Strain-Based Acceptance Criteria

for Spent Fuel Storage and Transportation Containments (Under Development)

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INTRODUCTION

- The U.S. NRC has a long history of assuring the safety of the public from the potential hazards associated with the transportation of radioactive material.

- For most of this history, the design of the packages used to transport this material has been based upon the ASME Boiler and Pressure Vessel Code Section III and guidance has been provided by U.S. NRC Regulatory Guide 7.6.

- Elastic analysis and stress-based criteria were essentially mandated. (Although inelastic analysis was allowed on a case-by-case basis.)

INELASTIC ANALYSIS

- Elastic analyses and stress (stress intensity) allowables were very useful methods when doing hand calculations.
- Today modern finite element codes can readily compute the stress/strain state at any point in the package. (In the hands of a qualified analyst.)
- If ASME Code and the regulators can revise their current analysis criteria, package designers would like to use inelastic analyses to determine the stress and strain.

Loading Events

- To better understand the need to move from stress-based criteria to strain-based criteria it is helpful to divide loading events into categories.

Loading Events

- Loading events can be divided into three basic categories

1. Load-Controlled or Force-Limited Events
2. Energy-Controlled or Energy-Limited Events
3. Displacement-Controlled or Displacement-Limited Events

Examples

1. Force-Limited Events
   - Dead Load
   - Lifting Loads
   - Internal Pressure

2. Energy-Limited Events
   - 9 meter Drop
   - 1 meter Puncture Drop
   - Non-mechanistic Tip-over
   - Aircraft Crash

3. Displacement-Limited
   - Thermal Expansion

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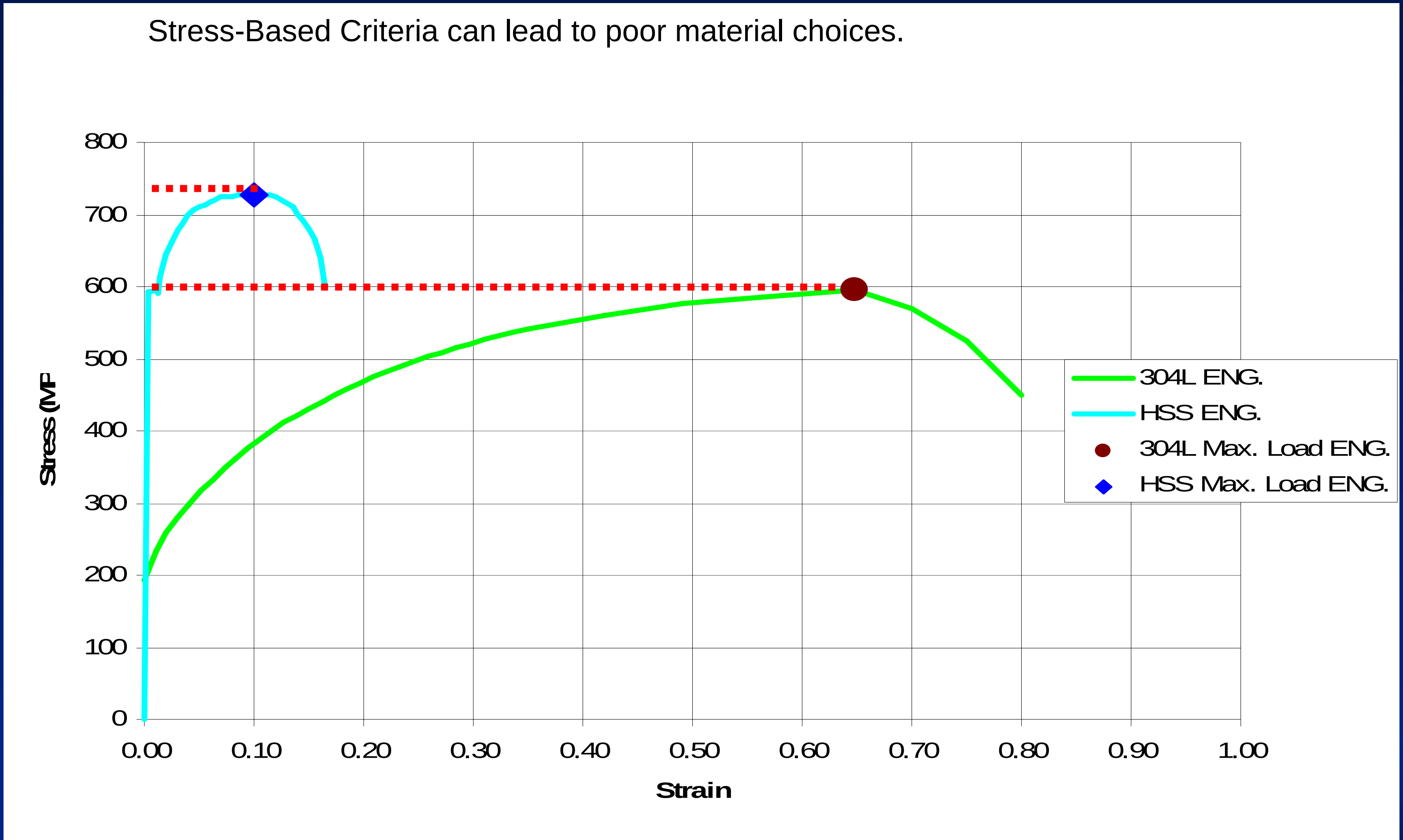
- It is clear from this breakdown and supporting examples that the design of storage and transportation containments is controlled by energy-limited events.

- Even the founders of the stress-based criteria in the ASME Code recognized its limitations.

