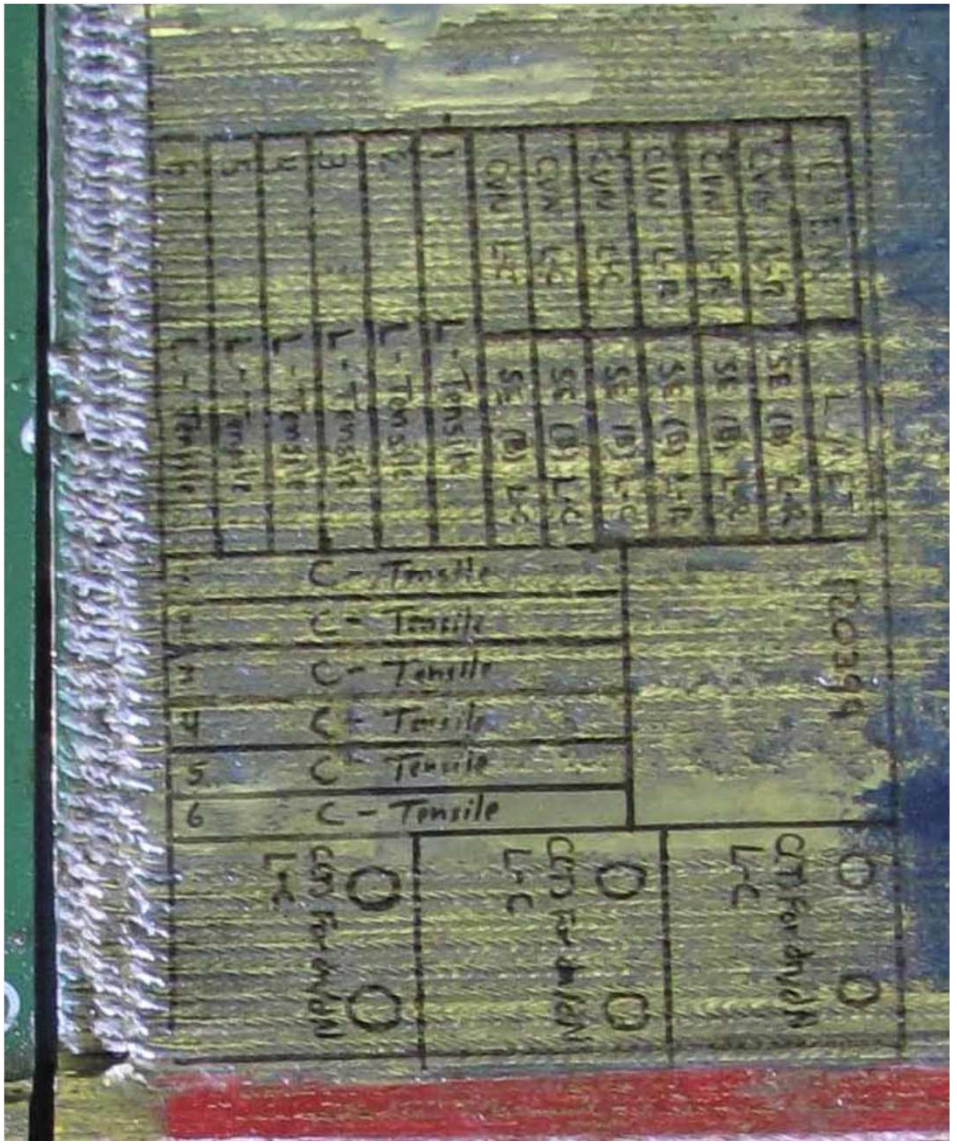


Test Scope

- Tensile Testing
- Metallographic Examination
- Hardness Survey
- Fracture Toughness and Fatigue Crack Growth
- Crack Growth
- Chemical Analysis
- Fatigue Testing

Test Specimens



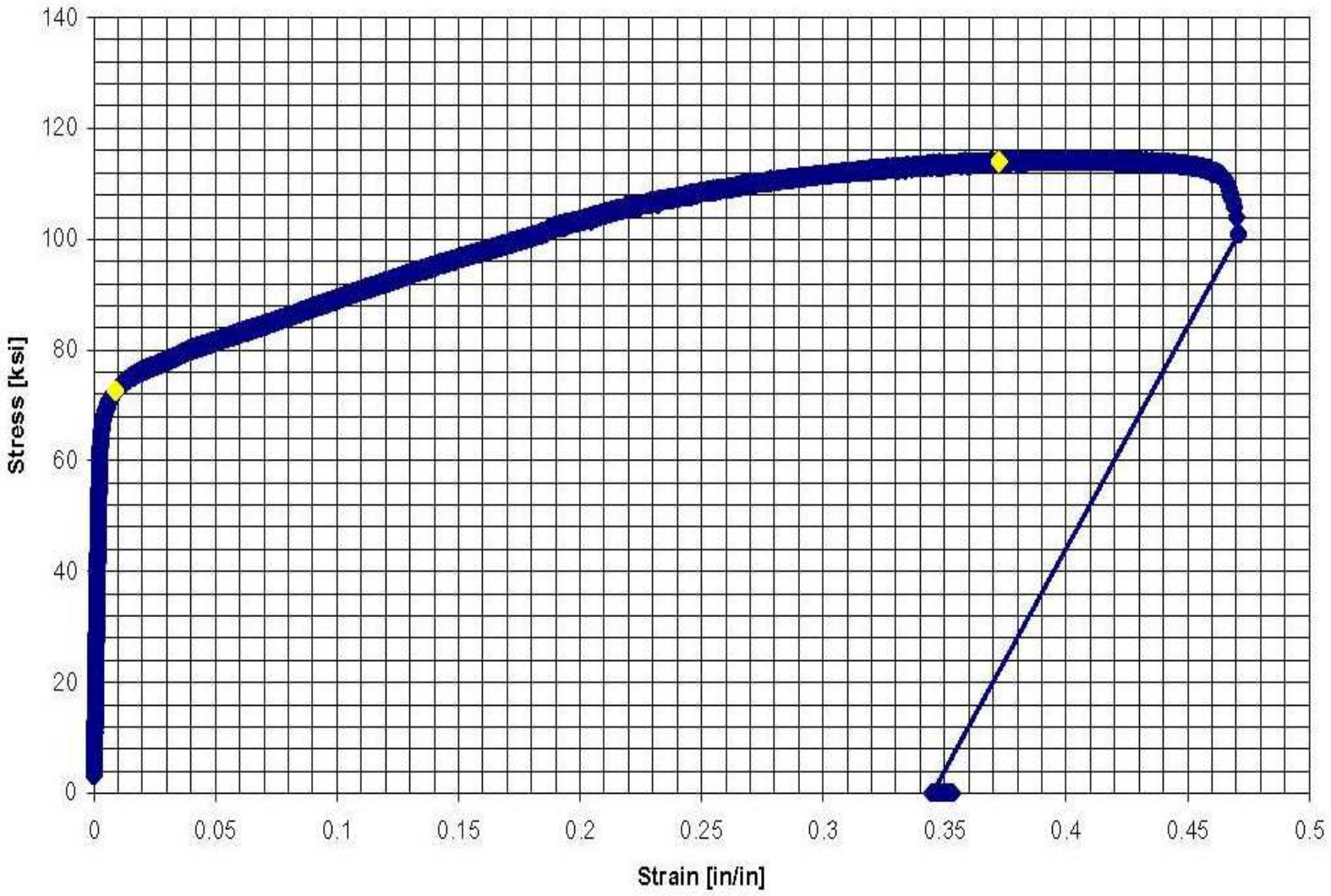


Tensile Testing

Basic mechanical strength of as-welded overlay.

- At room temperature
- At 450°F - typical mid-quench temperature.

