Distortion and Residual Stress Control in Integrally Stiffened Structure Produced by Direct Metal Deposition

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Outline

- Background and Objectives
- DMD Process – Electron Beam Freeform Fabrication (EBF^3)
- Analytical and Experimental Approaches
- Results
- Summary and Future Plans

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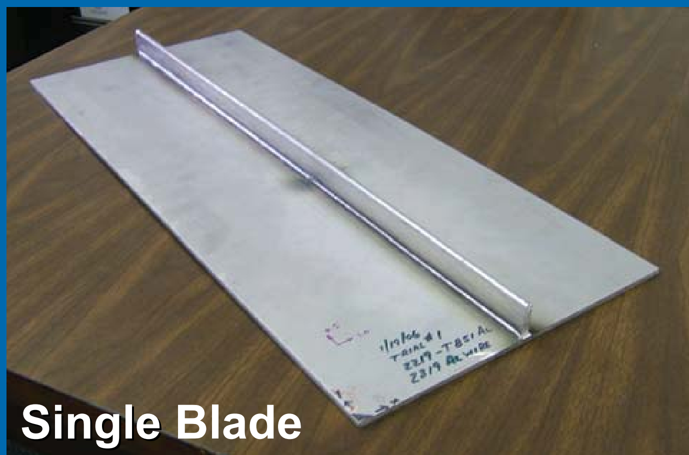
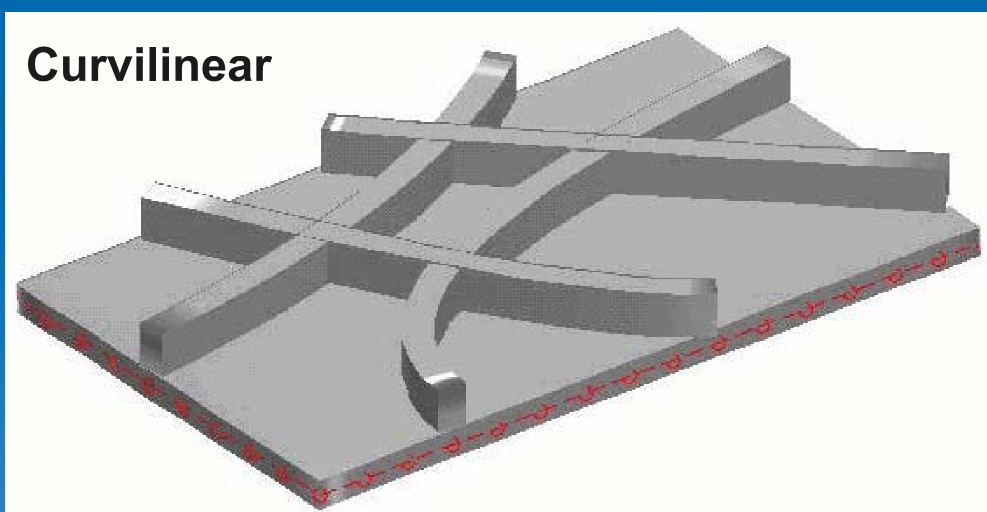
Integrally Stiffened Structure for Aerospace Applications





Features:

- Tailored stiffener arrays
- Near-net-shape fabrication
- Multi-functional novel designs

Benefits:

- Reduced cost, weight, part count, assembly time
- Enhanced structural performance

Fabrication:

- Machining
- Direct Metal Deposition
- Joining Methods

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Objectives

- Use FEA results to guide development of Direct Metal Deposition (DMD) fabrication process for aerospace structures
- Develop experimental methods to control distortion and residual stresses in integral structure produced by DMD
- Understand the effects of geometry, boundary conditions, and processing parameters on distortion and residual stresses in integral structures produced by DMD

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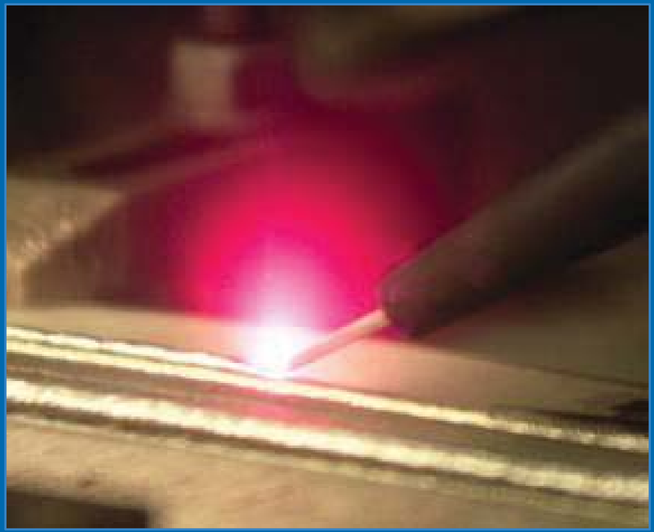
Electron Beam Free Form Fabrication (EBF^3)

- Direct metal deposition process
- Focused electron beam to create a molten pool on a metallic substrate
- Metallic wire fed into molten pool created by electron beam
- Substrate translated with respect to the electron beam to build up 3-D parts layer by layer
- Metallic parts build directly from CAD files without molds or tooling



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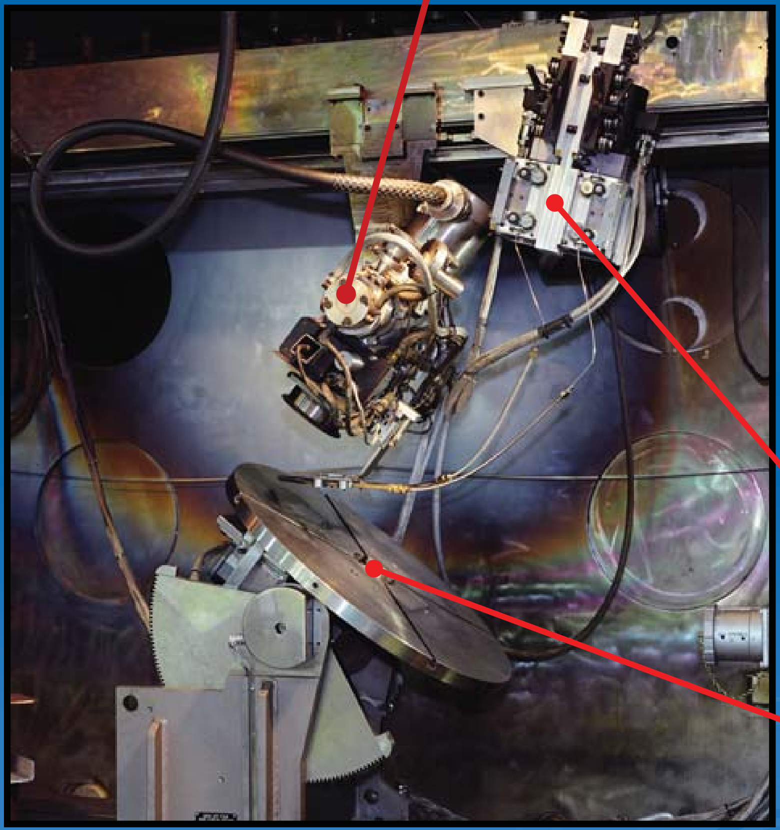
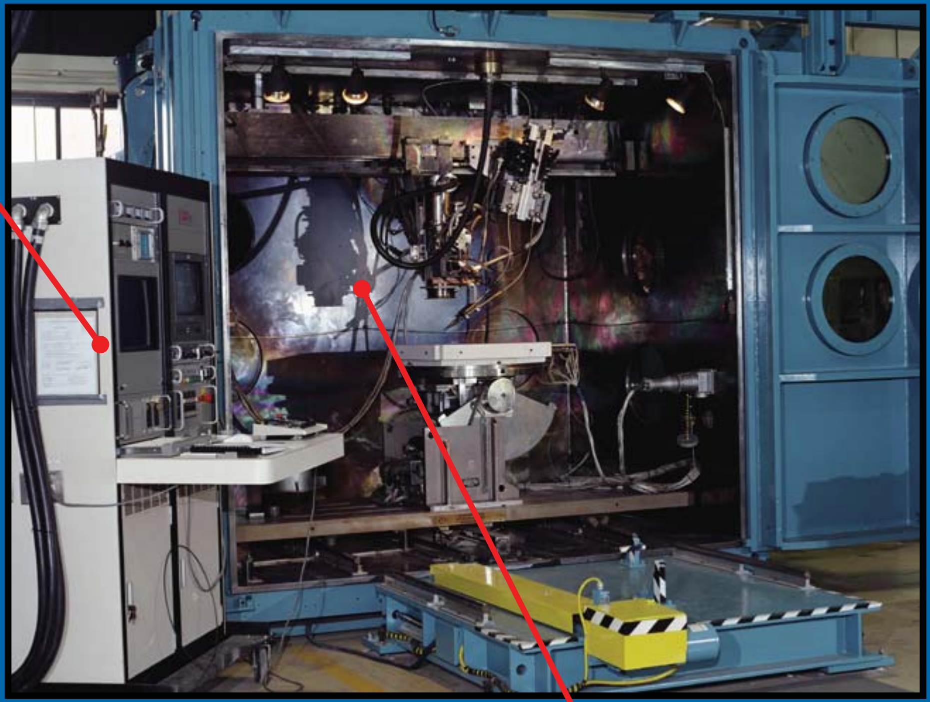
EBF^3 System