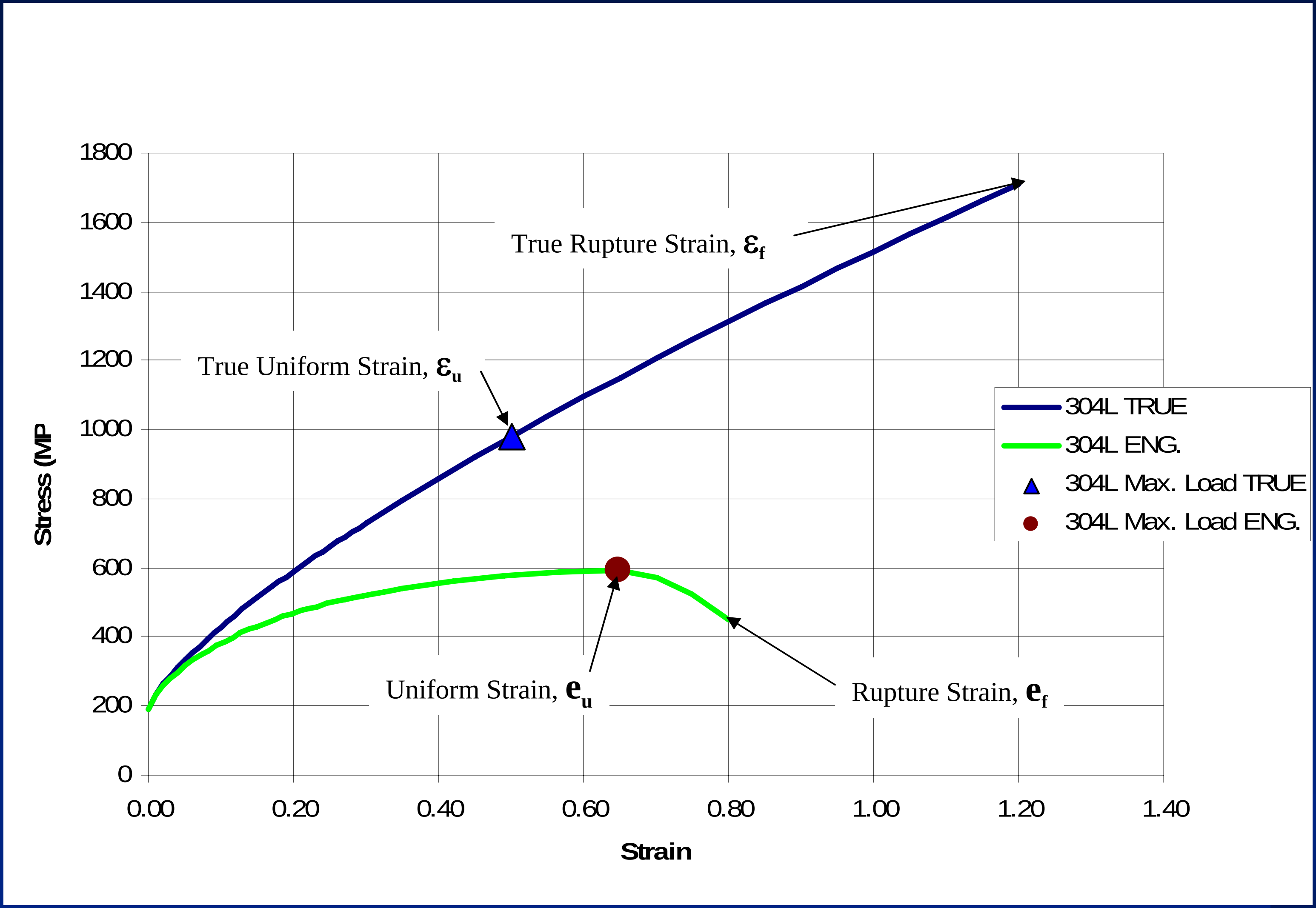
A Quote from Bill Cooper

5.3.4.5.2 Energy-controlled conditions. It is poor practice to apply criteria developed for load-controlled conditions to energy-controlled conditions when deformations do not have to be controlled; and, as was cited earlier, it is not the intent of Appendix F to limit deformations. If the condition is energy controlled, the structural acceptance criteria should be related to structural energy absorption. The only way to achieve that objective is to present the criteria in terms of strain limits which are proportional to the usable ductility of the material under the imposed stress state.

The ASME Code Stress-Based Criteria can Lead to Poor Material Choices



Strain-Based Acceptance Criteria for Energy-Limited Accident Events



Effect of State-of-Stress

- A complication to the development of strain-based acceptance criteria is the relationship between the strain to failure and the state of stress.
- The familiar uniaxial tensile test that generated the stress-strain curve on the previous slide represents only one state of stress.
- To address this issue, the concept of a stress triaxiality factor (TF) was proposed to account for the potential loss of ductility due to constraint of plastic flow caused by the state of stress.

Any Strain-Based Acceptance Criteria Must Have Four Essential Components

- Strain-Based Criteria must be based on specific characteristics of a material's behavior and its stress-strain curve.
  - Uniform Strain, ε_u
  - Failure or Rupture Strain, ε_f

- Uncertainty in material properties must be accounted for by using minimum properties (mean – 2σ, or 98% EP)

- Triaxiality Factor applied to the minimum properties to account for the potential loss of ductility due to state of stress

- The numerical factors chosen to limit ε_u and ε_f in the strain-based criteria to account for uncertainty in
  - Loading
  - Quality of Construction
  - Quality of the Analysis

Essentials of the Strain-Based Criteria for Energy-Limited Accident Events (Level D) under Development by ASME for Section III, Division 3

Limit Average Thru Thickness Equivalent Plastic Strain (EPS)

EPS $<$ 0.67 ε_u / TF (At 3t away from Discontinuity) TF >= 1

EPS $<$ 0.85 ε_u / TF (At Discontinuity) TF >= 1

Limit Maximum Surface Equivalent Plastic Strain

EPS $< (\varepsilon_u + 0.25(\varepsilon_f - \varepsilon_u)) / TF$ (Any where) TF >= 1

$(\varepsilon_f > 2\,\varepsilon_u)$

TF = Triaxiality Factor = First Stress Invariant / Oct. Shear Stress

(Accounts for effect of state of stress on ductility. TF is a function of time.)

$$TF = \frac{(\sigma_1 + \sigma_2 + \sigma_3)}{\sqrt{\frac{1}{2}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]}}$$

Typical Triaxiality Factors

Examples of Triaxiality Factor Calculations

Normalized Principal Stresses			Calculated TF	Description
σ_1	σ_2	σ_3		
1	0	0	1	Uniaxial Tension
1	1	0	2	Biaxial Tension
1	1/2	1/2	4	Triaxial Tension
1	1	1/4	3	Triaxial Tension
1	1	1/2	5	Triaxial Tension
1	1	1	∞	Triaxial Tension
1	-1	0	0	Tension/Compression
1	-1/2	0	0.378	Tension/Compression
1	1	-1	0.5	Biaxial Tension / Compression
1	-1	-1	-0.5	Tension / Compression / Compression
-1	-1	-1	- ∞	Triaxial Compression

Current Limitations for Using Proposed Criteria

- Accidental drop and impacts of non-sharp (i.e., blunt) objects [e.g., 6-inch diameter post with rounded edges, aircraft engine shafts, etc.]
- One-time energy-limited events (non-cyclic)
- Cannot be utilized for events moderated by external, non-integral impact limiters
- Only applicable to austenitic stainless steel
- Can only be used with a “Quality Model”

Accident Events (Level D Limits)

- 9m Drop with Impact Limiters

- Puncture Drop
- Drops without Impact Limiters
- Aircraft Crash

← 5% - 10% →   ← $0.67 \times \varepsilon_u = 34\%$ →

Average through Thickness Strains
Type 304 Stainless

Problem

- Structural Mechanics finite element codes for explicit dynamics are now sufficiently sophisticated and robust that complex impact events can be simulated with reasonable accuracy.

- Unfortunately, the ability of users to properly implement the features that make these codes so sophisticated and robust has become a noticeable problem.