Example Stress-Strain Diagram



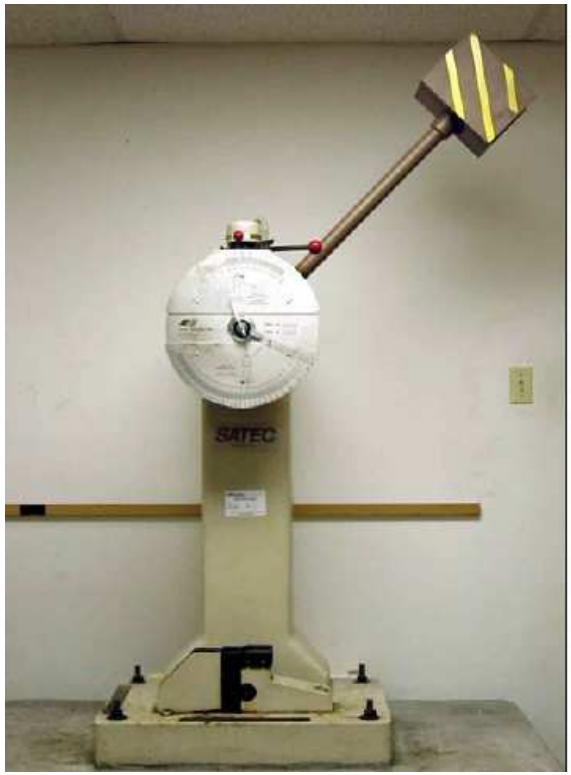
Toughness

Quantify ability to resist cracks.

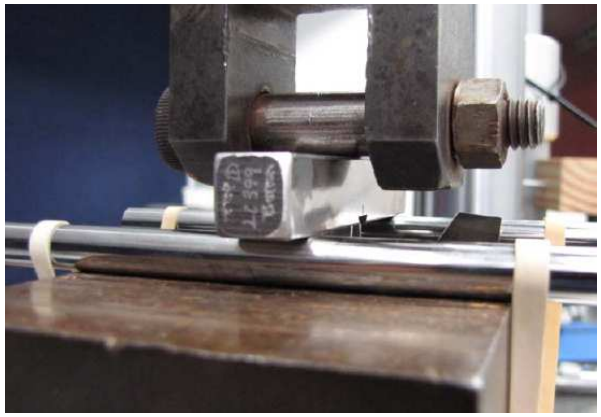
- Charpy V-notch Impact Test
- Fracture Toughness - Crack Tip Opening Displacement (CTOD), J_{IC}
- Crack Growth

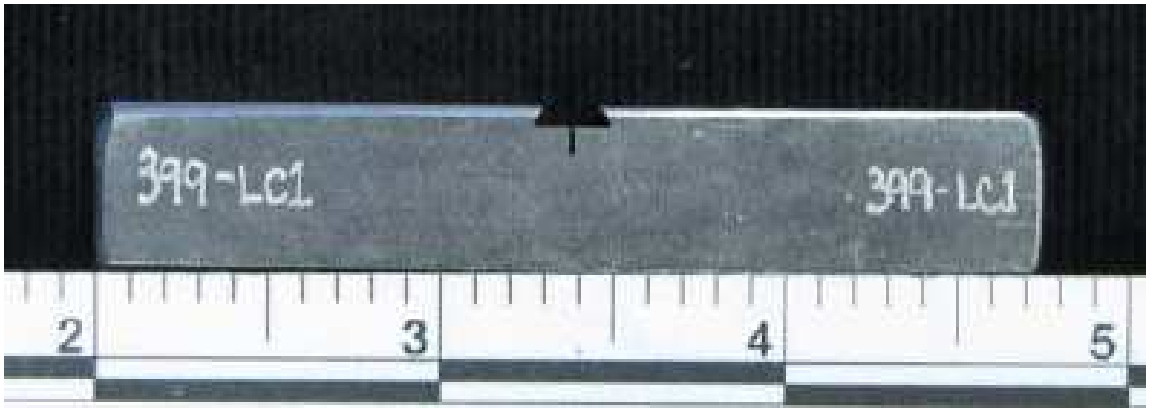
Charpy V-Notch Impact Testing

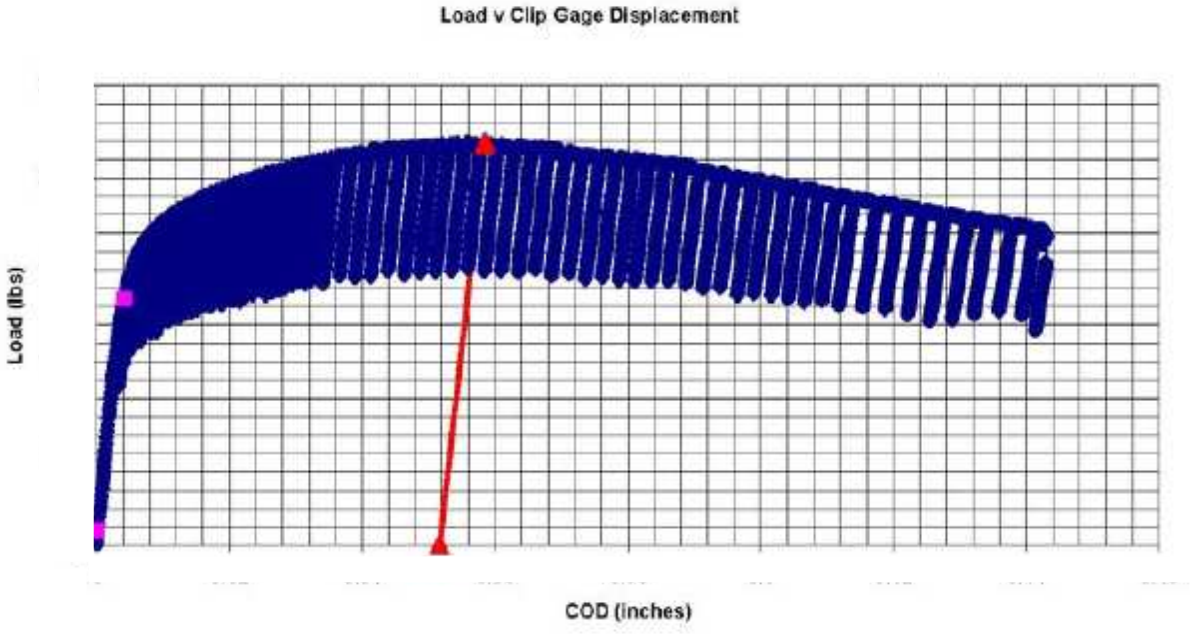
- Full-size specimens
- Ambient temperature
- Set of 3 specimens

