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Strain-Based Acceptance Criteria for Spent Fuel Storage and Transportation Containments

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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 and guidance has been provided by U.S. NRC Regulatory Guide 7.6.
- Currently, the relevant section of the Code is Section III, Division 3 (NUPACK).

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STRESS INTENSITY

- The ASME Code relies on the concept of stress intensity to establish allowable stresses elastic analysis.
- Stress intensity is the maximum difference between principle stresses.
- This is equal to twice the maximum shear stress.
- Allowable stress intensities vary with loading case (normal vs. accident) and type of stress (primary, secondary, membrane, bending, local, etc.).
- Some allowable stresses are above the yield stress.

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INELASTIC ANALYSIS

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

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STRESS BASED vs. STRAIN BASED

- Current Code philosophy for inelastic analysis is an extension of the **stress-based criteria** used for **elastic analysis**.

- The requirements are given in non-mandatory Appendix F to Section III, Division 1.

- For **energy-limited events** that are the major concern of package designers and for accident events, such as, aircraft crash, a **strain-based criteria** is more appropriate.

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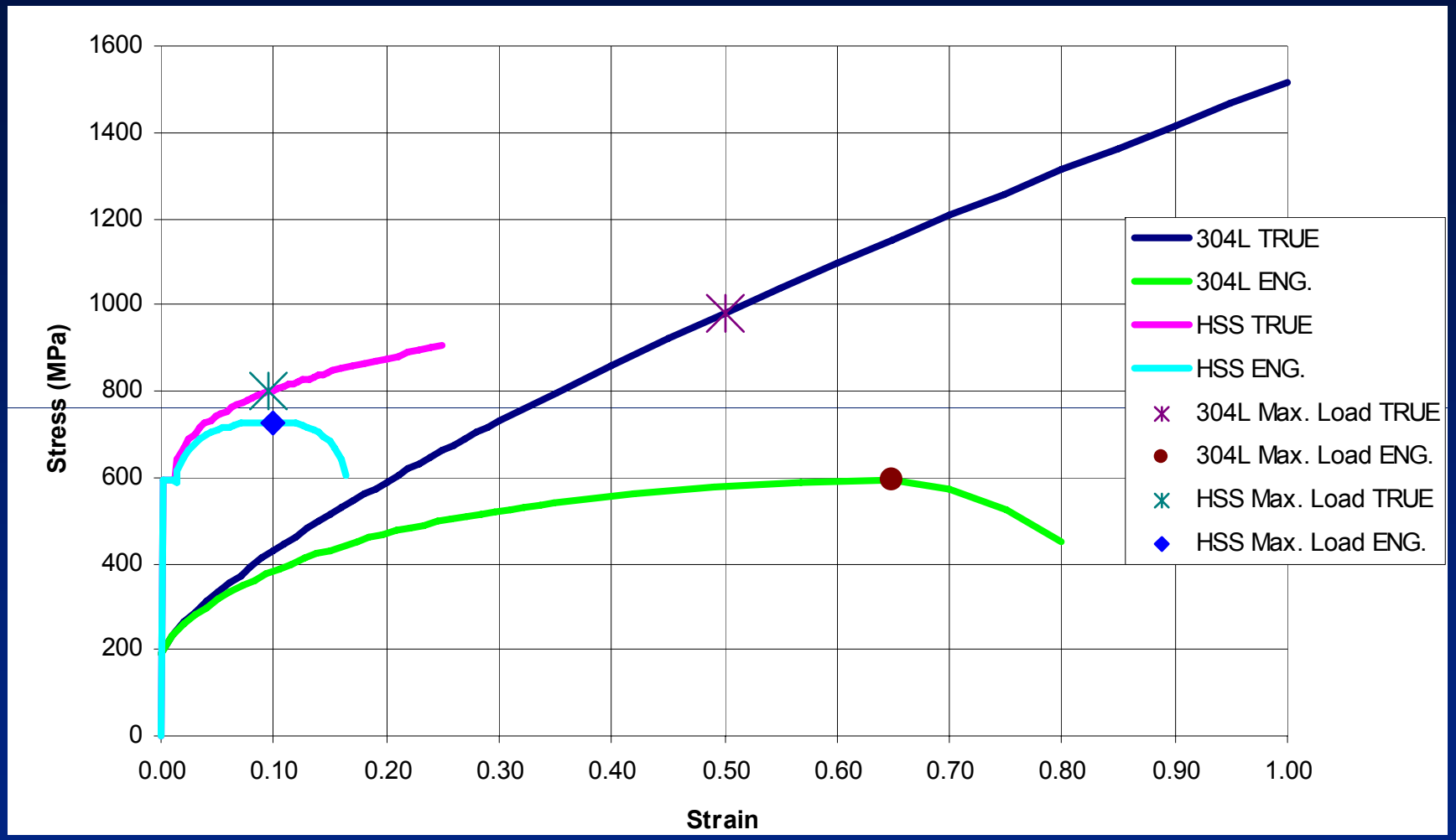
MATERIAL BEHAVIOR



- The ability of the material to absorb energy is related to the area under the stress-strain curve.