Activities of the ASME Task Group on Computational Modeling for Explicit Dynamics

- Strain-Based acceptance criteria shall be applicable only to "Quality Models."

- A Quality Model is a model that adheres to the guidance set forth in the ASME Computational Modeling Guidance Document for Explicit Dynamics Software, or has been developed with the use of convergence and sensitivity studies. This will be written into the ASME Code and NRC Reg. Guide 7.6

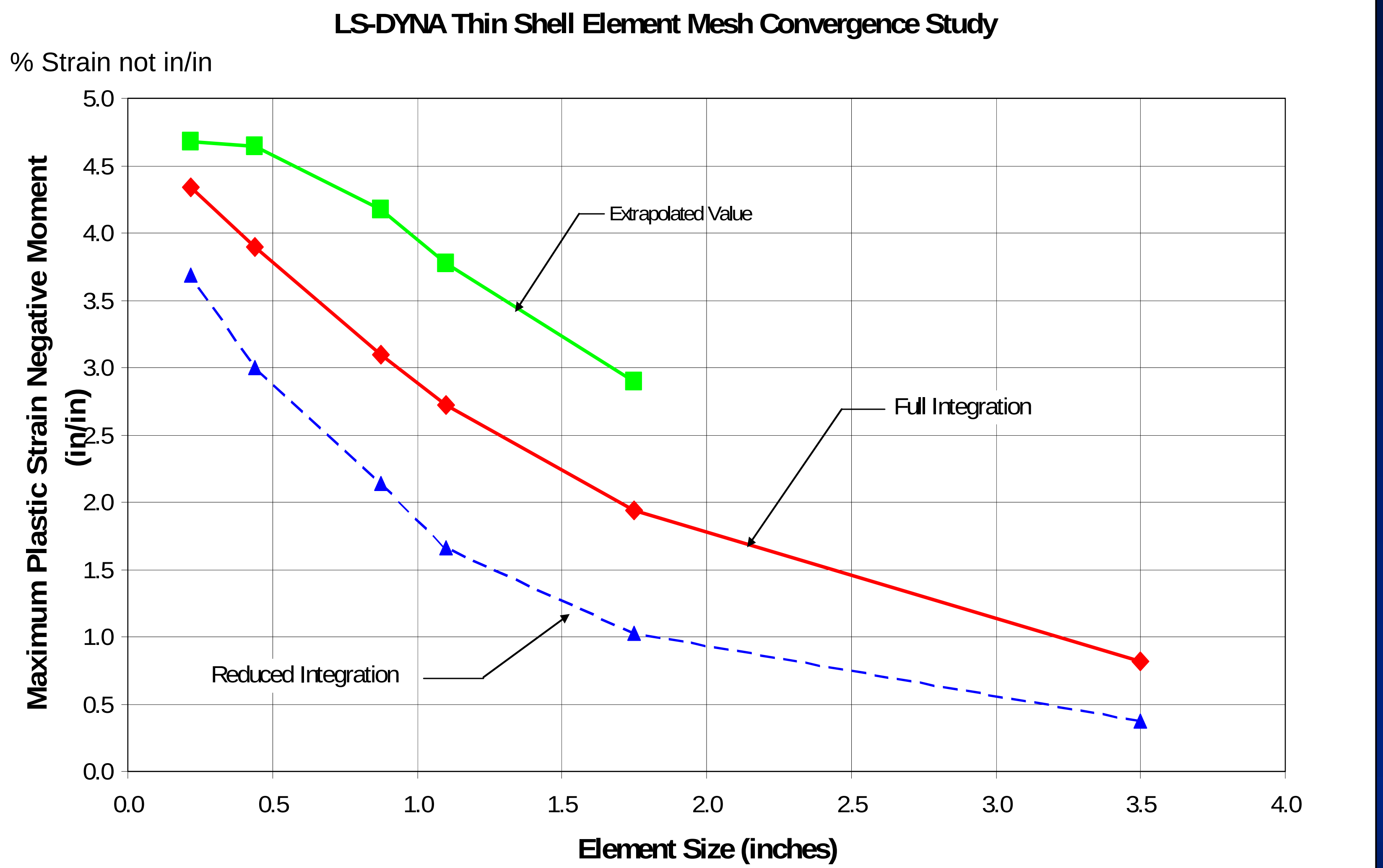
- The guidance document is currently being developed by the ASME Task Group on Computational Modeling for Explicit Dynamics.

- An entire session (on Thursday) at PATRAM-2010 is being devoted to Task Group Activities including Convergence Study Results.