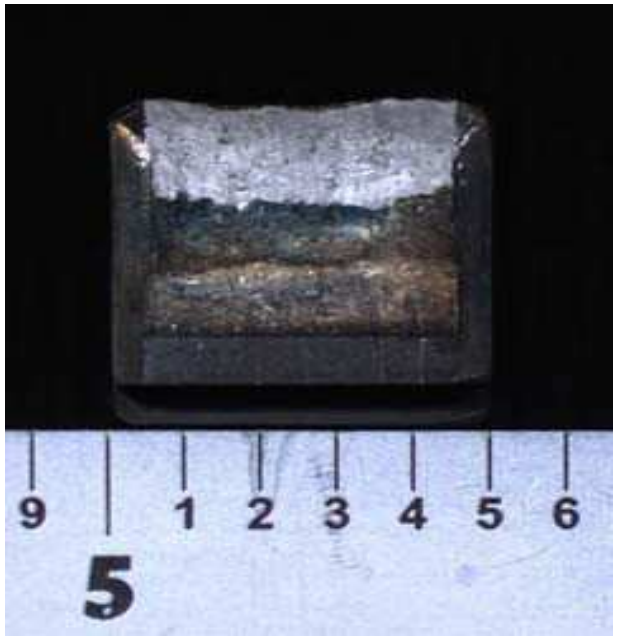


Fracture Toughness



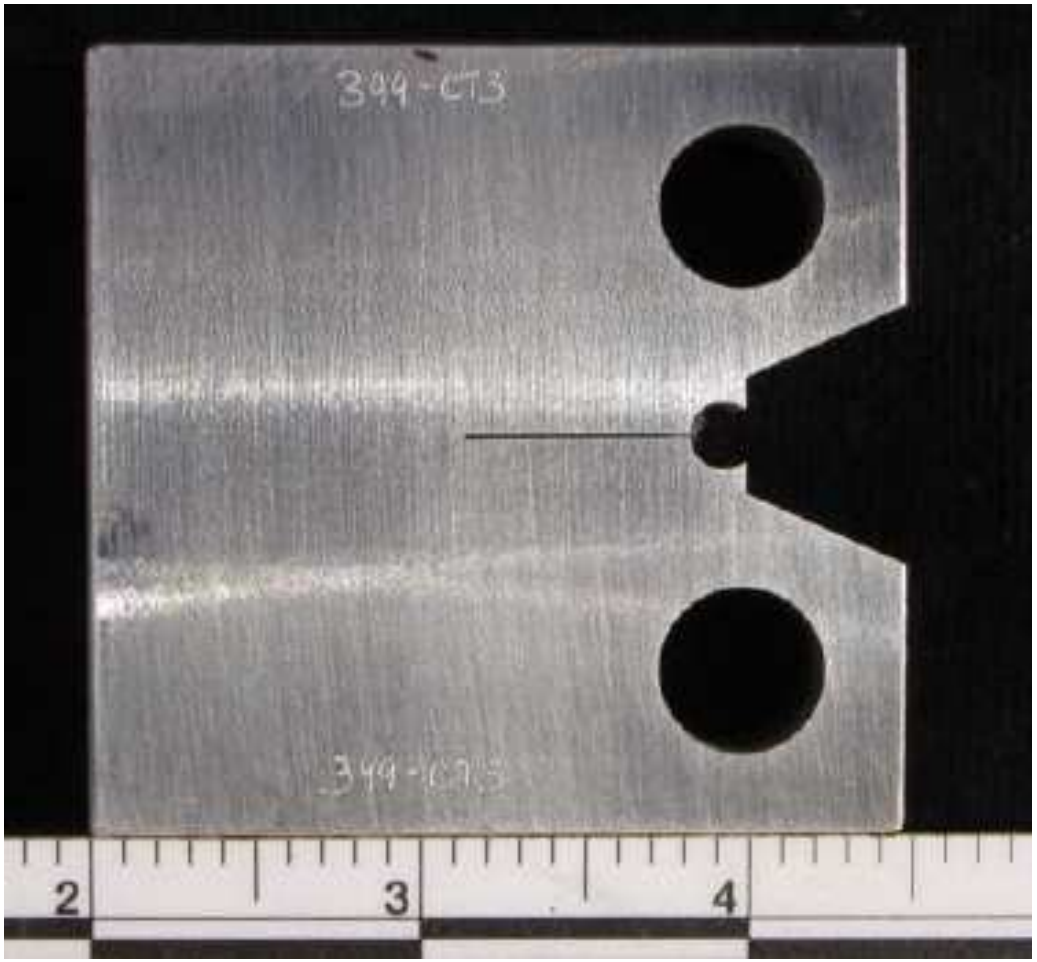






Fatigue Crack Growth

Crack propagation rates in through-wall & circumferential directions.



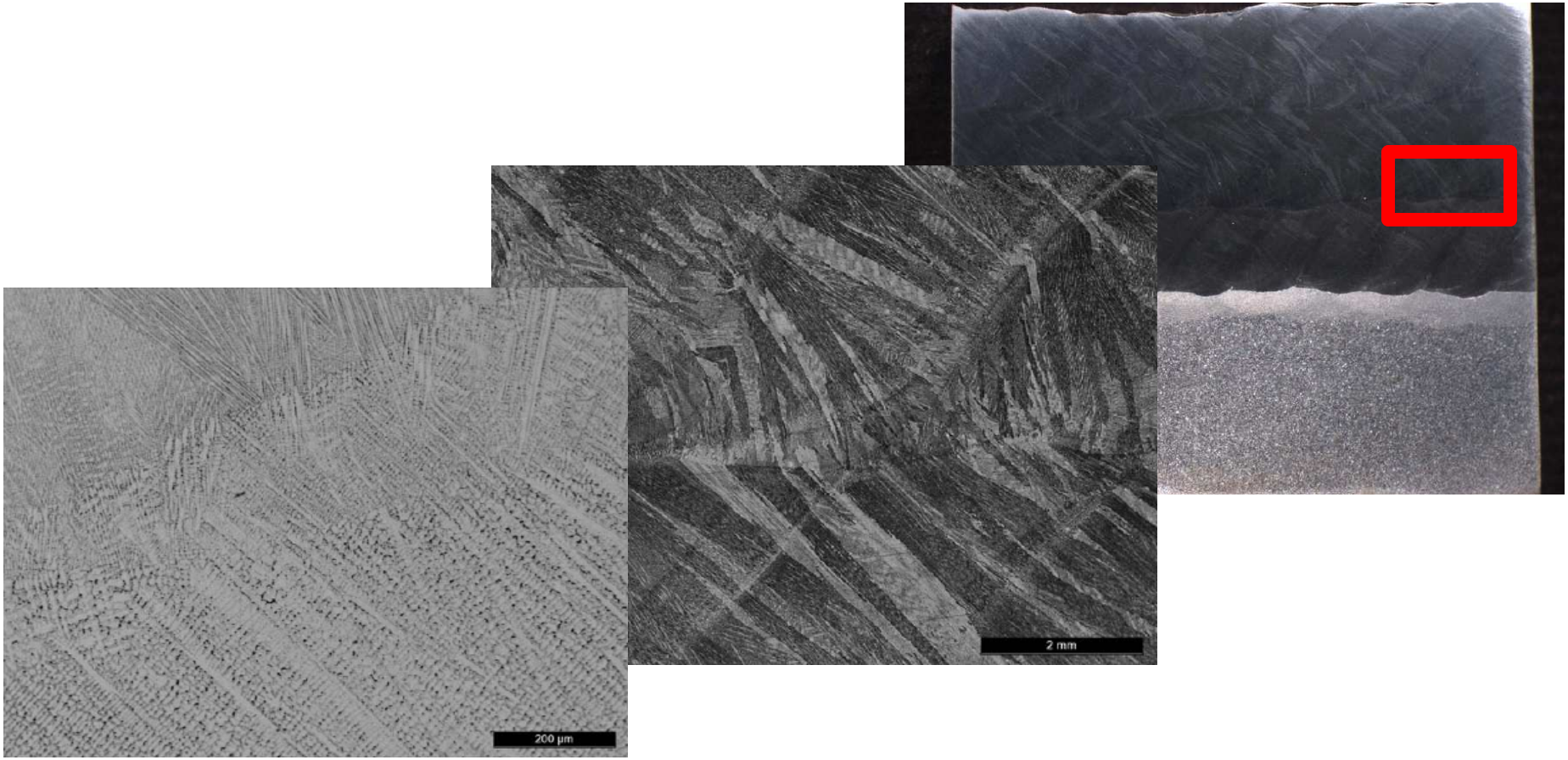
Metallographic Examination

Examination and documentation of the quality of bond between the overlay and base metal.

- A longitudinal cross section through the thickness is removed for metallographic examination of base metal and each of the three overlay quadrants.
- The fusion line of each of the overlay regions is photo-documented at various magnifications.