Computer Control System

42 kW EB Gun





Vacuum Chamber

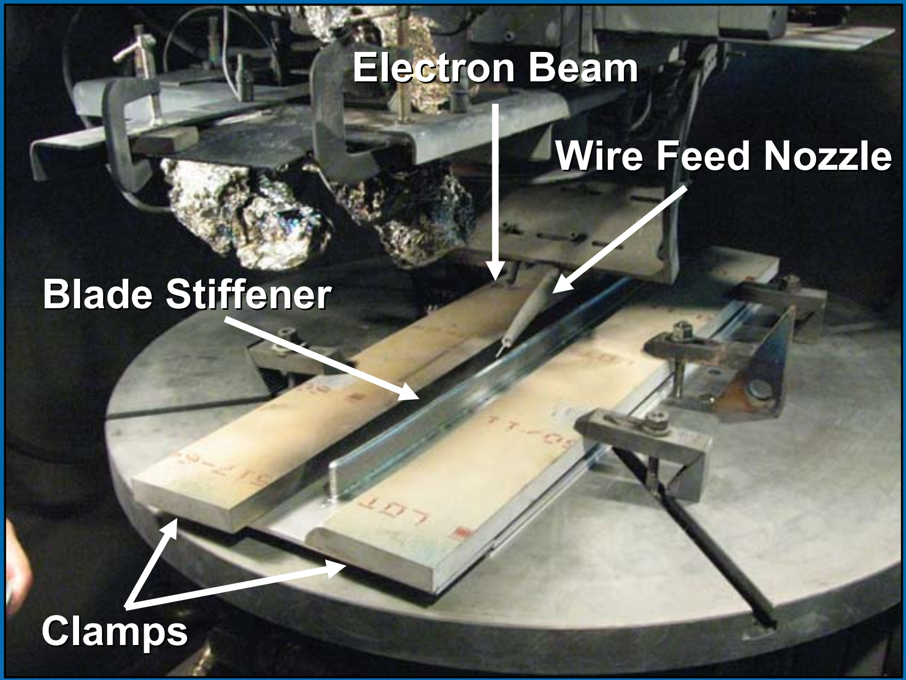
Dual Wire Feeders

Tilt/Rotate Positioner

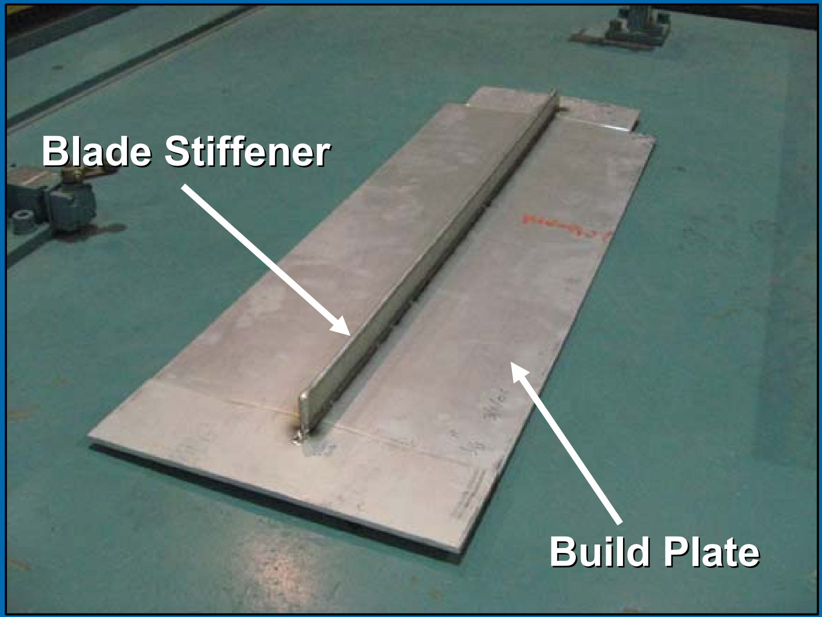
Website: http://ebf3.larc.nasa.gov

Fabrication of Single-Blade Stiffened Panel Using EBF^3 Deposition Process

Fabrication Arrangement



Completed Panel



Build Plate

- Al 2219-T8
- 0.190 in. thick

Wire

- Al 2319

Panel Distortion

- Transverse (across width)
- Axial (lengthwise) curvature

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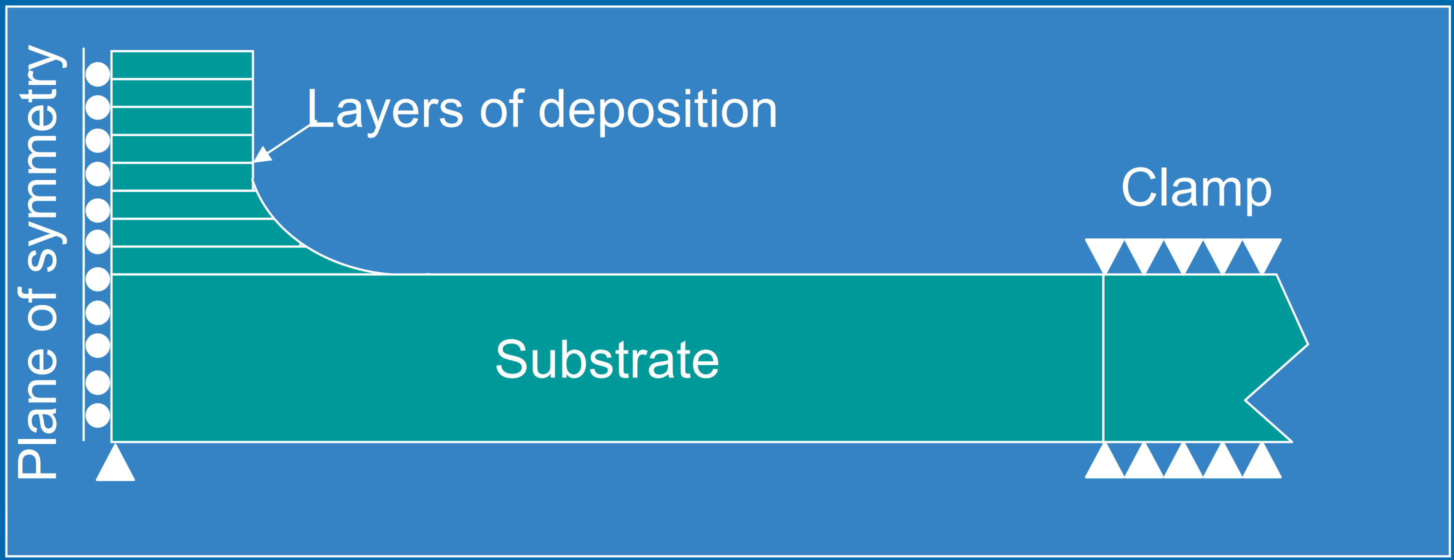
Finite Element Approach

- PATRAN and NASTRAN FEA software
  - 2-D plain strain model
- Transient thermal analysis
  - To determine temperature profiles at any instance
- Thermal-mechanical analysis, nonlinear
  - To determine mechanical strain, stress, and distortion based on temperature change and boundary conditions
  - Elastic / perfect plastic material, temperature dependent
- Repeat transient thermal and thermal-mechanical analysis for each deposited layer
- Mechanical analysis, linear
  - To determine the effects of clamp release

Finite Element Approach – cont.

- All intrinsic processing parameters held constant:
  - wire feed speed, voltage, beam current, translation speed
- Experimental data used to supplement boundary conditions
  - melt pool depth and width
  - temperature profile
  - residual stresses and distortion
- Single-variable parametric study
  - Number of build deposit layers
  - Clamp position / clearance
  - Plate thickness
  - Machined build lands
  - Elastic/plastic pre-strain
  - Selective pre-heating / cooling / insulation

FEA Model



FEA Input Parameters

- Material: Aluminum 2219-T81 base plate and 2319 Al weld wire
- Deposition Temperature = 1200°F (latent heat fusion ignored; melt pool size increased)
- Room Temperature = 70°F
- Yield Stress = 50 ksi (temperature dependent)
- Young's Modulus = 10.5 Msi (temperature dependent)
- Poisson's Ratio = 0.33
- CTE = $12.4E^{-6}$ in/in/°F

Experimental Approach

- All intrinsic processing parameters held constant:
  - wire feed speed, voltage, beam current, translation speed
- Single-variable parametric study
  - Number of build deposit layers
  - Clamp position / clearance
  - Plate thickness
  - Machined build lands
  - Elastic / plastic pre-strain
  - Selective pre-heating / cooling / insulation
- Measurements to determine effect of parametric study on panel distortion and residual stresses and to validate FEA
  - Melt pool depth
  - Temperature distribution
  - Residual stresses
  - Panel distortion

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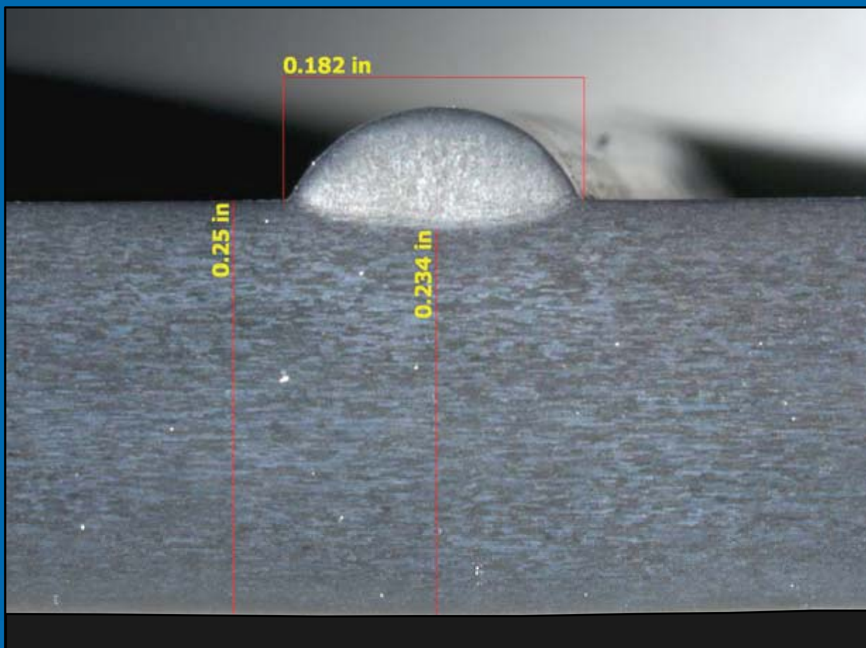
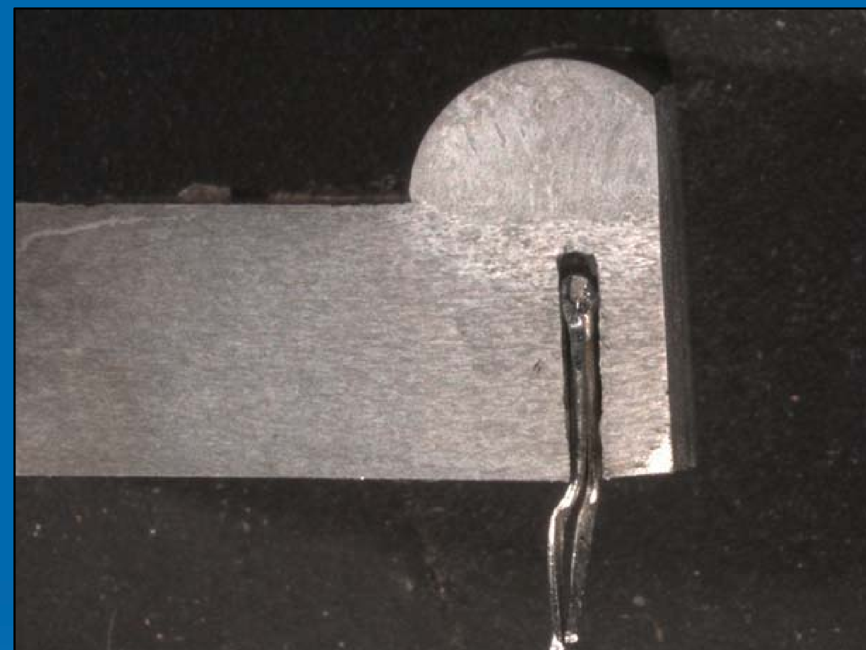
Melt Pool Geometry and Temperature Profile Measurements