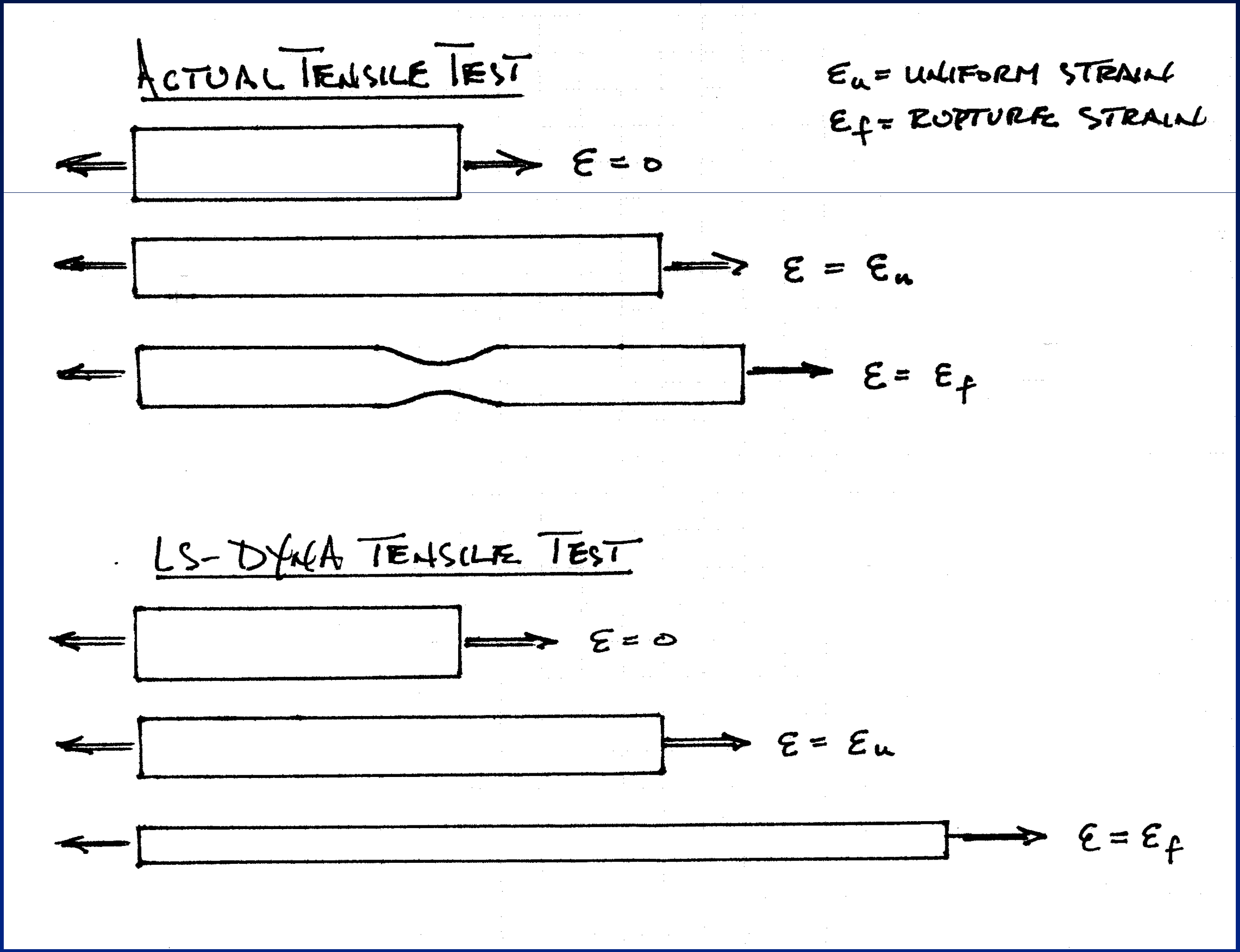
Summary

- Strain-Based Criteria for Accident Events (Level D)
  - Energy Limited Events
  - Monotonic Loading
  - Transportation Packages (9m Drop, Puncture)
  - Storage Casks (Aircraft Crash, Non-Mechanistic Tip-over)
  - Address the Entire Containment Boundary
    - Average thru Thickness
    - Max Surface
  - Consistent and Transparent Basis for Establishing Minimums
- Results Must be Obtained from a Quality Model
  - Confirms to ASME Task Group Guidance Document
  - Based on Convergence and Sensitivity Studies
- ASME Code and RG 7.6 will Link Strain-Based Criteria to the use of a Quality Model

Convergence Study



Compare an actual tensile test with the same tensile test performed in LS-DYNA



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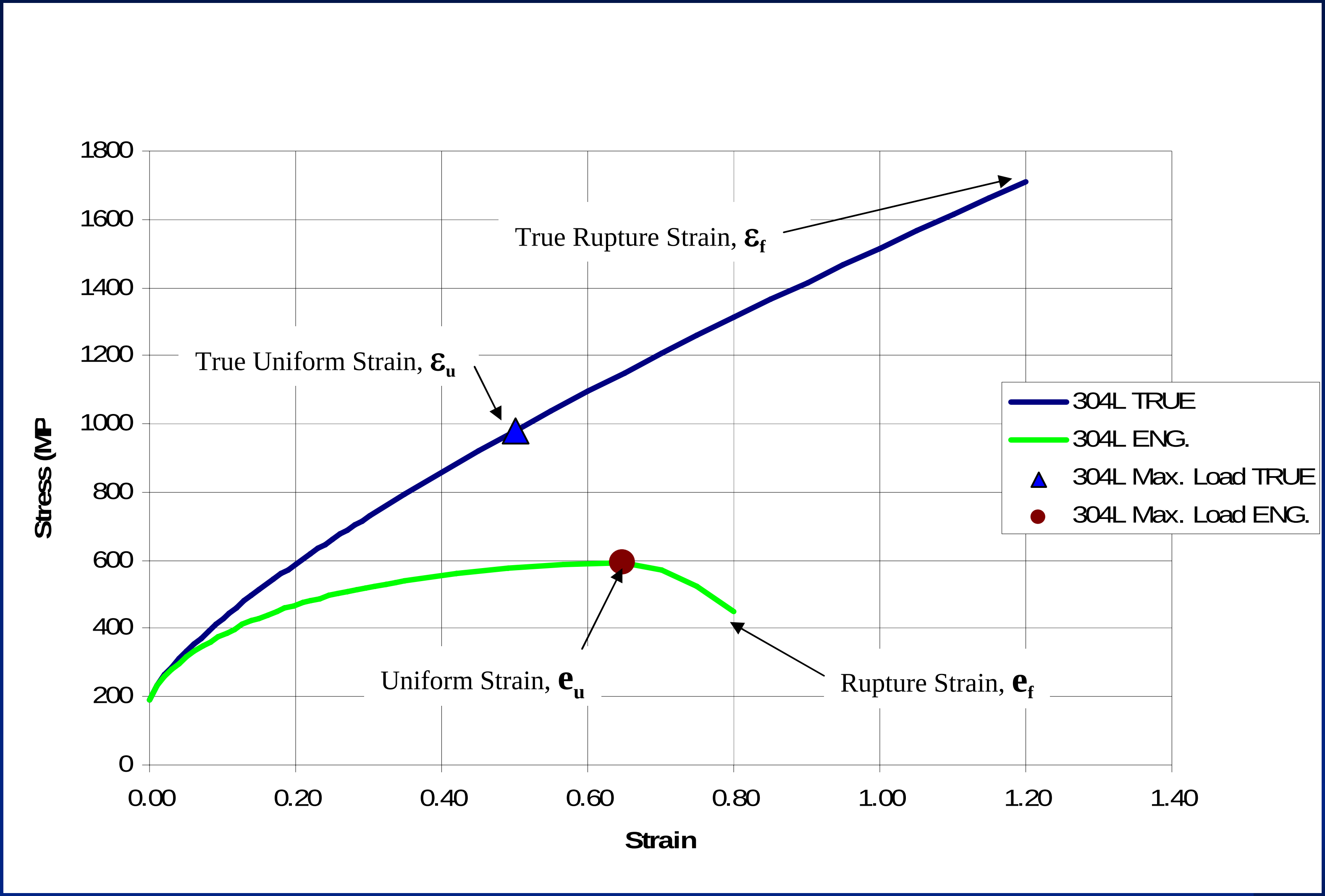