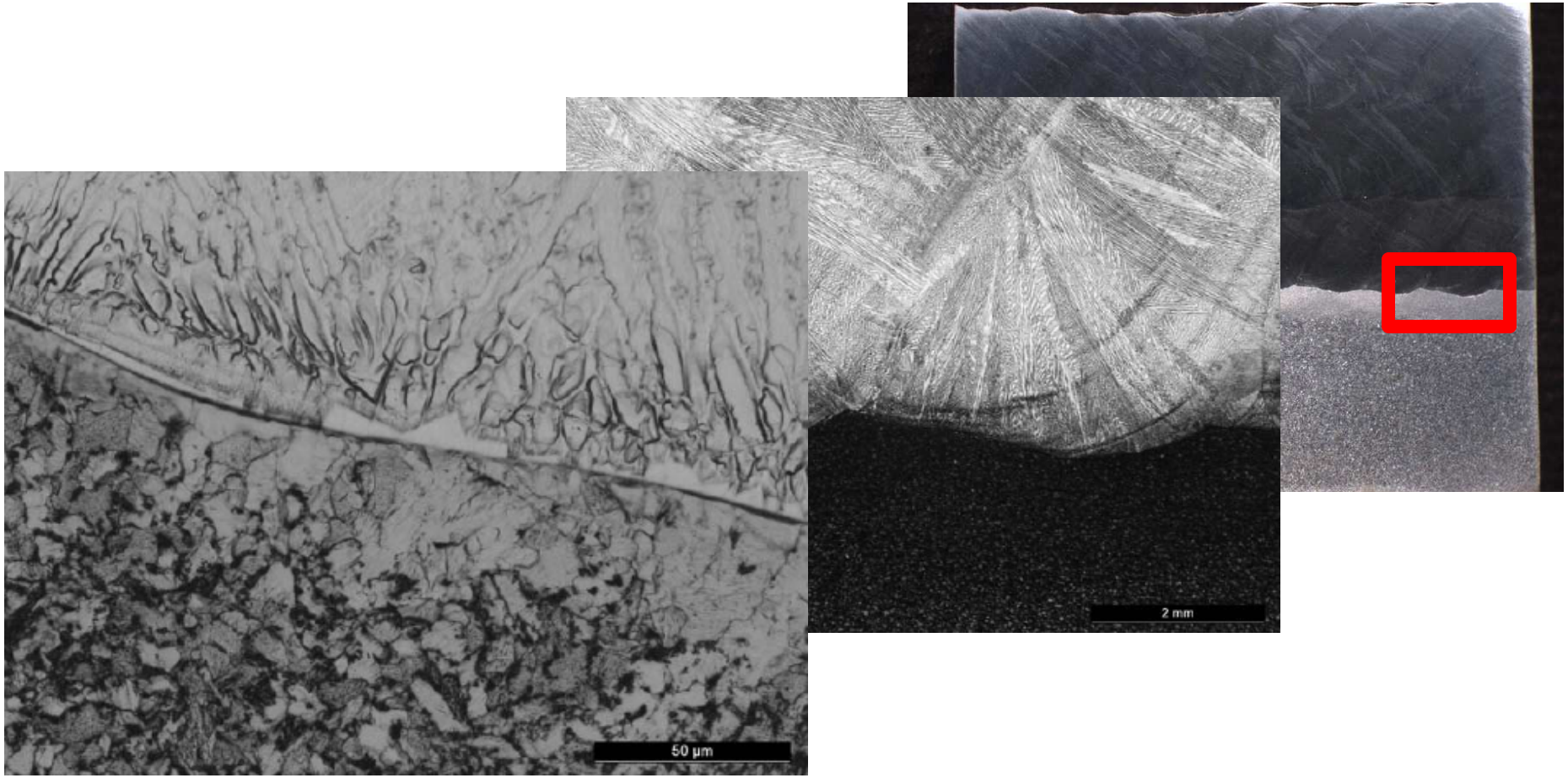
Metallographic Examination

Bond quality between the layers.



Metallographic Examination

Bond quality between base metal and weld.



Hardness Survey

- Microhardness testing was performed on each of the metallographic cross sections per ASTM E92.
- This was followed up with Rockwell hardness testing per ASTM E18.
- Results consistently showed the overlay material to have Rockwell B hardness values from 91 to 98.
- Microhardness measures converted reasonably well the Rockwell measurements; they also corresponded to hardness values for wrought and annealed Inconel 625.

Chemical Analysis

- Conducted to determine the chemistry of the three layers of the as-welded overlay.
- Matches nominal composition.

Element	Top Overlay Weld Pass Composition [weight %]	Middle Overlay Weld Pass Composition [weight %]	Bottom Overlay Weld Pass Composition [weight %]	Inconel 625 Nominal Composition [weight %]
Carbon	0.023	0.022	0.021	0.05
Manganese	0.11	0.11	0.11	*
Phosphorus	0.006	0.006	0.007	*
Sulfur	<0.002	<0.002	<0.002	*
Silicon	0.19	0.18	0.19	*
Iron	0.34	0.57	0.79	2.5
Molybdenum	8.49	8.59	8.60	9.0
Chromium	22.18	22.23	22.10	21.5
Copper	0.11	0.11	0.11	*
Aluminum	0.13	0.13	0.13	0.2
Vanadium	<0.01	<0.01	<0.01	*
Titanium	0.18	0.18	0.18	0.2
Niobium	3.47	3.46	3.60	3.6
Cobalt	0.05	0.05	0.05	*
Boron	<0.001	<0.001	<0.001	*
Tungsten	0.03	0.03	0.03	*
Zirconium	<0.01	<0.01	<0.01	*
Tin	<0.005	<0.005	<0.005	*
Nickel	Balance	Balance	Balance	61.0

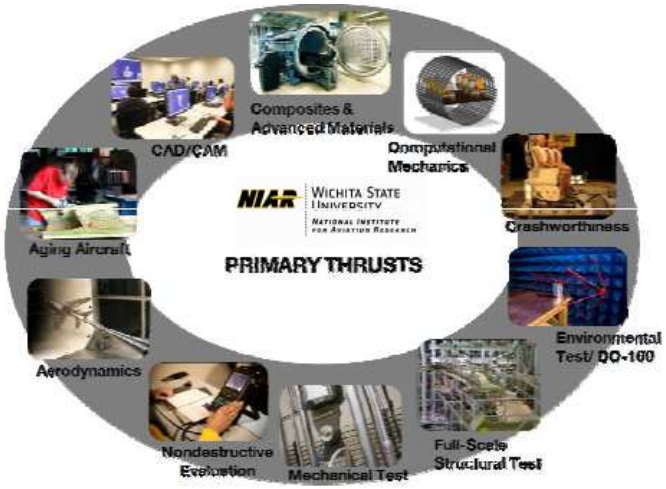
Fatigue Testing

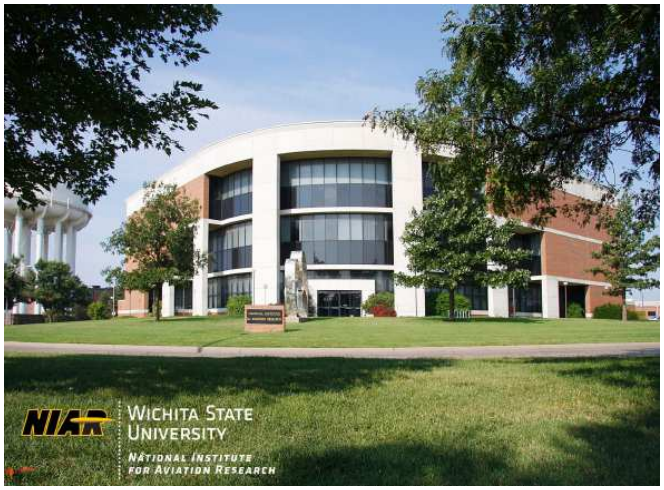
- S-N fatigue curve for as-welded overlay.
- Qualitative comparison of fatigue strength of un-repaired plate (green), repaired-on-base plate (red), and repaired-on-clad plate (yellow).
- Metallurgic examination of fracture surface to determine modes of failure (e.g. fatigue, overload, fracture,..) and initiation locations (e.g. overlay, base metal, clad, interface,..).