- Experimental measurements for FEA input parameters

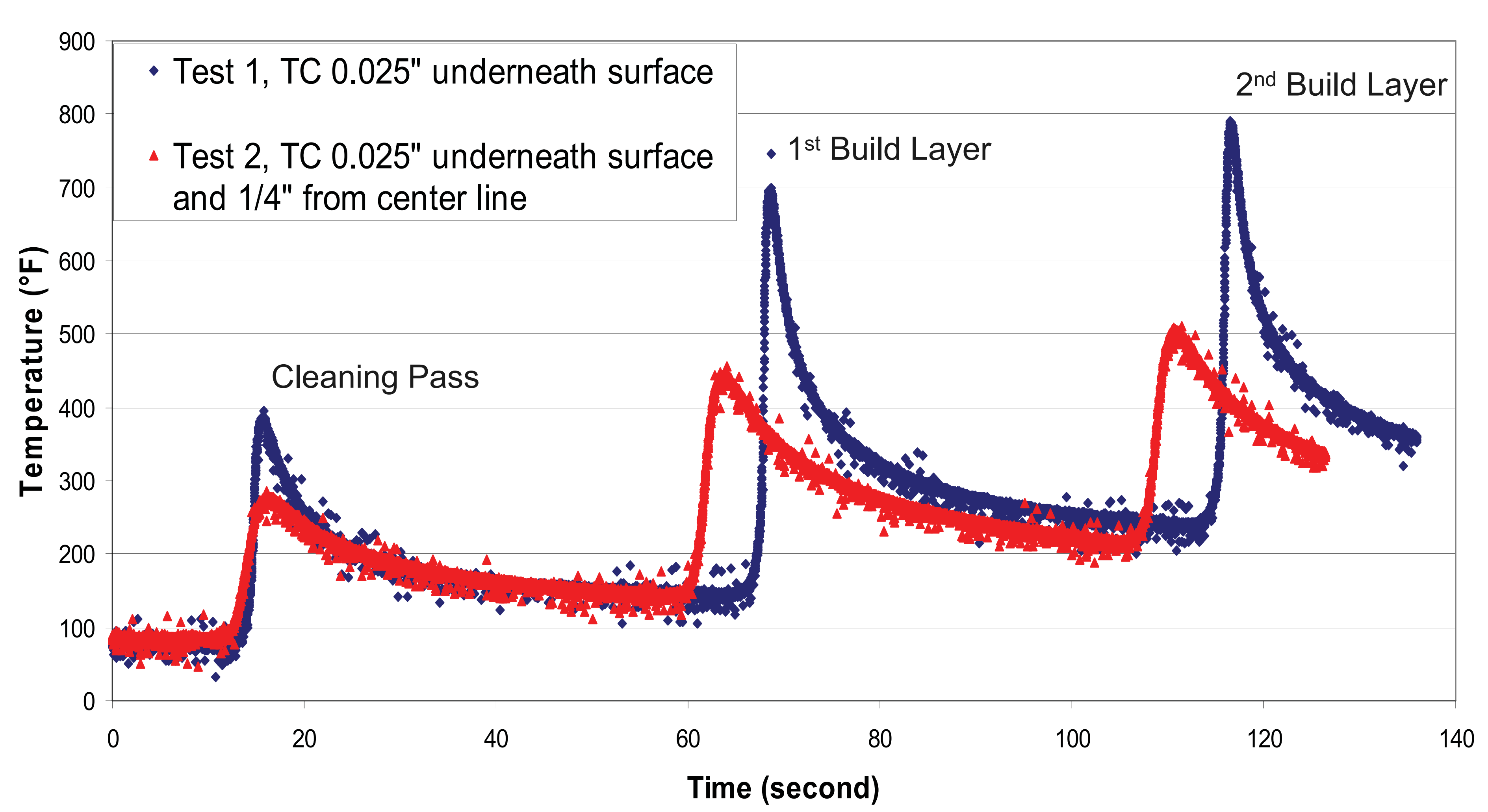




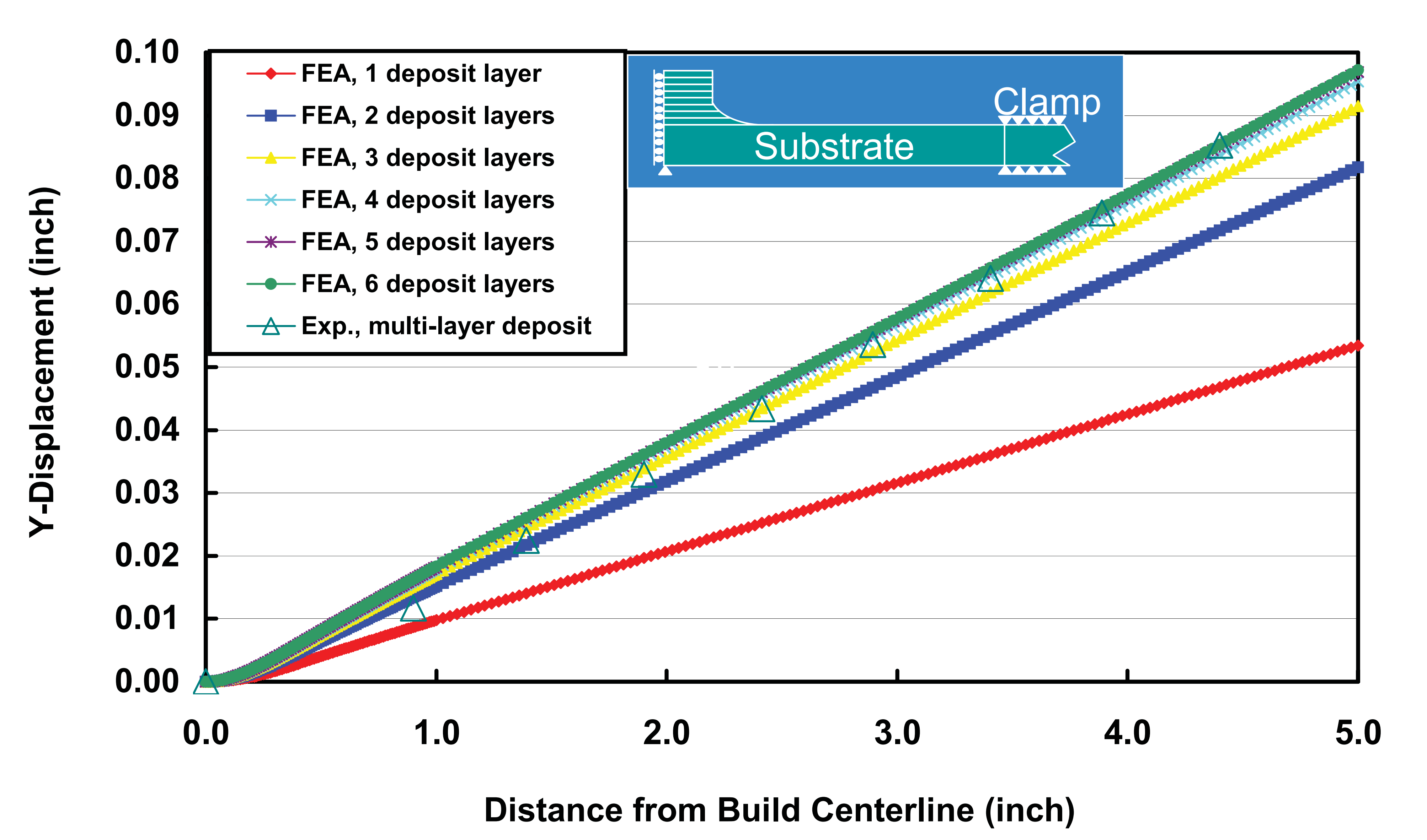
- Melt pool depth estimated at 0.015 in.
- Multiple cross sections of single and two layer builds
- Based on maximum depth

- Thermocouples embedded from back side of build substrate
- Terminate at various depths below surface
- Placed on and adjacent to build line