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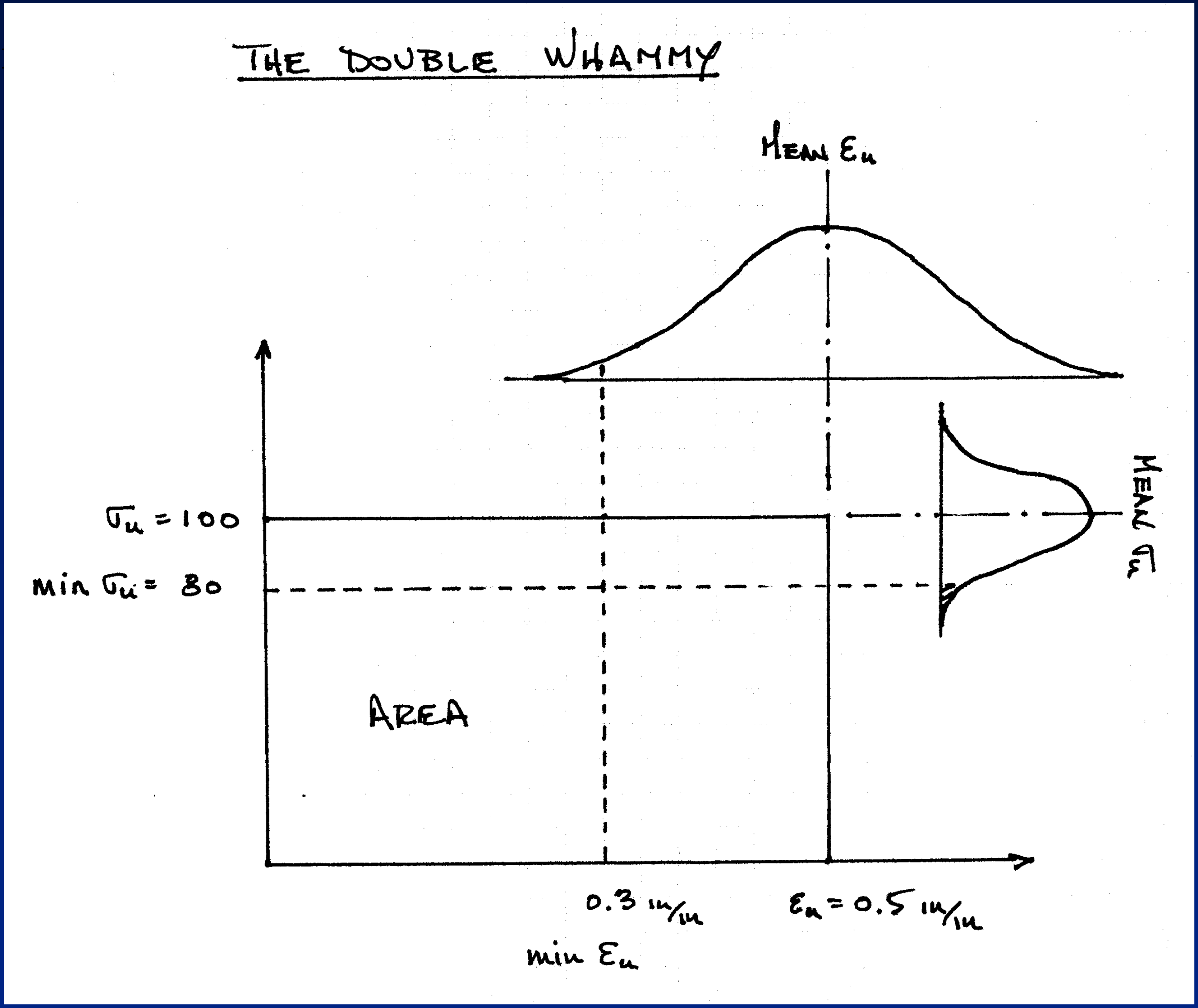
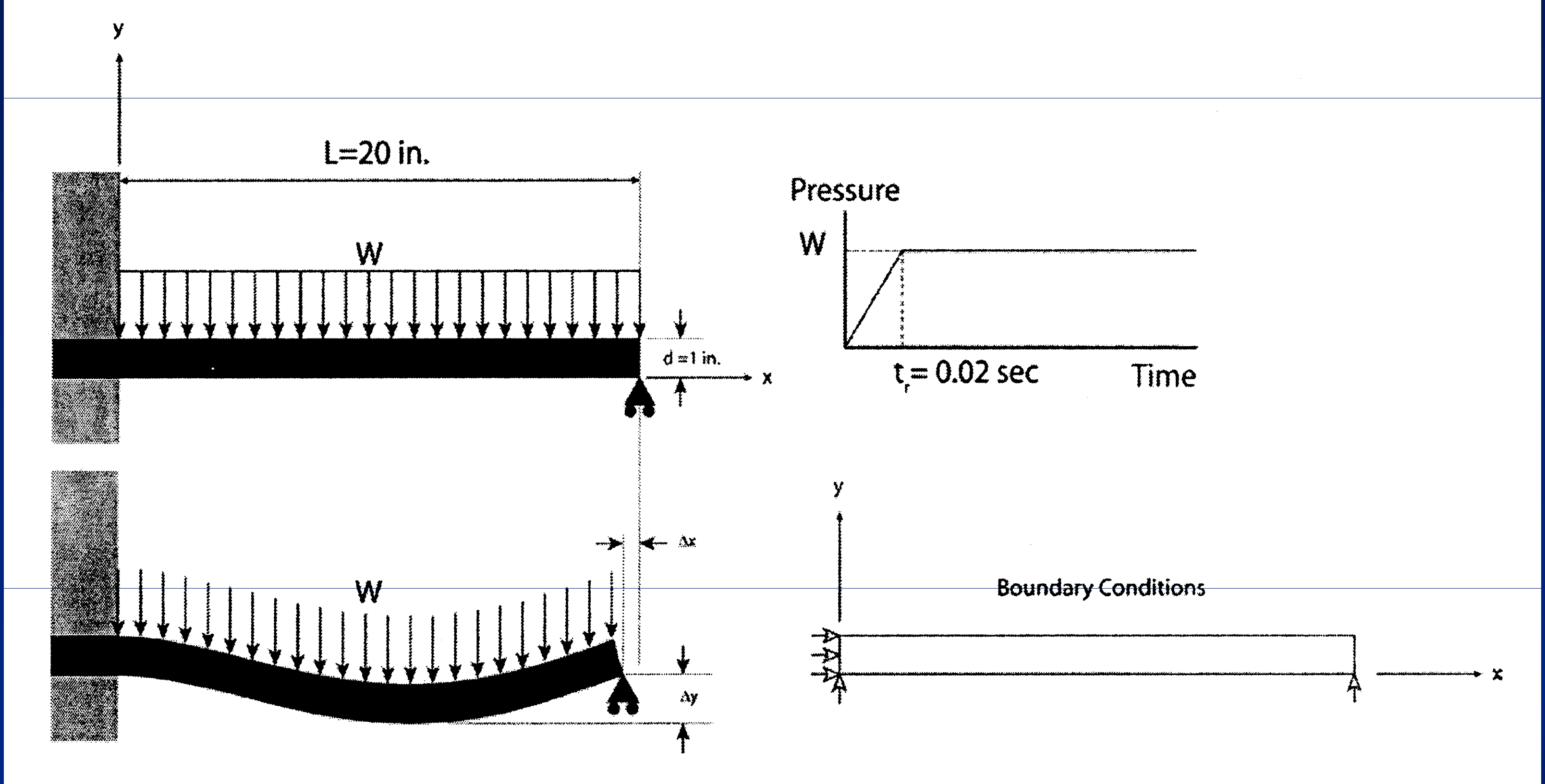