Fatigue Testing

- Important for severe cyclic operation
- Isothermal room temperature tests
  - Standard axial tests for as-deposited weld
  - Fully-reversed bending for composite plates

Fatigue Testing Facility





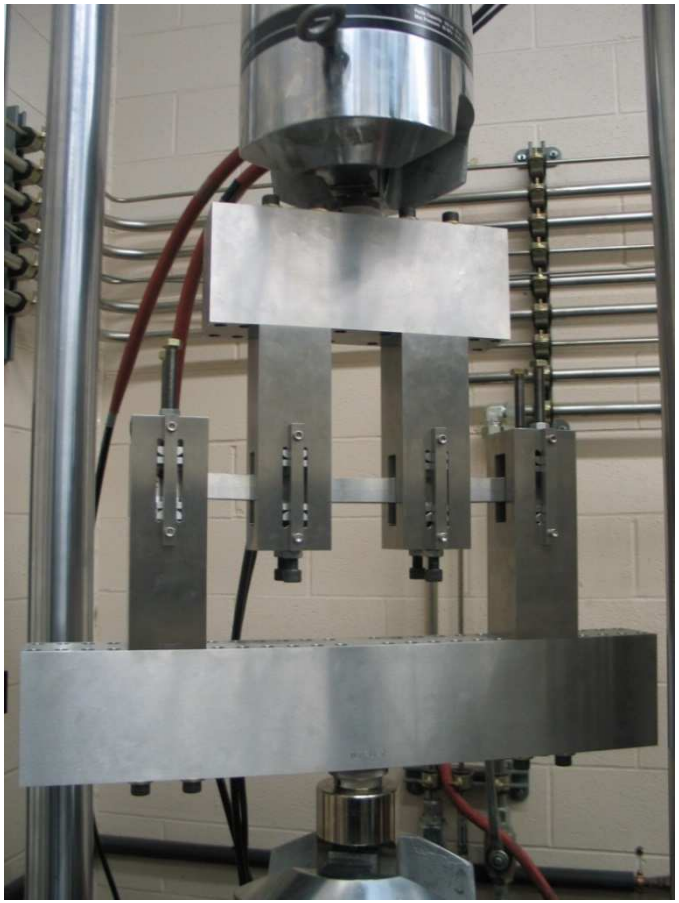
Fully-Reversed Bending Fatigue

- Challenging
  - Coupon thickness not perfectly uniform.
  - Coupons not perfectly flat.
  - Weld overlay surface not perfectly smooth.
  - Non-symmetric coupons
  - Two or three materials involved
- Non-standard procedure
- Custom fixtures
- Costly
- Time-consuming