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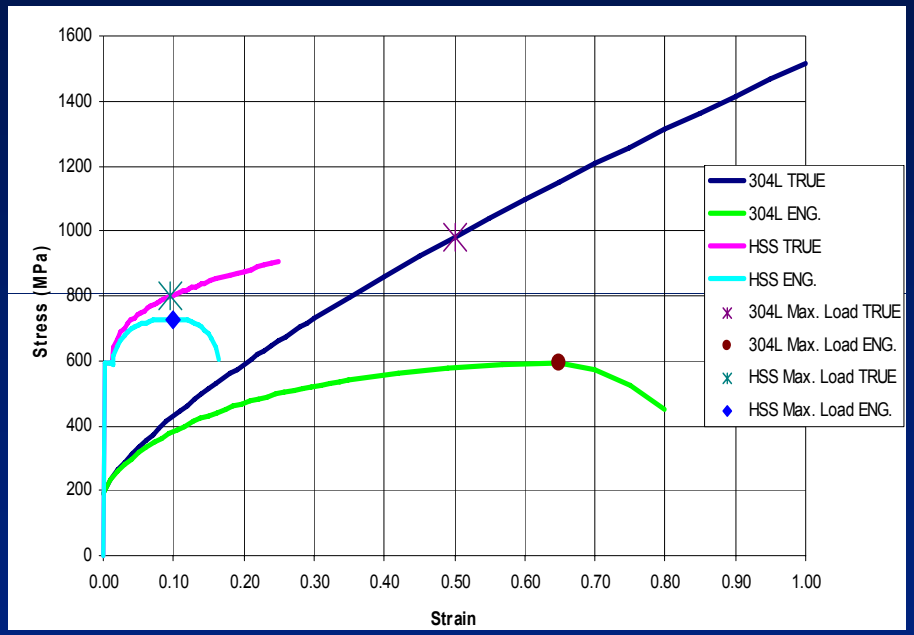
MATERIAL BEHAVIOR (cont.)

- The high-strength steel has a higher allowable stress but lower energy absorption capacity.
- Stress-based acceptance criteria drive designers towards higher-strength materials.
- These materials may not actually provide additional safety for energy-limited events.



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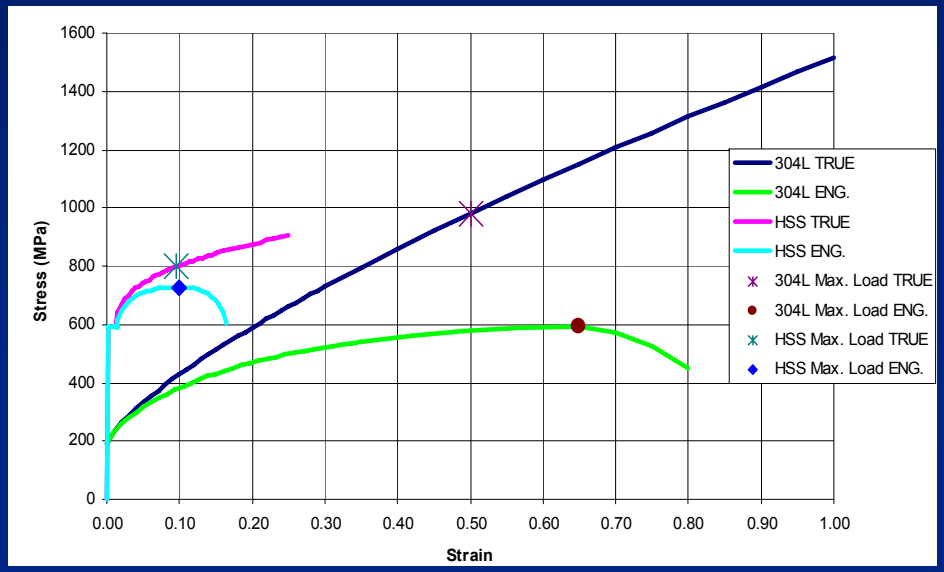
Uniform Strain and Failure Strain

- The true strain at fracture (including necking) can be calculated from the reduction in area. $\varepsilon_f = ln\left(\frac{1}{1 - RA}\right)$
- The strain at maximum load (the point of onset of necking), which is called the **uniform strain**, is considerably less than the true strain at fracture and should be the basis for any strain-based criteria.
- The strain to failure is a function of the stress state.



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ASME PROPOSED STRAIN LIMITS

- Applicable only to “Quality Models”
- Away (>$3t_n$) from discontinuities
  - Average through thickness < (0.67 x $\varepsilon_{uniform}$)/ TF
  - Maximum <[$\varepsilon_{uniform}$ + 0.25 x ($\varepsilon_{fracture}$ - $\varepsilon_{uniform}$)]/ TF
- At discontinuities or location of impact
  - Average < (0.85 x $\varepsilon_{uniform}$)/ TF

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

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APPLICATION OF ASME STRAIN LIMITS

- The proposed strain limits do not supersede the requirement that the closure region should remain essentially elastic.
- The common practice of limiting package accelerations by the addition of impact limiters/impact limiting material should reduce the allowable strain in the containment vessel.
- The criteria is only valid for energy limited events.