THE DOUBLE WHAMMY
MEAN ε_u
$\sigma_u = 100$
min $\sigma_u = 80$
MEAN σ_u
AREA
0.3 in/in
$\varepsilon_u = 0.5$ in/in
min ε_u

Current Task Group Activities

- **Propped Cantilever** Convergence Study
  - Hex Elements
  - Reduced Integration
  - Thin Shell Elements
- **Flat Plate Puncture Drop**



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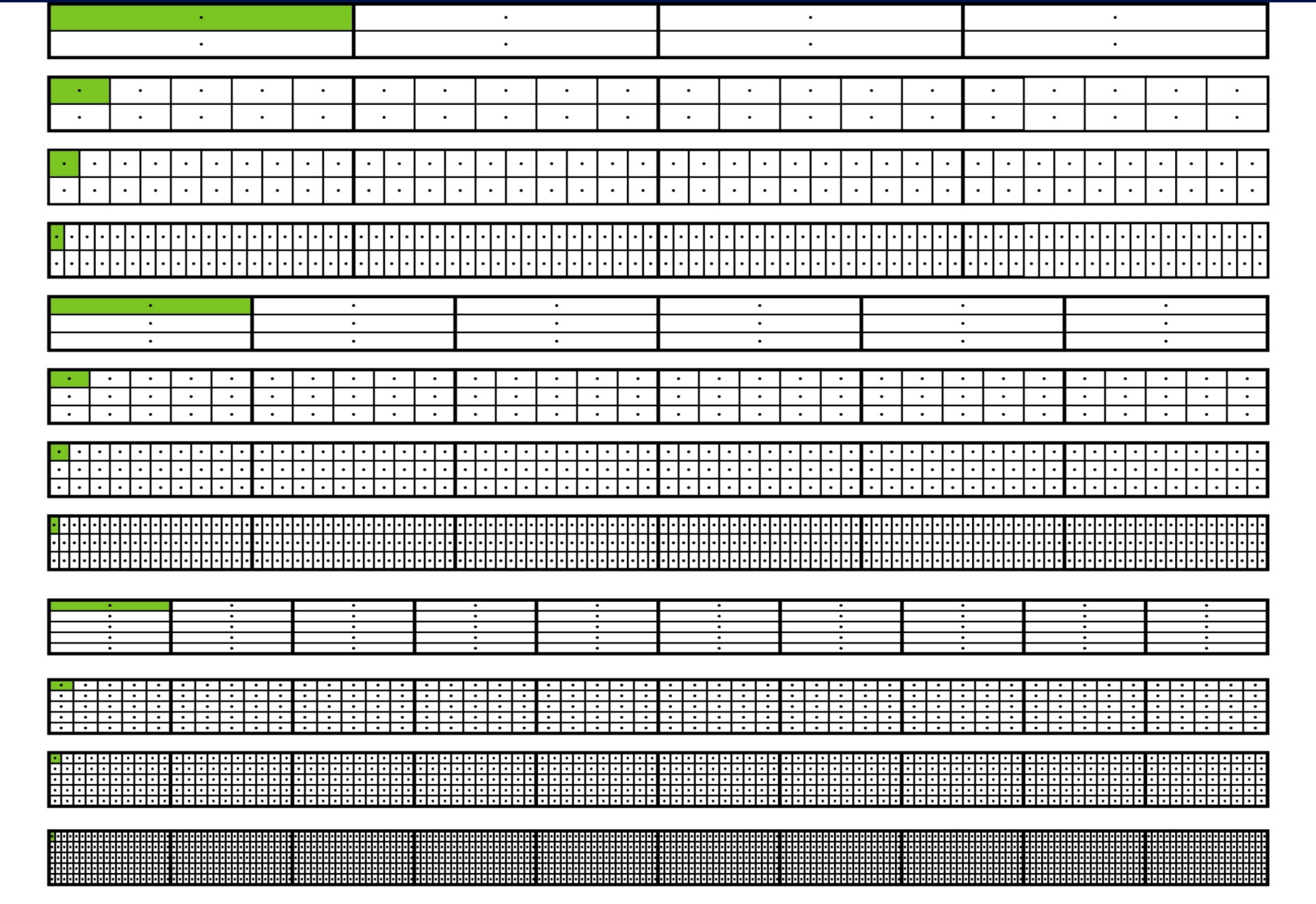
- Propped Cantilever Convergence Study Meshes
  - Hex Elements
  - Reduced Integration



- Propped Cantilever Convergence Study Meshes
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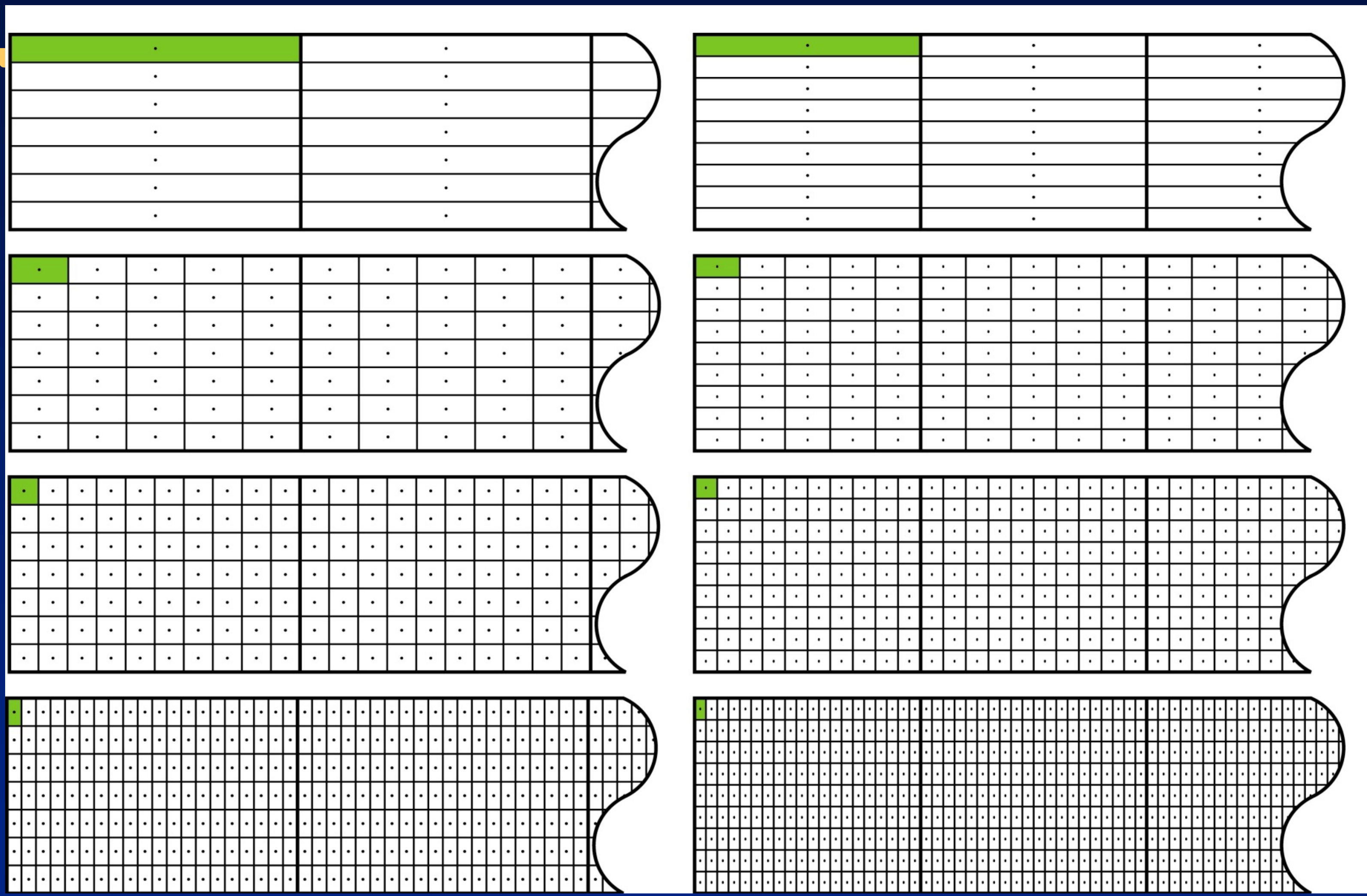