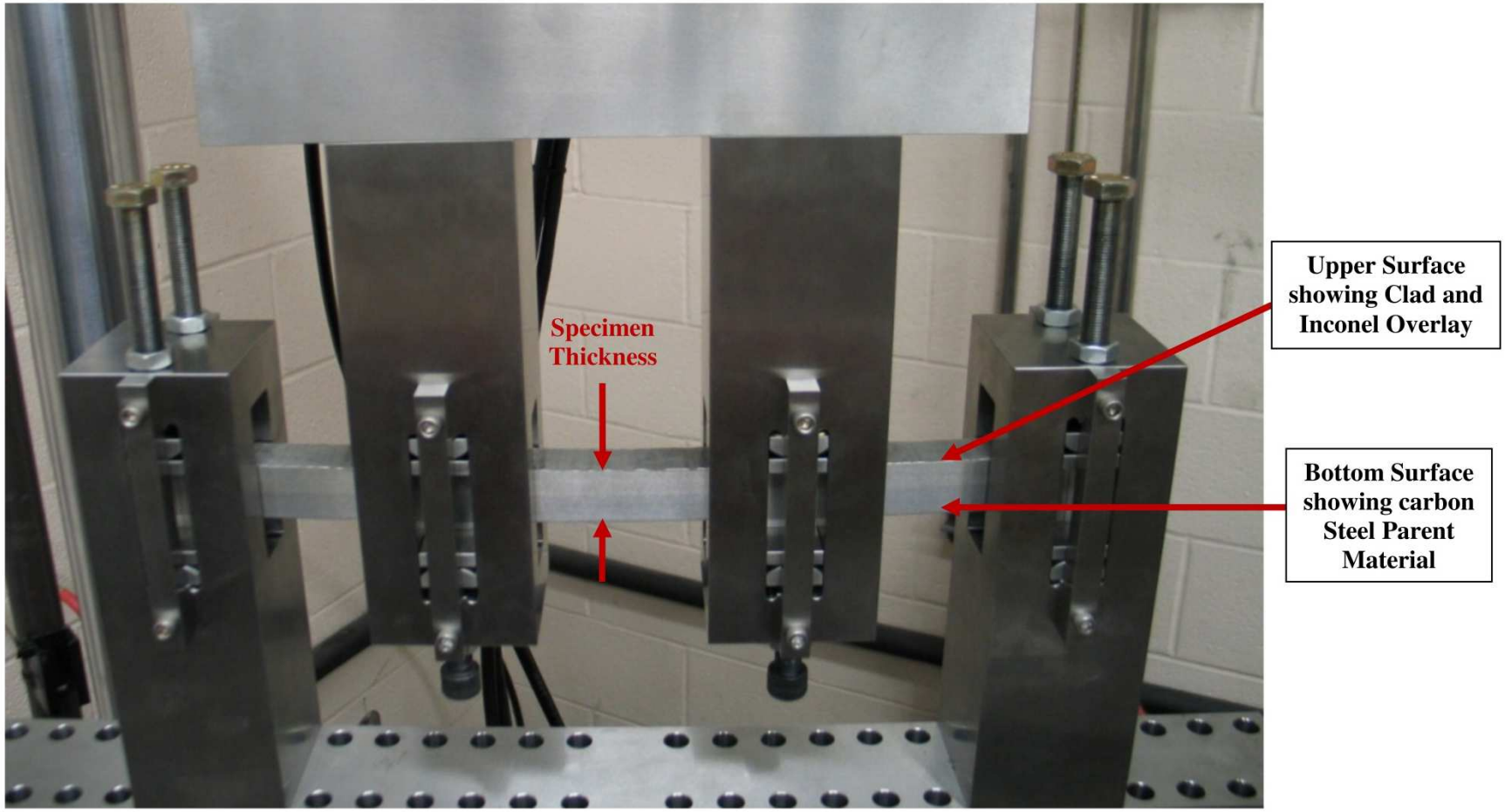
Fully-Reversed Bending Test

Standard frame

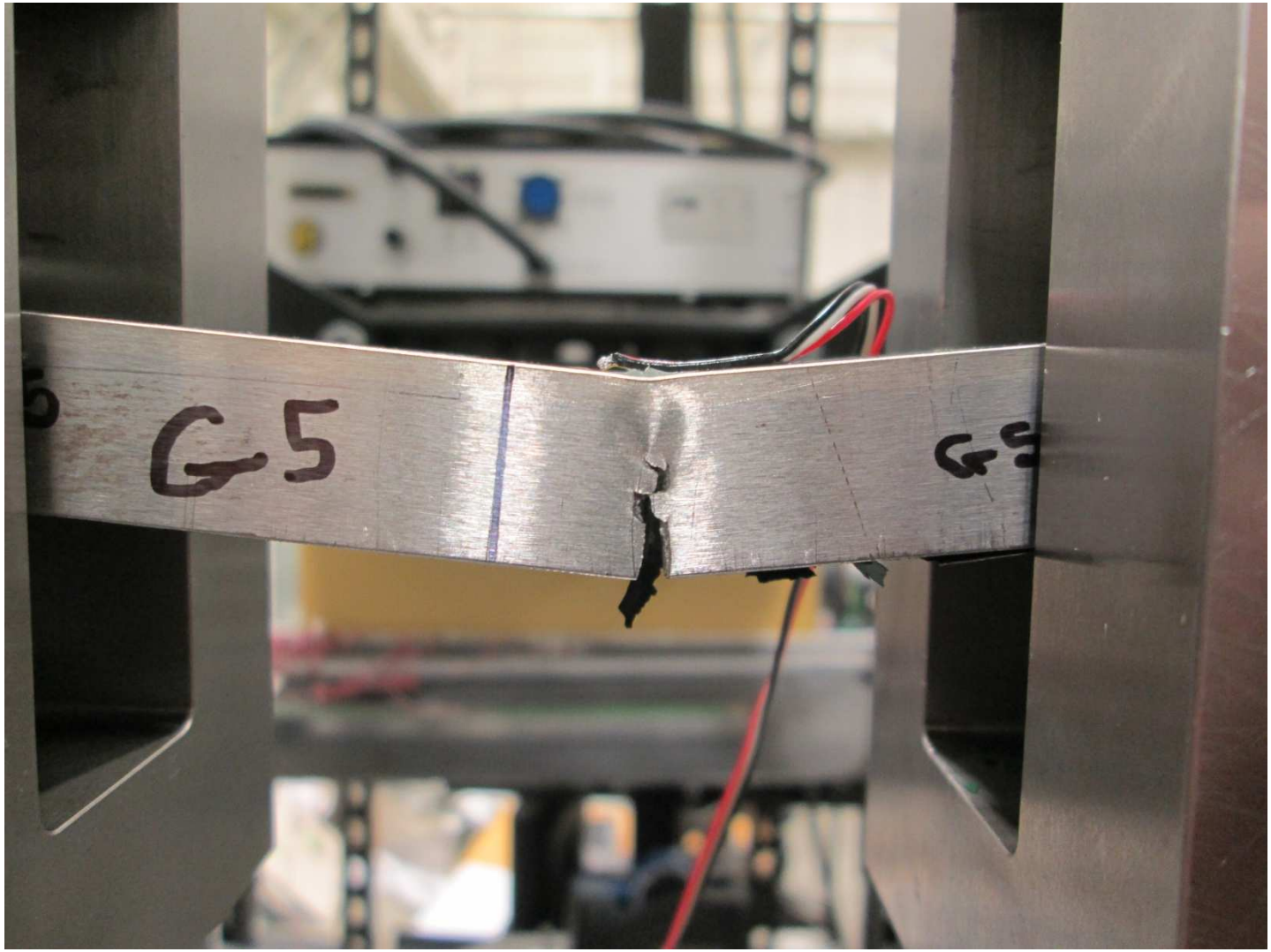
Custom fixture



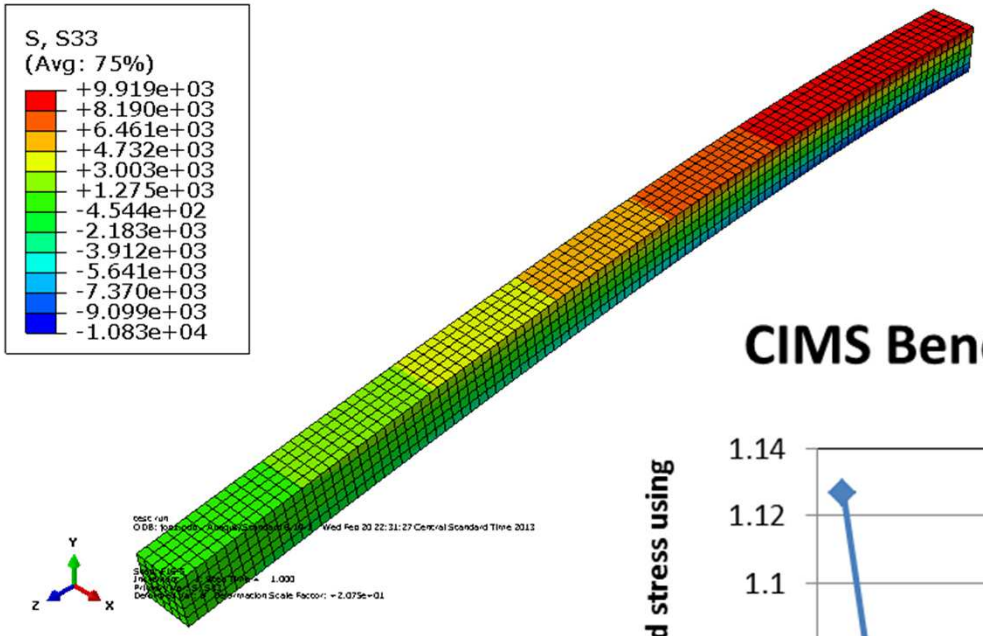
Bending Test Close-Up

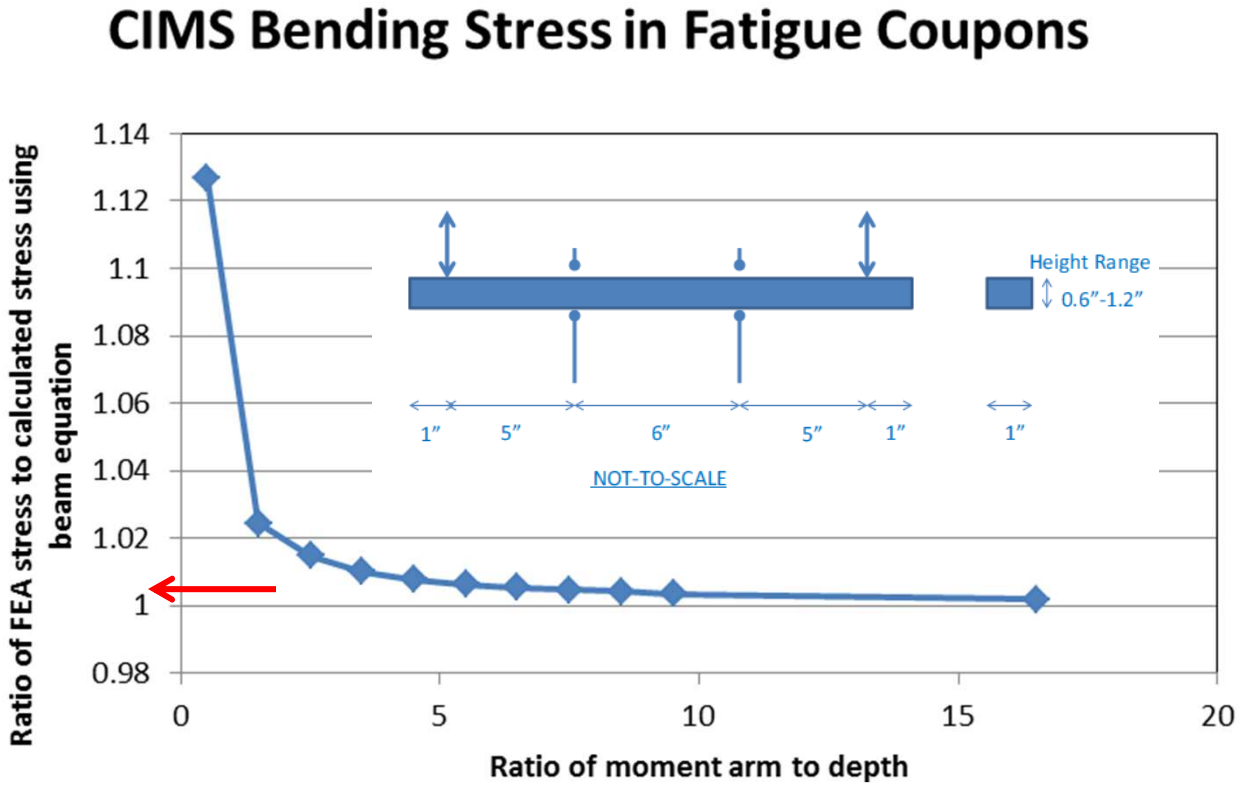


Fatigue Test Failures



Verification of Bending Test





Fatigue Testing Coupons

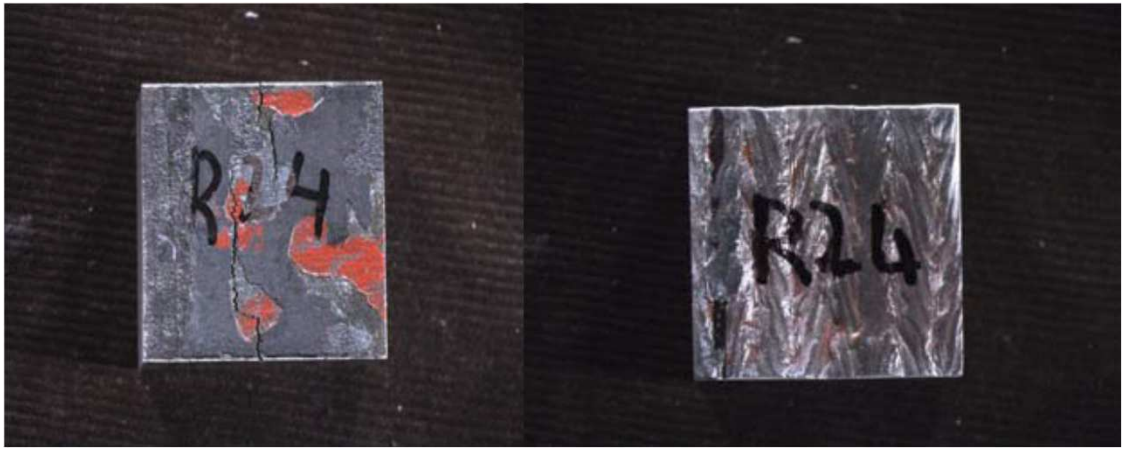
Fully-reversed bending.