Experimental Measurement of Melt Pool Temperature

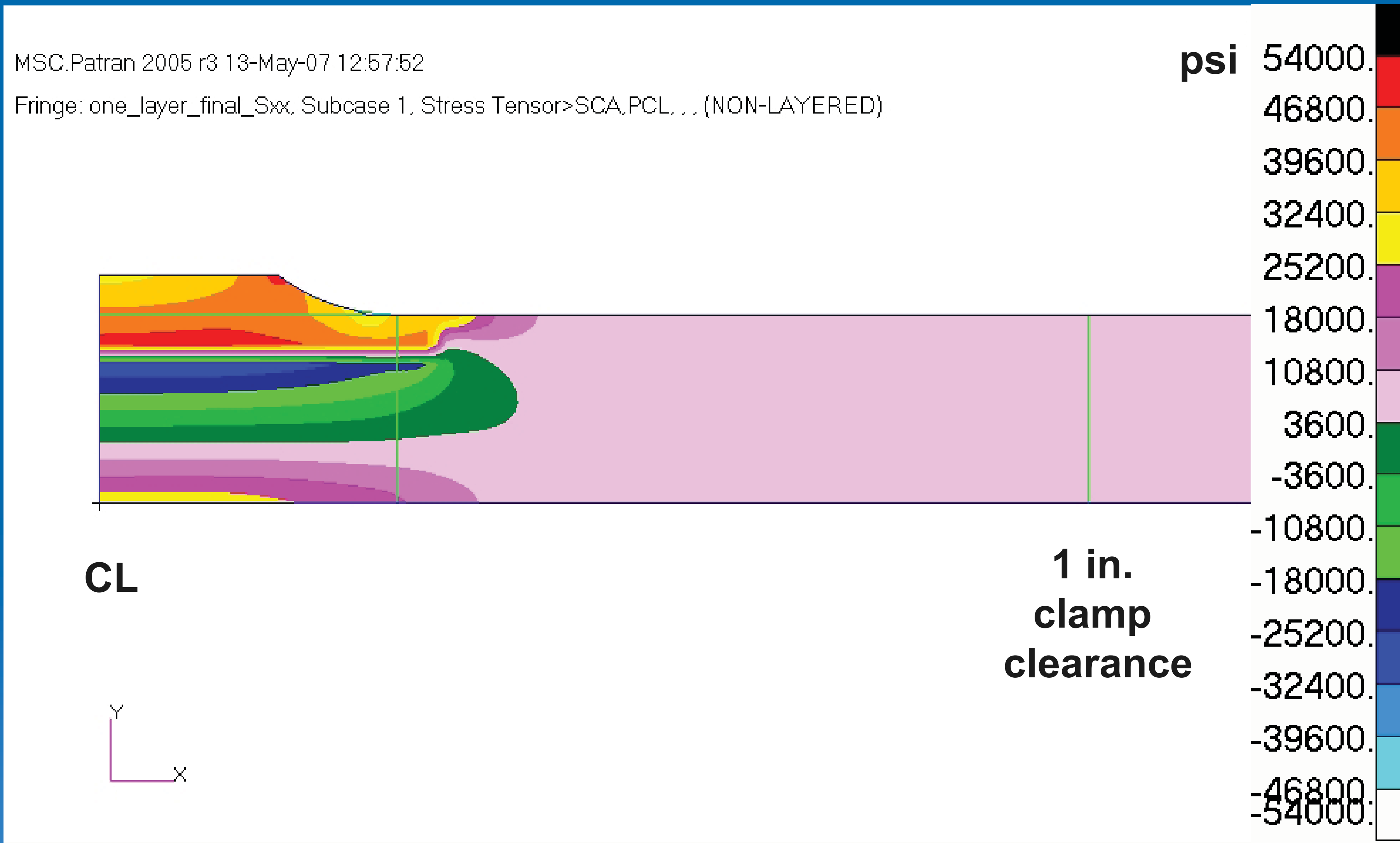


Distortion as a Function of Number of Build Deposit Layers



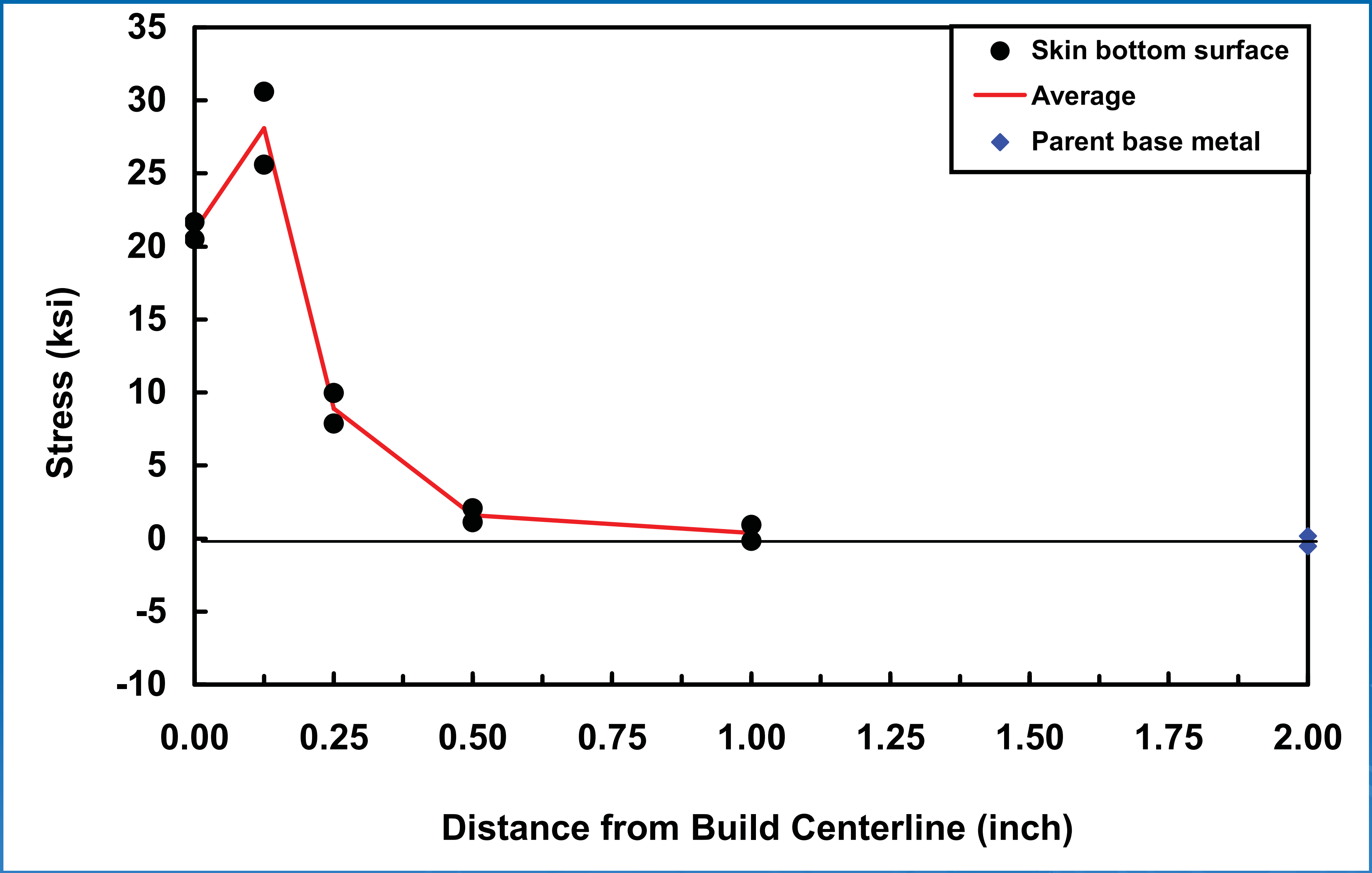
In-plane Stress (σ_x) Distribution

(Single layer deposit; 1 in. clamp clearance)



Residual Stress Distribution

ASTM E837(Hole Drilling)



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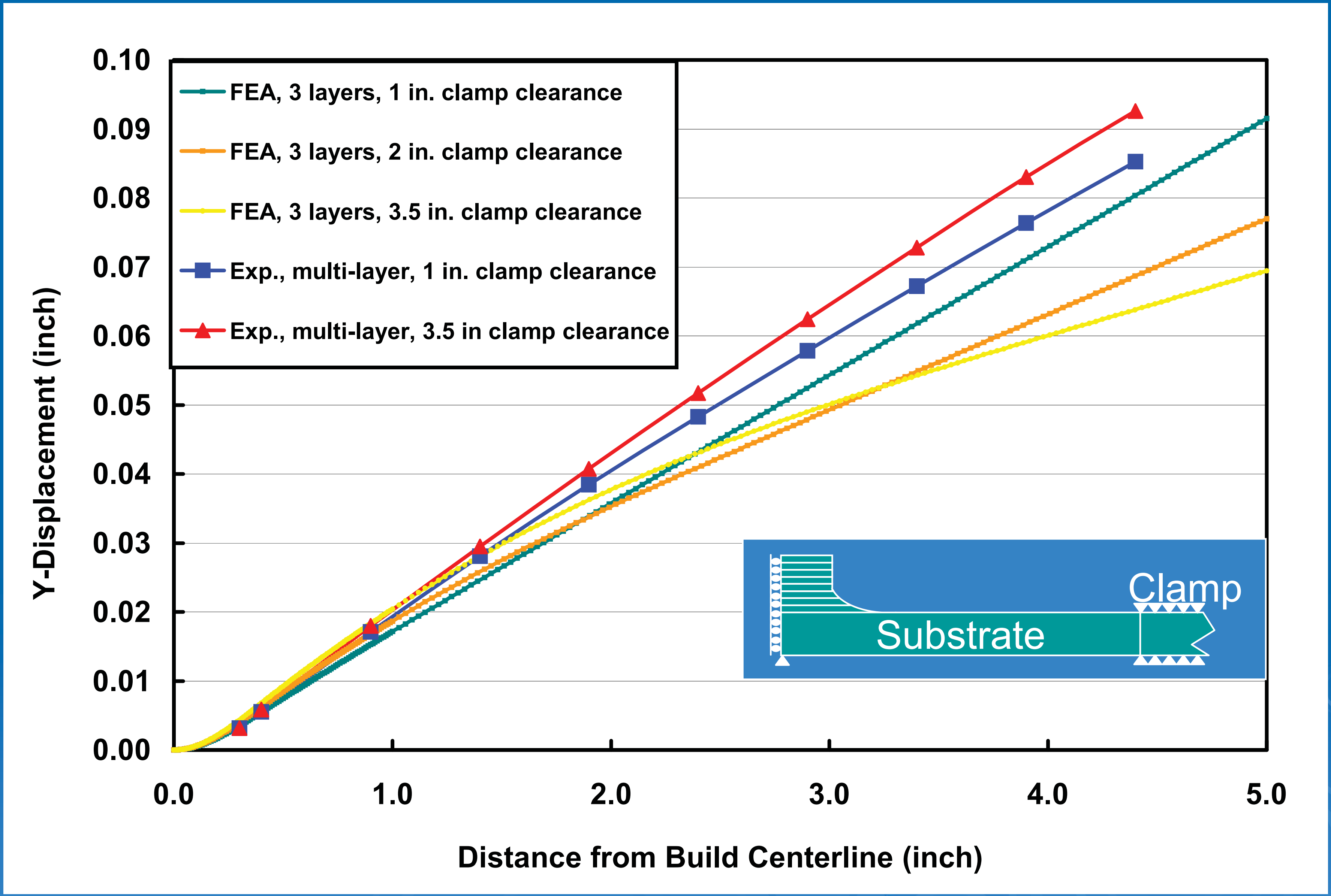
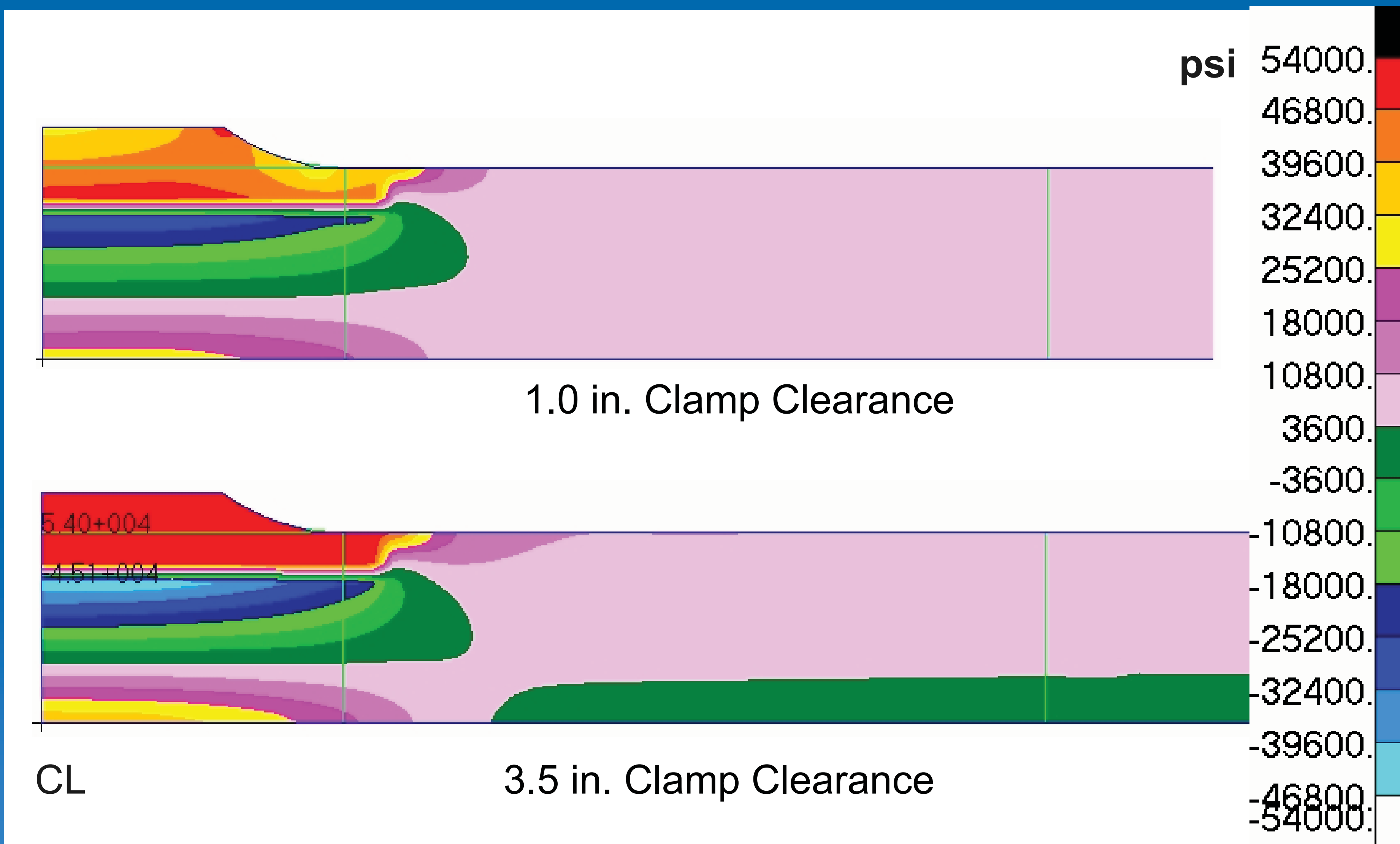
Distortion as a Function of Clamp Clearance