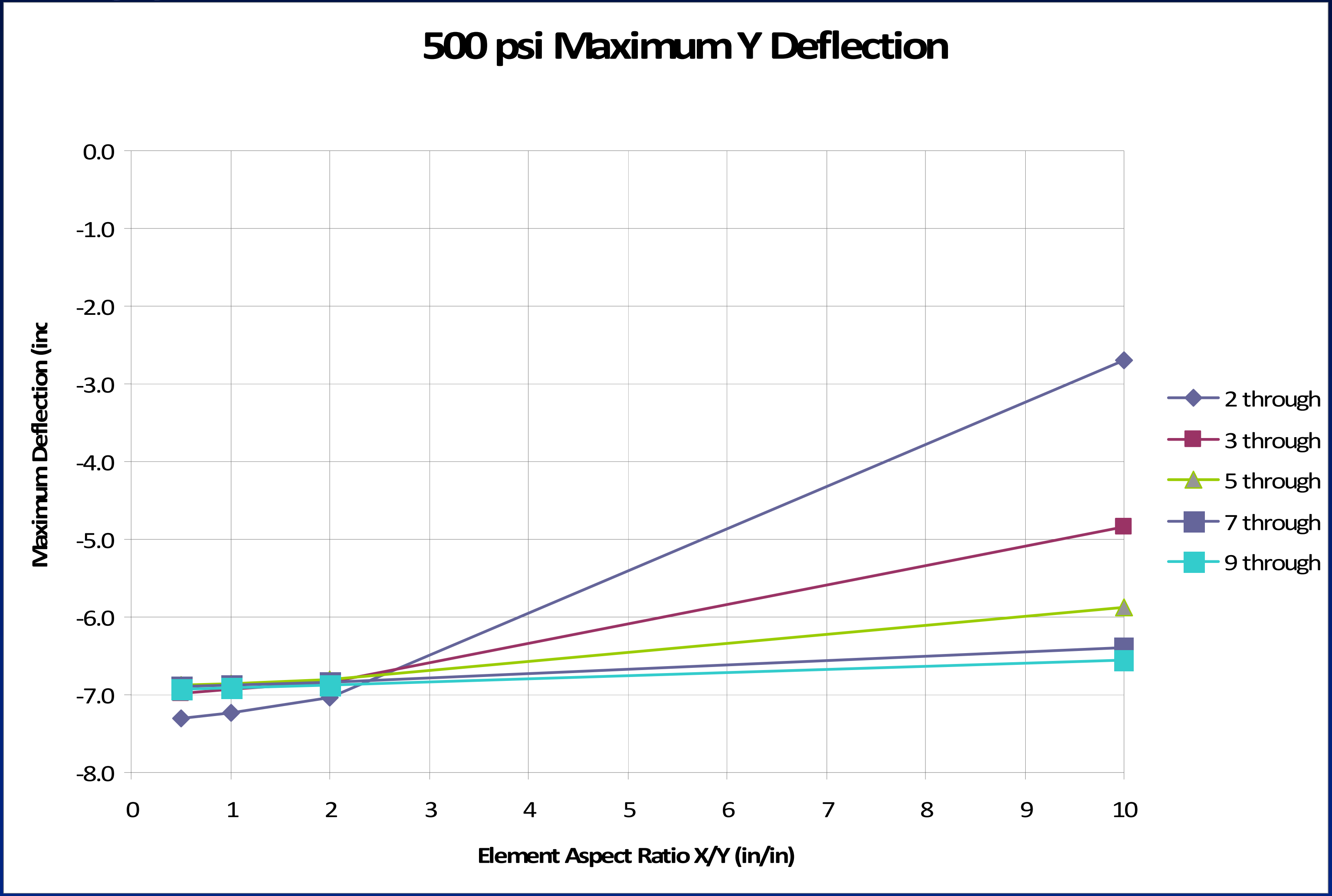

500 psi Maximum Y Deflection
0.0
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
-7.0
-8.0
Maximum Deflection (inc
0
1
2
3
4
5
6
7
8
9
10
Element Aspect Ratio X/Y (in/in)
2 through
3 through
5 through
7 through
9 through