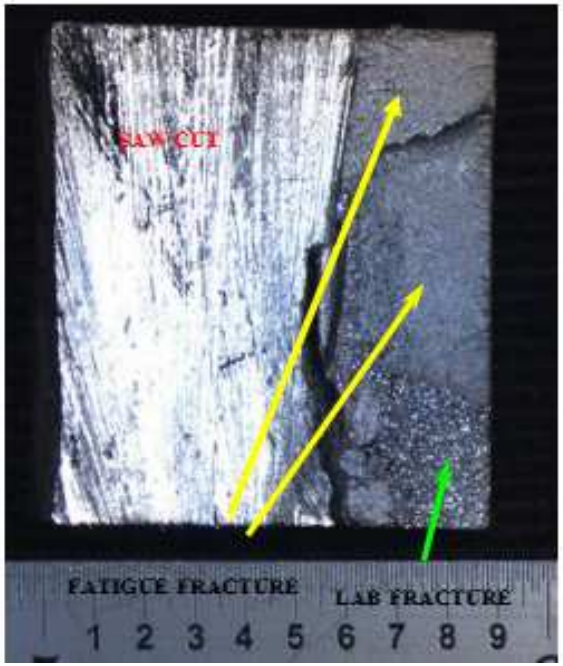
Standard axial fatigue.

Bending Test Fractography

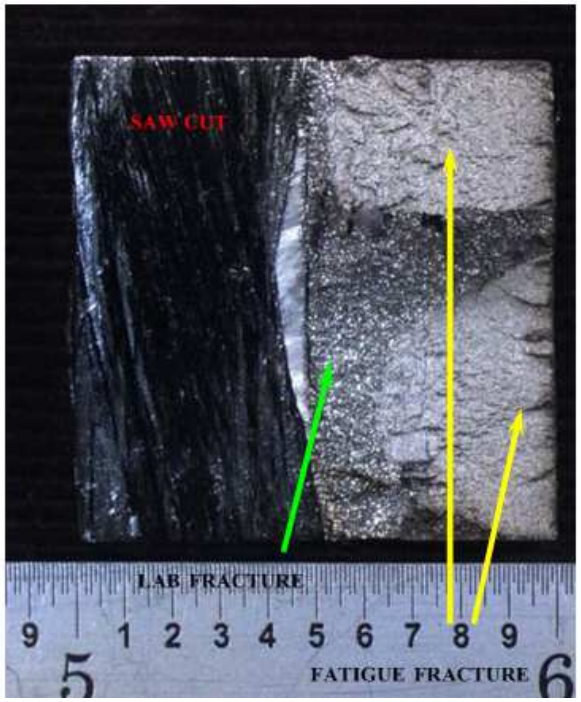
- All fractures initiated in the base metal and propagated toward the opposite surface (cladding or overlay).
- Ratchet marks were present on every sample. These marks are indicative of multiple fatigue crack origins initiating on slightly different planes. As the fractures grow the step between the planes creates the ratchet mark.
- Fatigue crack initiations were distributed across the sample face indicating a uniform loading along the side of the specimen.
- No visually observed defects were associated with crack initiations.

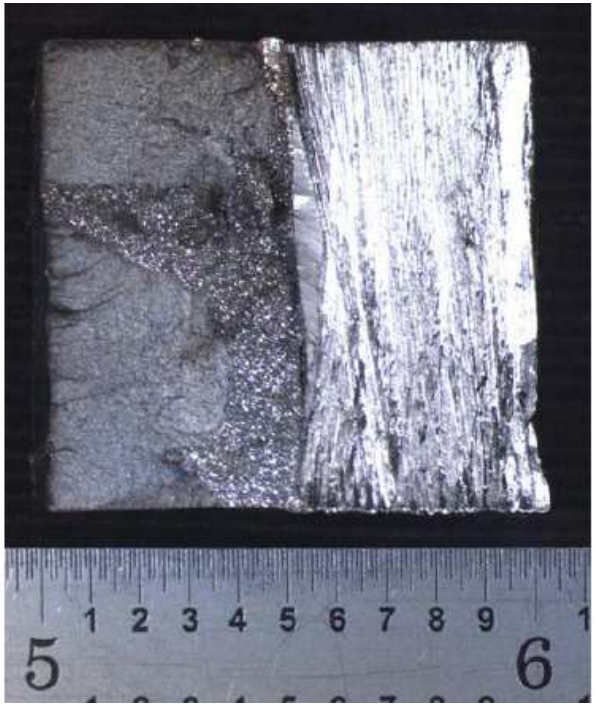
Example Red (2 layers on base)



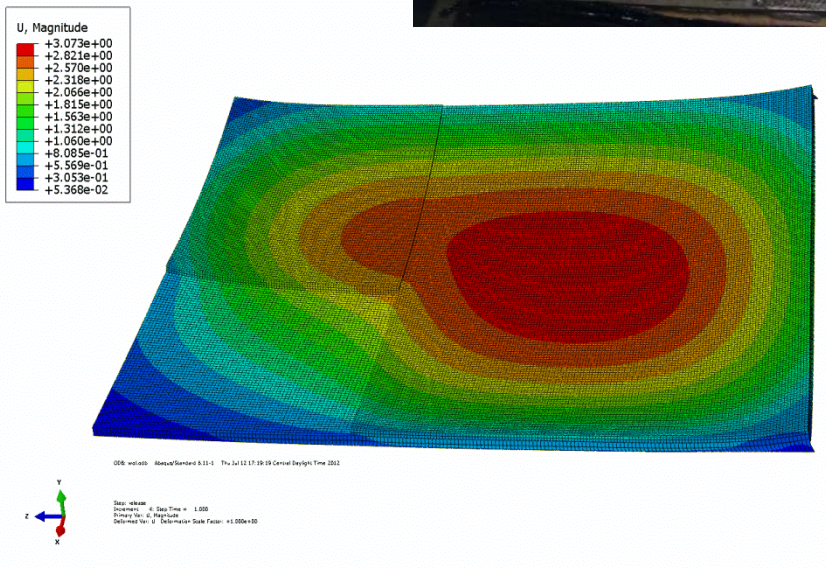


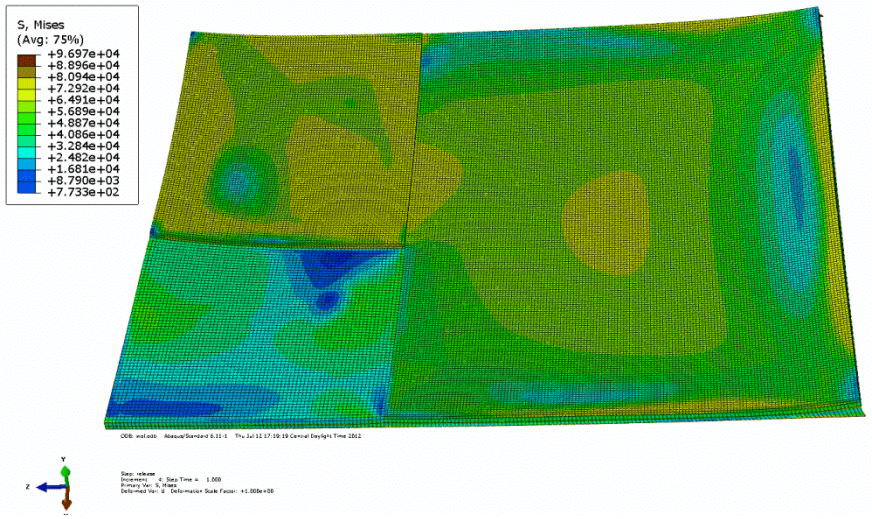
Example Yellow (2 layers on clad)