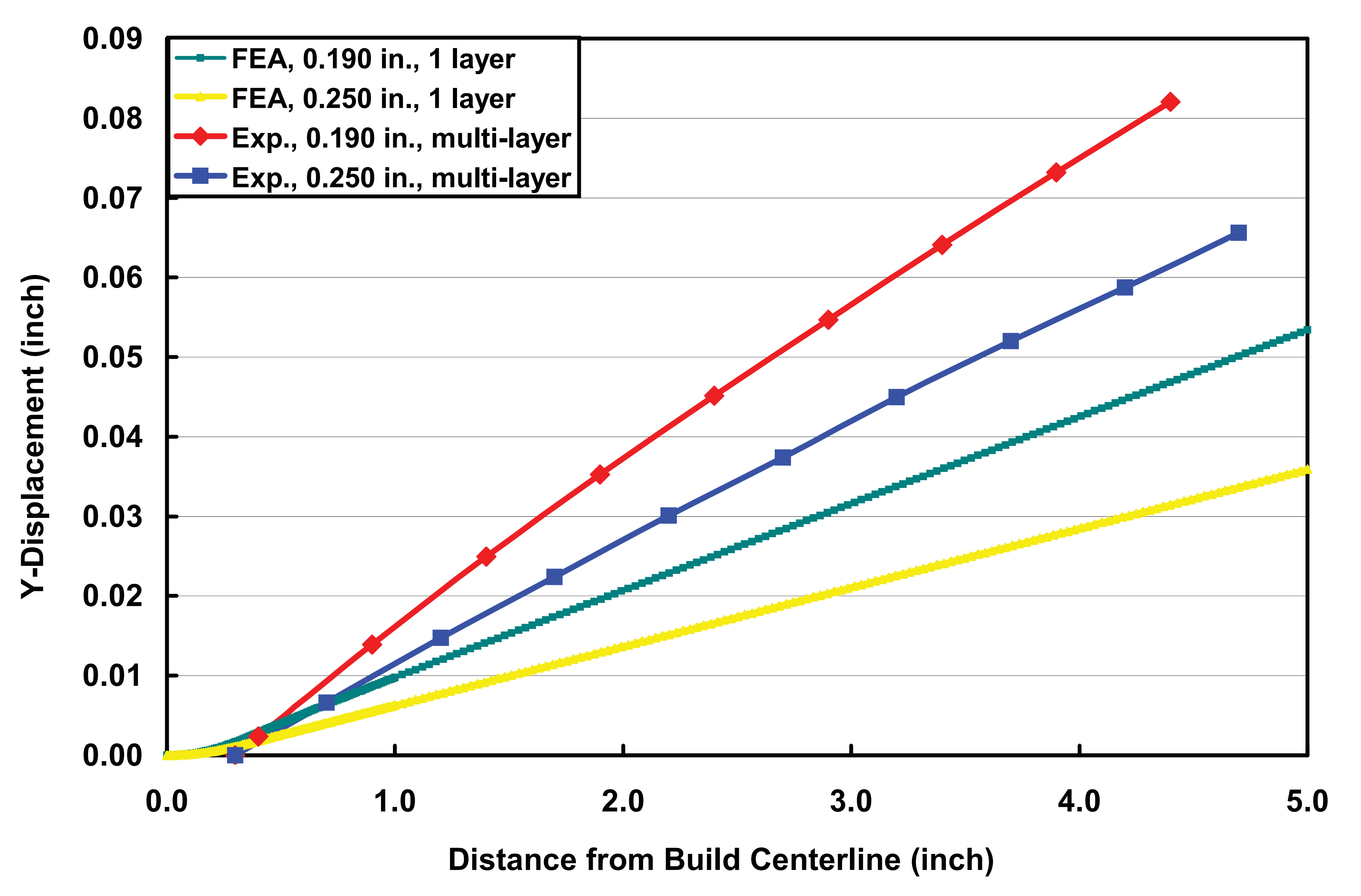


In-plane Stress (σ_x) Distribution

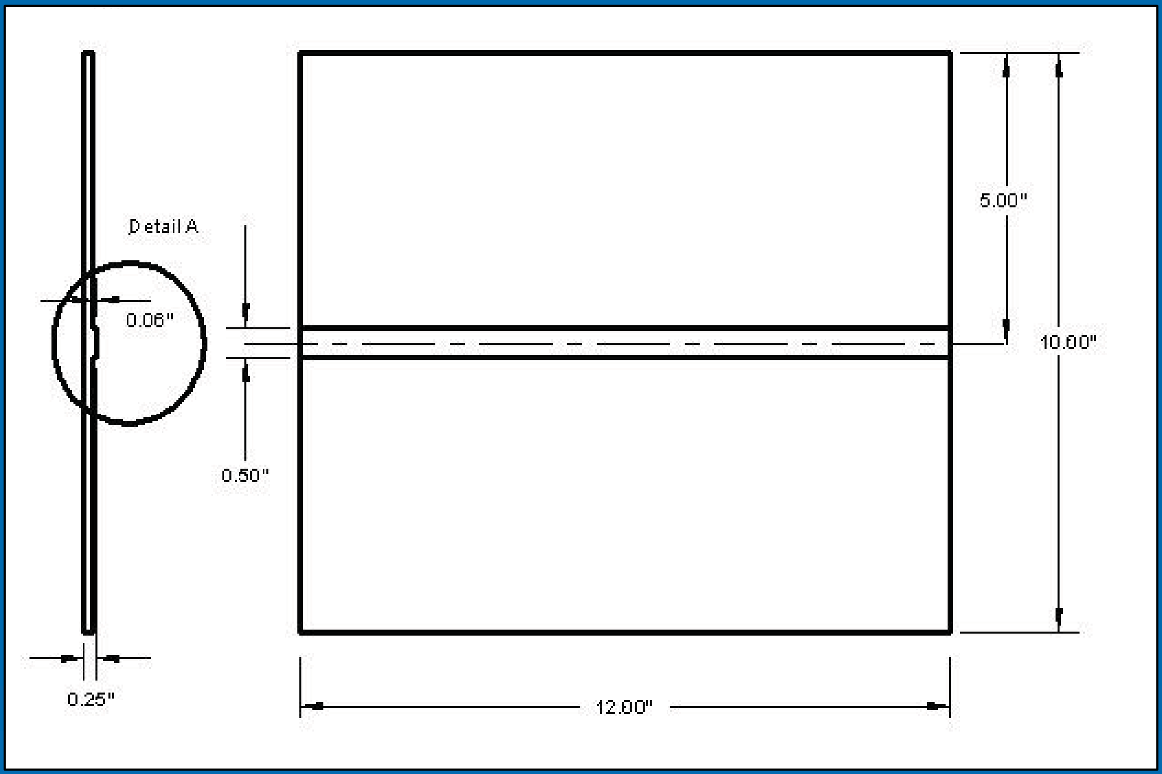
(Clamped at 1.0 in or 3.5 in. from Build Centerline)

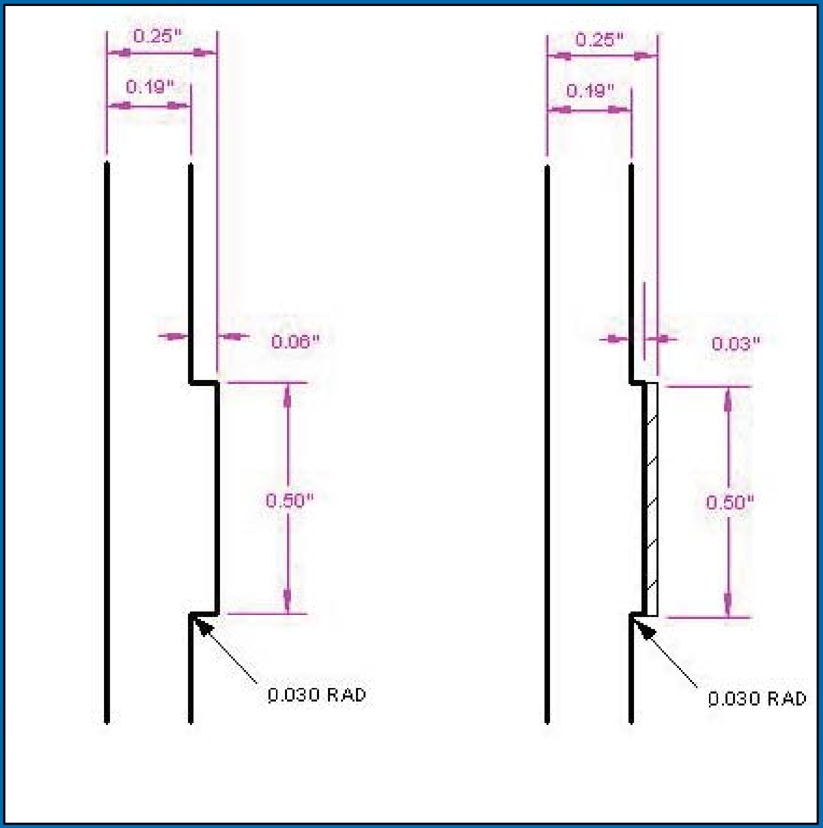


Distortion as a Function of Plate Thickness
(clamped at 1.0 in. from build centerline)