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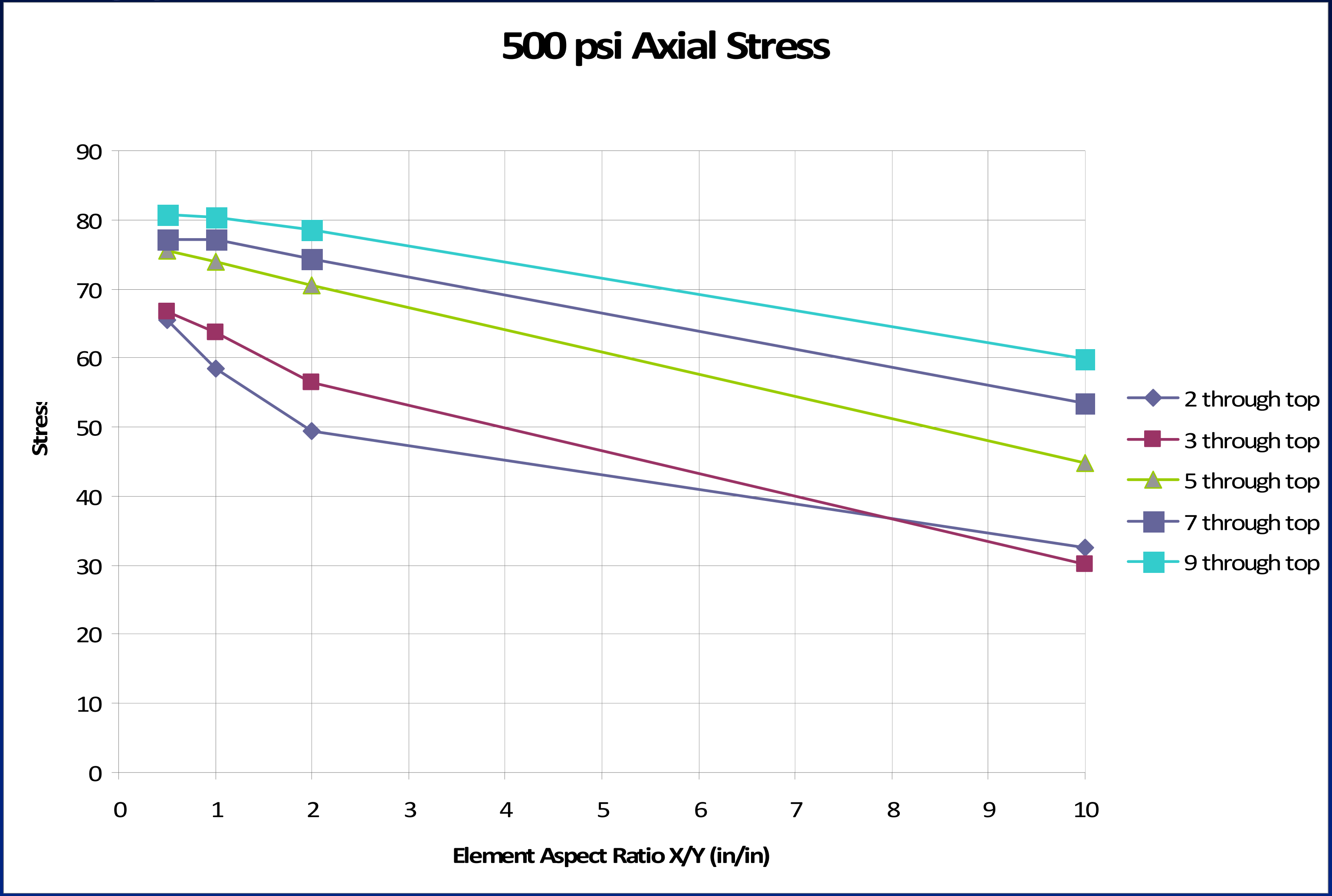

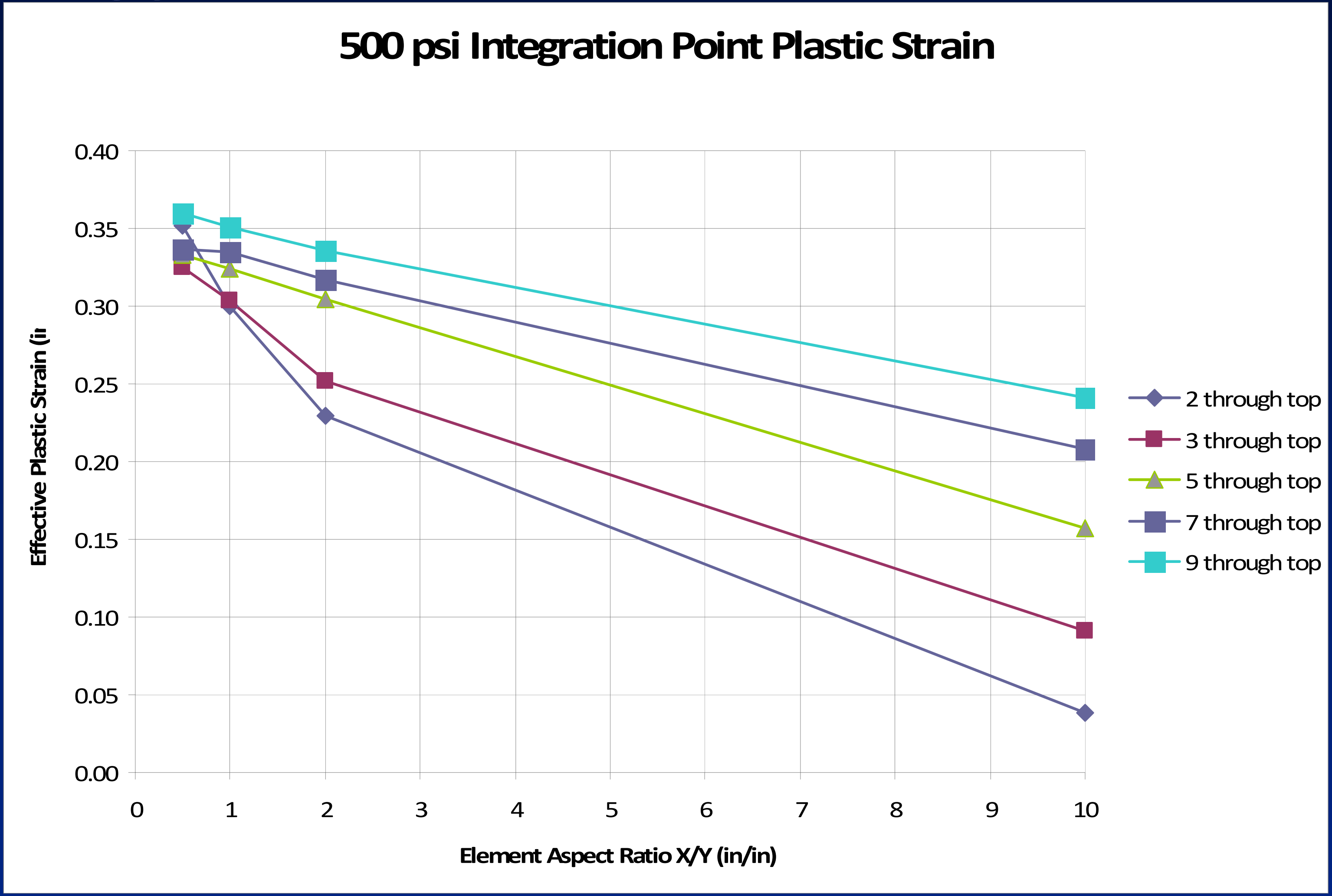

500 psi Integration Point Plastic Strain
Effective Plastic Strain (i
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
1
2
3
4
5
6
7
8
9
10
Element Aspect Ratio X/Y (in/in)
2 through top
3 through top
5 through top
7 through top
9 through top

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