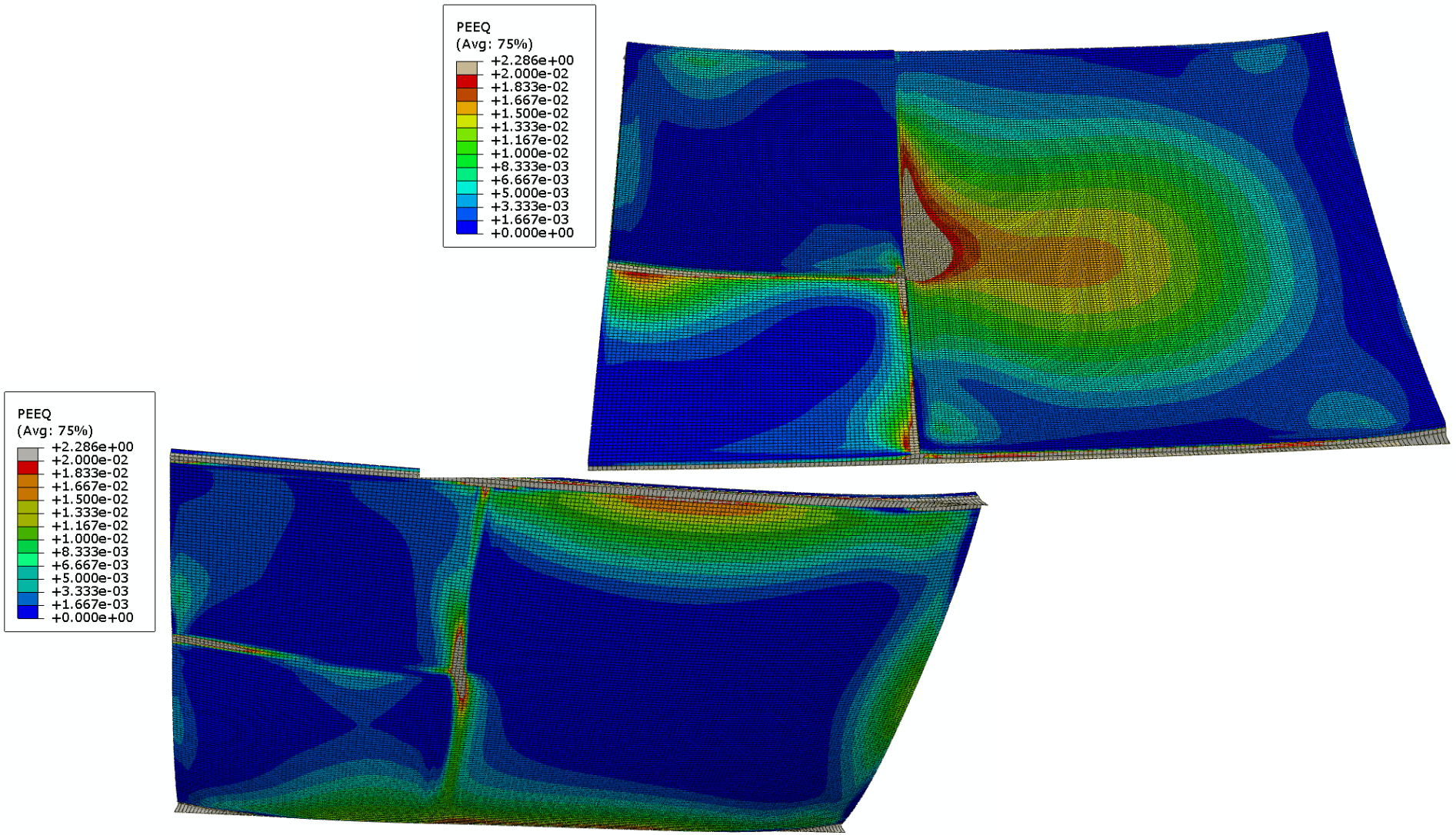


Finite Element Simulation



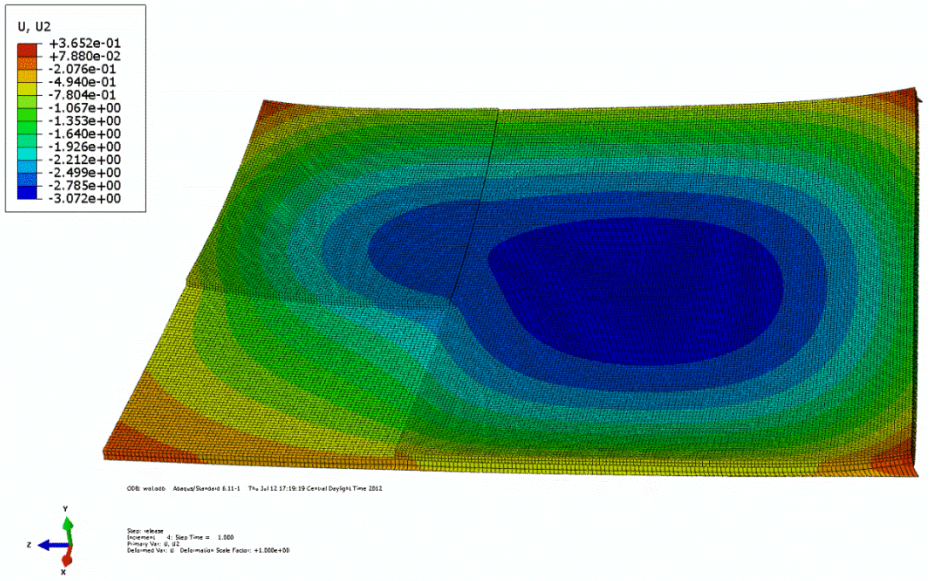


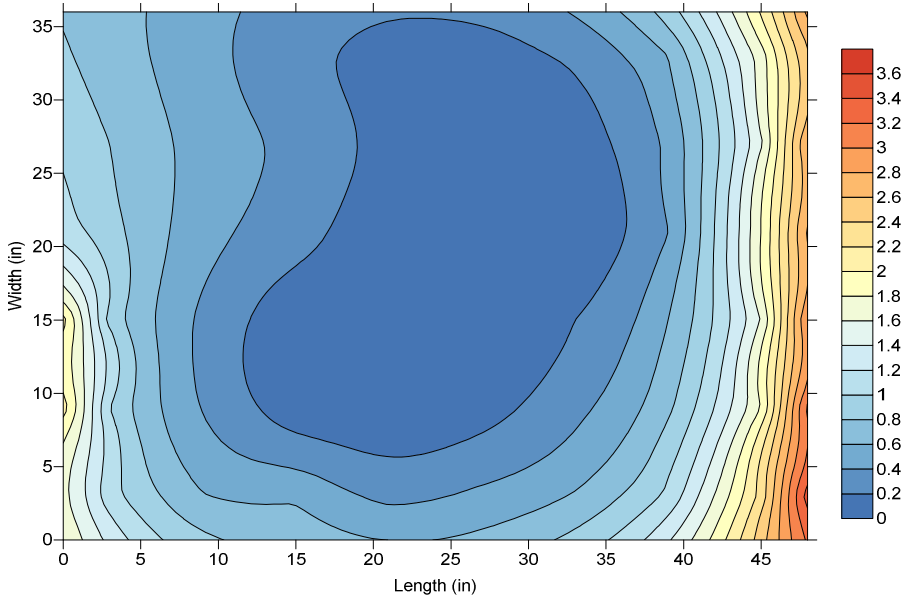
Equivalent Plastic Strain



Calculated vs. Measured

- Maximum differential displacement in out-of-plane direction (Maximum minus minimum Y-axis displacement):
  - Calculated: 3.4 inches.
  - Measured: 3.465 inches.
- Magnitude of distortion correlated well but cupping pattern was slightly different probably because some edge restraints broke off during welding.





Summary

- Automated weld overlay can be used to provide consistent high-quality structural repairs to large equipment.
- Test program has provided unique material properties of as-welded Inconel 625 overlays that can be used for performing structural integrity calculations.
- Weld overlays can substantially improve fatigue life of a vessel wall. Also, applying weld overlays directly on cladding may result in a more significant improvement of fatigue life.
- Modeling procedure correlated well with measured distortions.
- Measured properties and performance are only relevant to subject weld repair procedure.