Build Plate with Machined Build Land



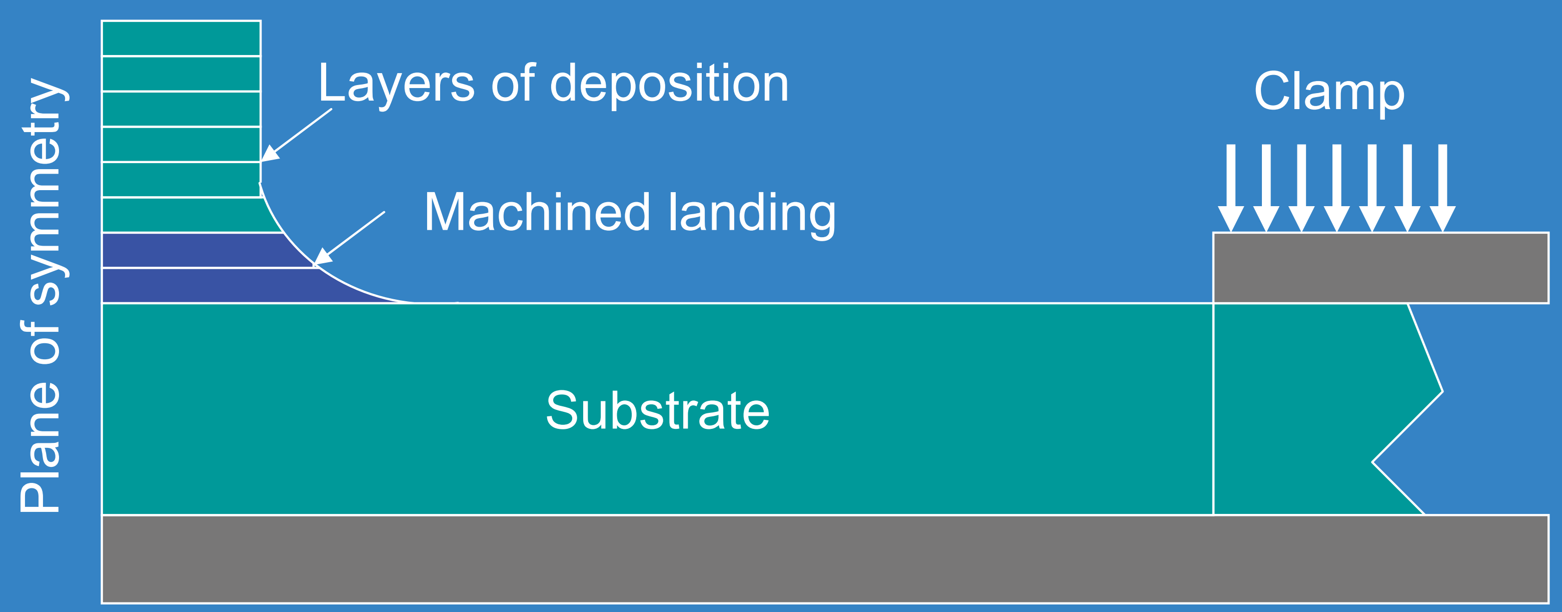


0.060 in build land **0.030 in build land**

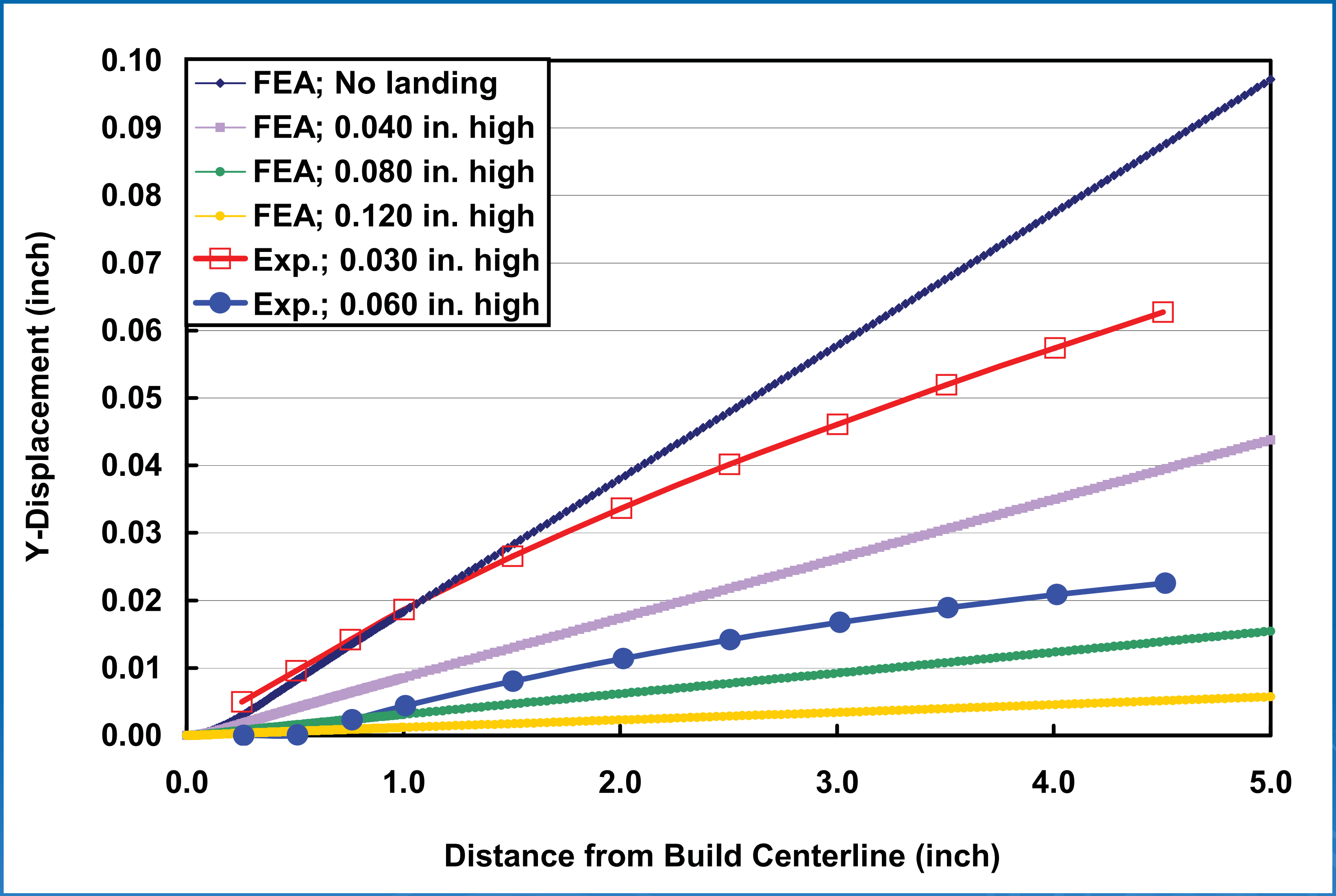
Machined build plate

Detail A

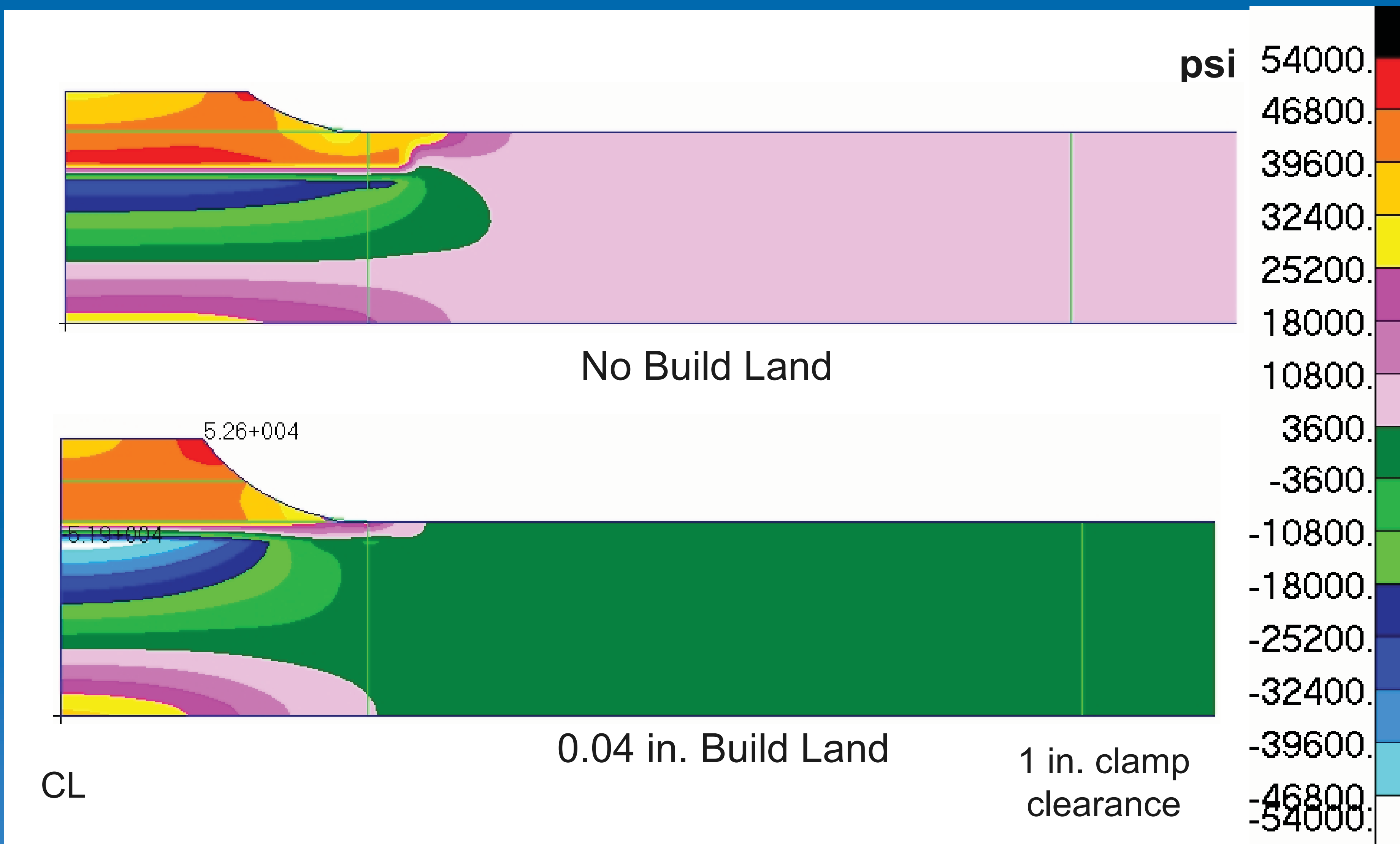
Build Plate with Machined Build Land



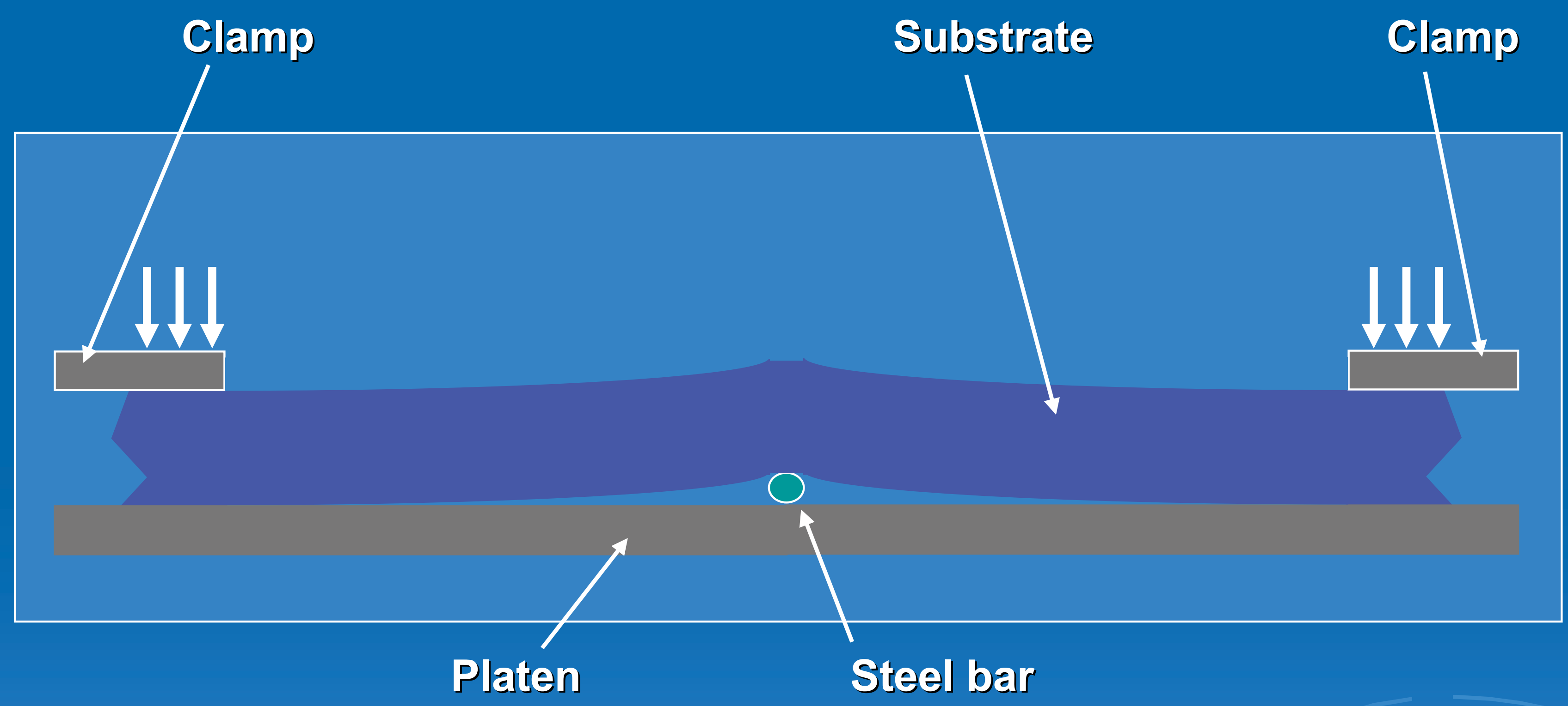
Distortion as a Function of Machined Build Land Height