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COMPARISON OF ACCEPTANCE CRITERIA

- The goal of the Code for the design of radioactive material transportation packages is the same whatever acceptance criteria are used – to assure the package can perform its intended function of containing the radioactive contents.

- It is expected that the design of packages will not change significantly with any change of acceptance criteria, but rather that **the acceptance criteria will make it easier to demonstrate compliance** with the intent of the regulations.

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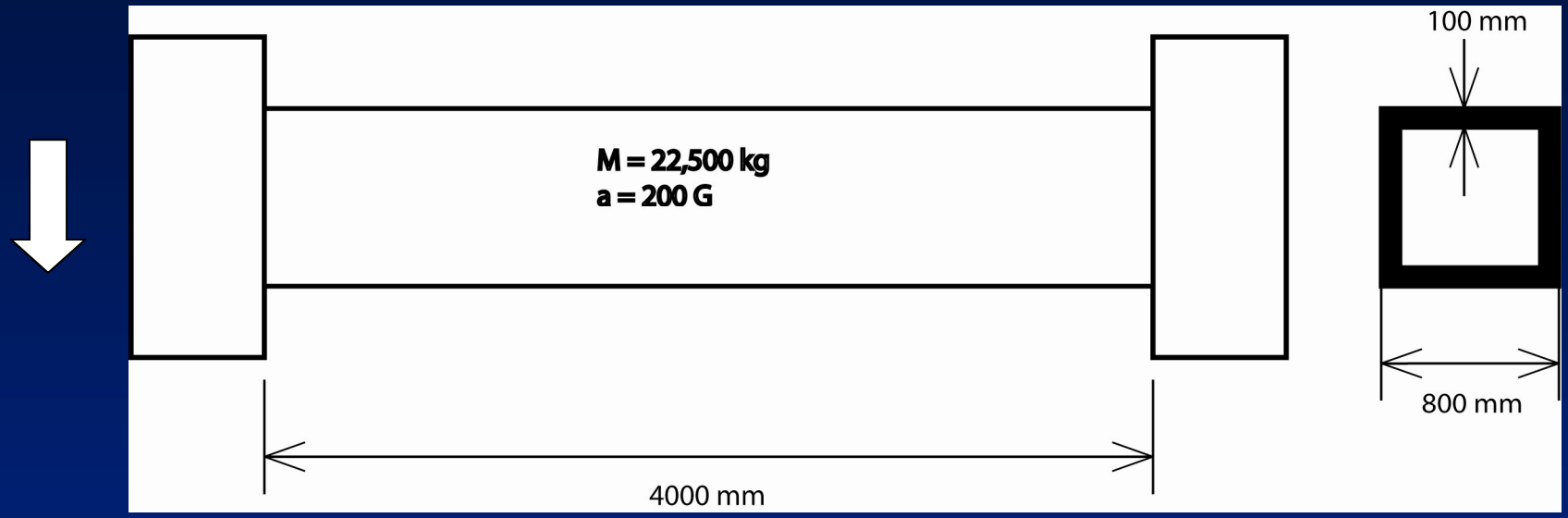
EXAMPLE PACKAGE



- Stresses and strains for this example package subjected to a side impact will be compared.
- Material: Type 304 stainless steel (S_m = 20 ksi)

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ELASTIC ANALYSIS

	Maximum from Analysis	Code Allowable
Membrane Stress	331 MPa [48 ksi]	331 MPa [48 ksi]
Membrane Plus Bending Stress	378 MPa [55 ksi]	496 MPa [72 ksi]

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INELASTIC ANALYSIS
(input actual stress-strain curve)

	Maximum from Analysis	
Membrane Stress	306 MPa [44.4 ksi]	
Membrane Plus Bending Stress	318 MPa [46.1 ksi]	
Strain	**5.3%**	

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REVISION TO DESIGN

- What acceleration leads to inelastic stress equal to the Appendix F design allowable (0.7 S_u)?

  234 G

- The maximum strain in this case is about **9.5%,** significantly less than 0.67 x $\varepsilon_{uniform}$

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QUALITY MODELS

- 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 (currently being developed by the ASME Task Group on Computational Modeling for Explicit Dynamics), or has been developed with the use of convergence and sensitivity studies.
- Topics for the Task Group include benchmarking, convergence studies, and qualification of analysts.

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Accident Events (Level D Limits)

- 9m Drop <u>with</u> Impact Limiters

- Puncture Drop
- Drops <u>without</u> Impact Limiters
- Aircraft Crash

← 5% - 10% → ← 0.67 x ε_u = 34% →

Average through Thickness Strains

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"Primary Membrane" Stress and Strain Margins Against Failure

- Current ASME Stress-Based Criteria for Load-Limited Events

  Su / 0.7 Su = 1.4

- Proposed ASME Strain-Based Criteria for Energy-Limited Events

  100% / 34% = 3.0

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CONCLUSION

- The analysis sophistication of the design community has progressed sufficiently to allow inelastic analyses.
- Energy limited events should be analyzed using strain-based acceptance criteria.
- The ASME recognizes this and is developing standards for these analyses.