In-plane Stress (σ_x) Distribution With and Without Build Land

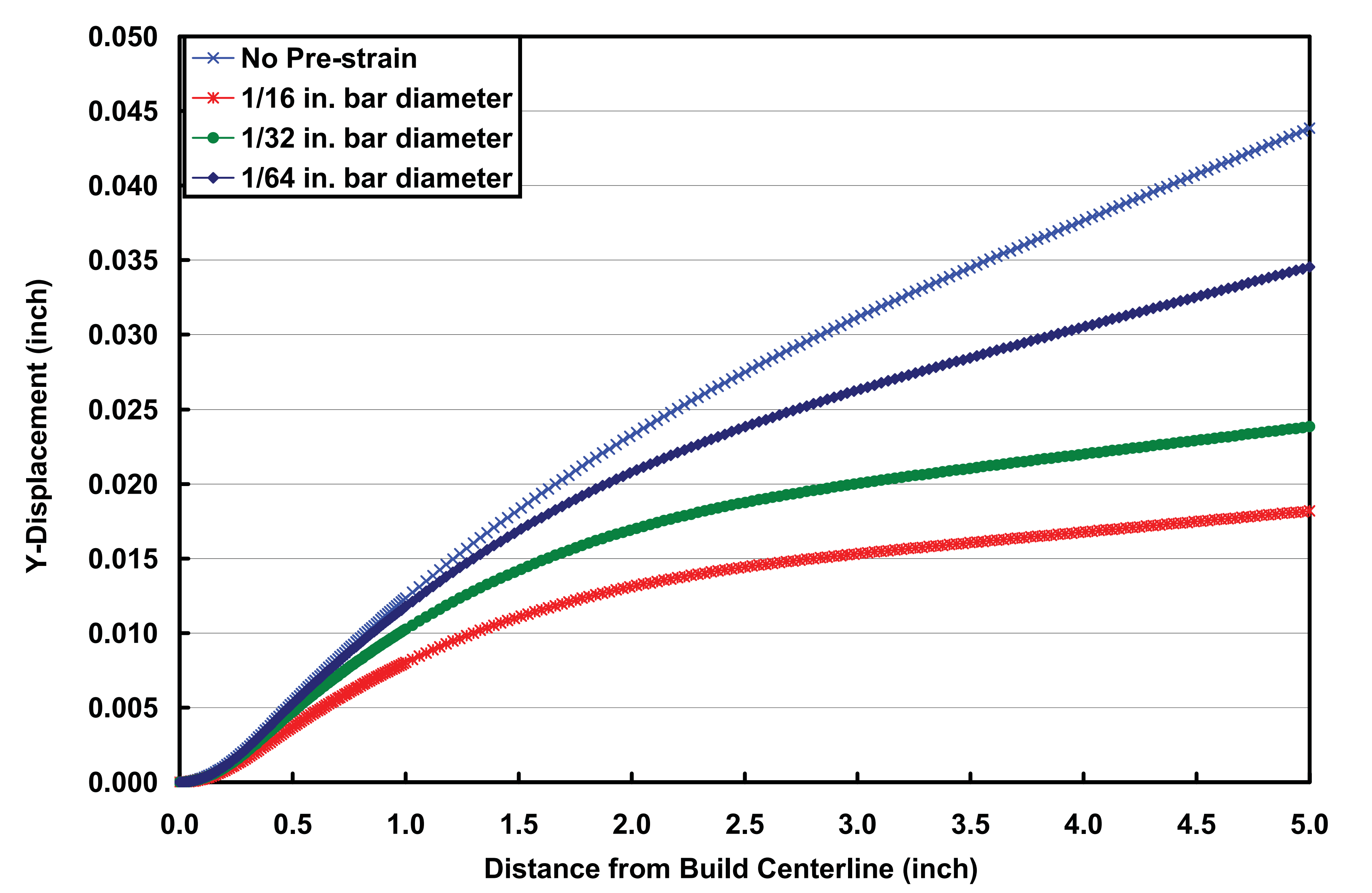


Elastic / Plastic Pre-strain Setup

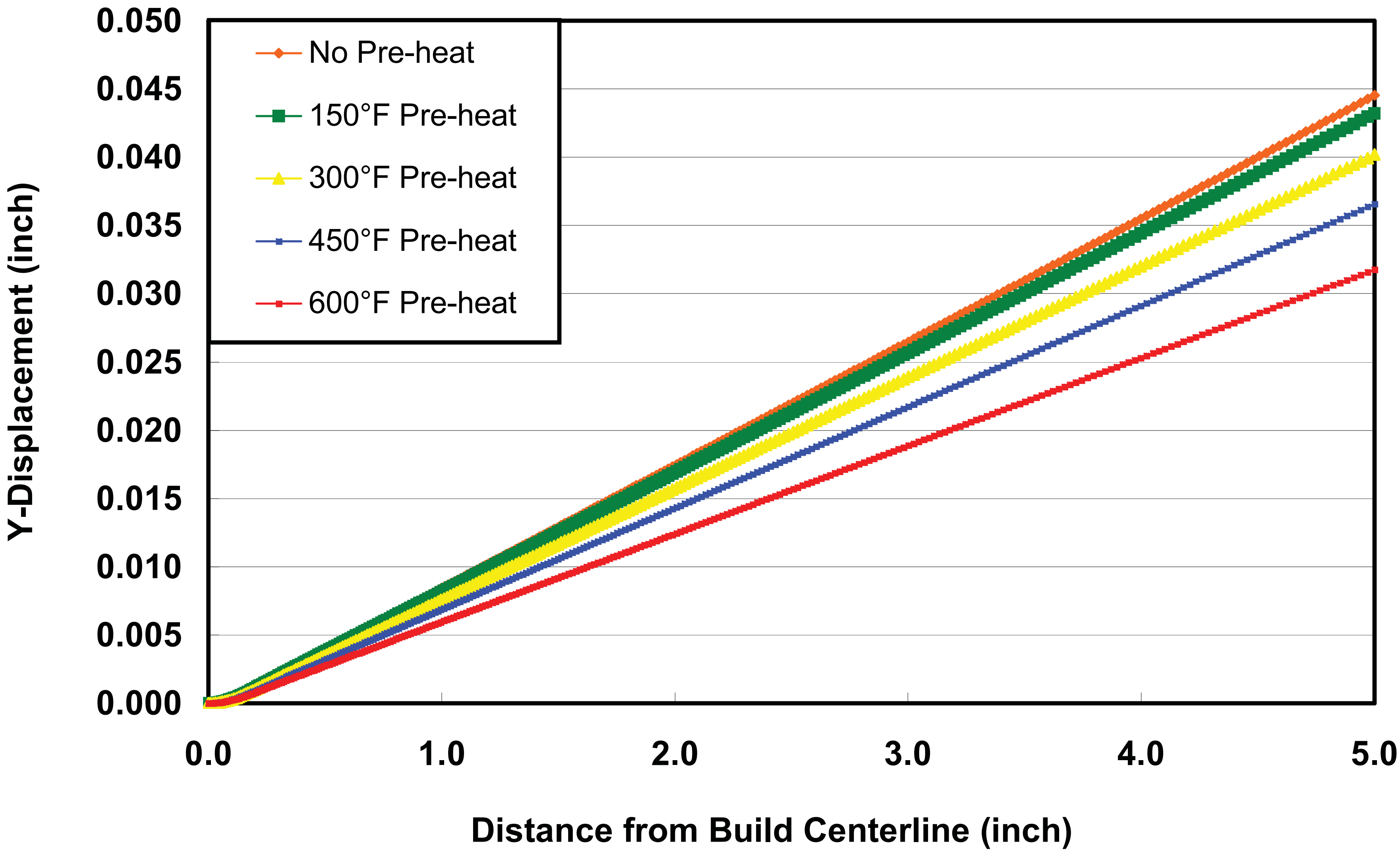


Effect of Pre-strain on Panel Distortion

(clamped at 3.5 in. from build centerline)

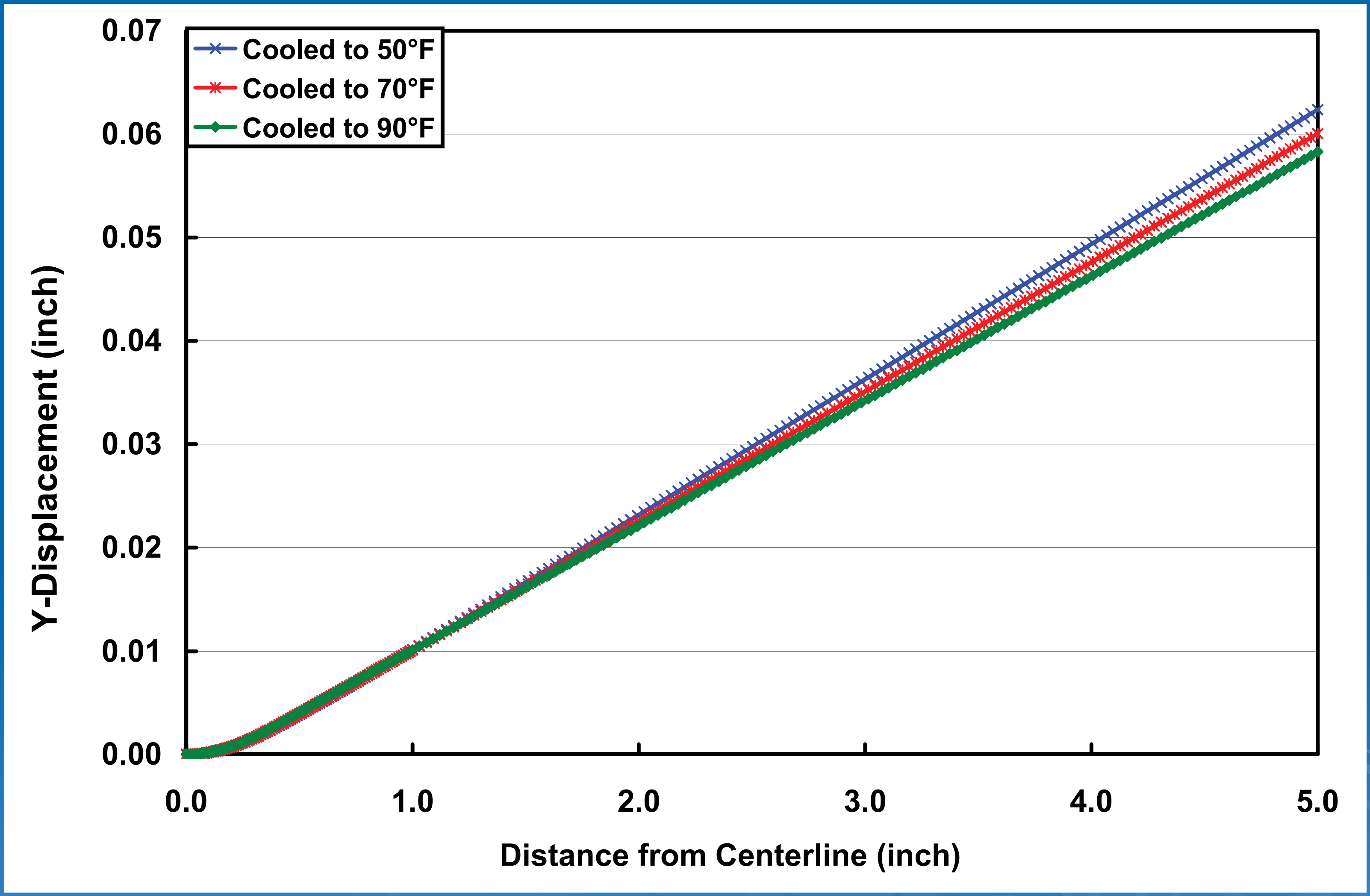


Distortion as a Function of Build Plate Pre-heat Temperature



Effect of Localized Cooling on Panel Distortion

(Cooled at Bottom of Build Plate to 50°F, 70°F and 90°F)



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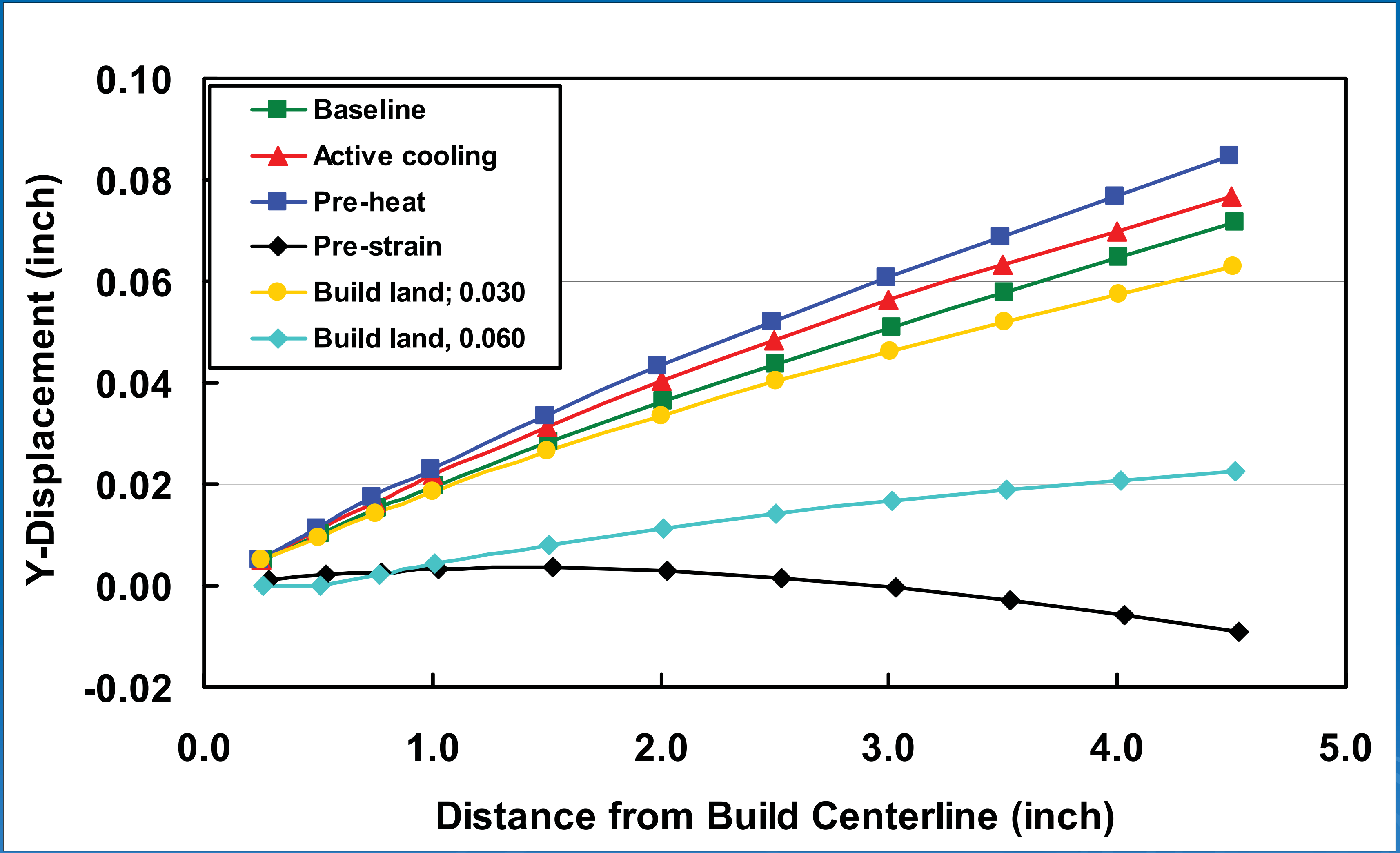
Summary of Experimental Results on Panel Distortion



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Summary

- **2-D thermo-mechanical model developed to characterize distortion and residual stresses in integral structure produced by DMD**
  - Demonstrated as a tool to guide experimental development of DMD fabrication process for aero structures
- **Distortion and residual stresses are local to deposit**
  - Most distortion develops during deposition of the first few layers;
  - Little change in distortion or residual stresses after fifth deposit layer
  - Most of distortion is localized just beneath the build
- **Thicker build plates and the use of build lands results in greatest decrease in levels of distortion**
- **Pre-straining shown to reduce distortion**
  - Difficult to implement, particularly for complex stiffener arrays
- **Clamp position has complex effect on distortion and stresses**
  - Overall distortion reduced with decreasing clamp clearance
  - Larger clamp clearances induce bending
- **Use of pre-heat and active cooling show minor influence on panel distortion**
  - Generate changes in thermal gradients in the build plate

Future Plans

- Refinements to the FEA Model including
  - 3-D analysis
  - Additional alloy systems
  - Document procedures for the FEA process
- Experiments involving DOE on intrinsic processing parameters
  - Beam power
  - Accelerating voltage
  - Wire feed speed
  - Translation speed
- Use of vibratory stress relief