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Inelastic Analysis Acceptance Criteria for Radioactive Material Transportation Containers[1]

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ABSTRACT

The design criteria currently used in the design of radioactive material (RAM) transportation containers are taken from the ASME Boiler and Pressure Vessel Code (ASME, 1992). These load-based criteria are ideally suited for pressure vessels where the loading is quasistatic and all stresses are in equilibrium with externally applied loads. For impact events, the use of load-based criteria is less supportable. Impact events tend to be energy controlled, and thus, energy-based acceptance criteria would appear to be more appropriate. Determination of an ideal design criteria depends on what behavior is desired. Currently there is not a design criteria for inelastic analysis for RAM transportation packages that is accepted by the regulatory agencies. This lack of acceptance criteria is one of the major factors in limiting the use of inelastic analysis. In this paper inelastic analysis acceptance criteria based on stress and strain-energy density will be compared for two stainless steel test units subjected to impacts onto an unyielding target. Two different material models are considered for the inelastic analysis, a bilinear fit of the stress-strain curve and a power law hardening model that very closely follows the stress-strain curve. It is the purpose of this paper to stimulate discussion and research into the area of strain-energy density based inelastic analysis acceptance criteria.

Material Properties

One of the major disadvantages to the use of inelastic analysis is the greater detail required for knowledge of the material response to loading. In elastic analysis the only material properties required are yield strength, modulus of elasticity, and Poisson's ratio. For inelastic analysis a description of the stress strain curve to higher levels of stress is required. Generally this description is broken into two regions, below yield and above yield.

For the 304 stainless steel used in this study, stresses less than yield stress may be expressed as:

$$\sigma = E\varepsilon \qquad \text{(EQ 1)}$$

where σ is the true stress, E is Young's modulus (28 x 10^6 psi), and ε is the true strain. For stresses larger than the yield stress the stress-strain relationship may be expressed as (Wellman and Salzbrenner, 1992):

$$\sigma = \sigma_p + A\varepsilon^n \qquad \text{(EQ 2)}$$

where σ_p is the limit of proportionality (28,000 psi), A is the hardening constant (192,746 psi), and n is the hardening exponent (0.74819).

It is possible to approximate this curve with a linear hardening model. With this model EQ 1 represents the stress-strain behavior prior to yielding and the post-yield behavior is represented by:

$$\sigma = \sigma_p + E_h\varepsilon \qquad \text{(EQ 3)}$$

where: E_h is the linear hardening modulus (345,060 psi used in this study) and the rest of the variables are as defined earlier. Figure 1 shows a comparison of the true stress vs. true strain curve from the equations given above and experimental data from a tensile test. For strains less than 17% the bilinear curve has lower strain-energy density than the power-law hardening curve.

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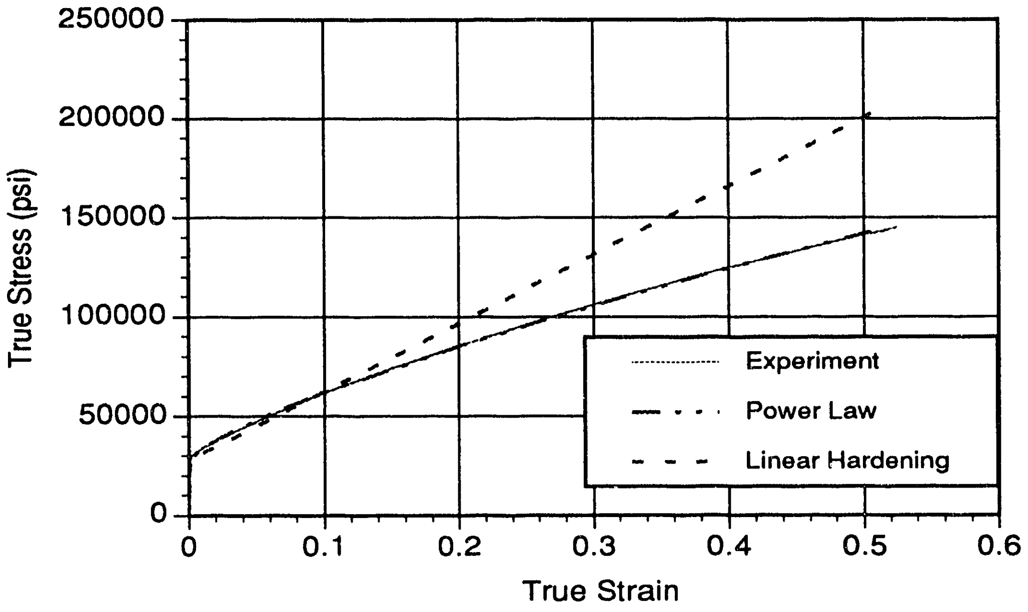


FIGURE 1: TRUE STRESS VERSUS TRUE STRAIN FOR 304 STAINLESS STEEL

Failure Criteria

Two failure criteria are examined. The first is derived from the ASME Boiler and Pressure Vessel Code Section III, Division 1, Appendix F (ASME, 1992) and the second is based on one half of the strain-energy density at a conservative estimate of the true strain at ultimate load in a tensile test. From the Boiler and Pressure Vessel Code the allowable stress for inelastic analysis is the greater of $\sigma_y+1/3(\sigma_u-\sigma_y)$ and $0.7\sigma_u$ for primary membrane stress intensity. For 304 stainless steel (σ_y = 30,000 psi, σ_u = 75,000 psi) $0.7\sigma_u$ governs, and takes a value of 52,500 psi. For primary membrane plus bending stress intensity the allowable limit is $0.9\sigma_u$, and is equal to 67,500 psi for the 304 stainless steel used in this study. Each of these stress limits was converted to a plastic strain limit by using equations 2 and 3, resulting in an allowable plastic strain of 6.35% for membrane action and 12.02% for membrane plus bending action using the power law hardening model and 7.10% for membrane action and 11.45% for membrane plus bending action using the linear hardening model.

Strain-energy density is determined by integration of the true stress vs. true strain curve. When these curves are expressed mathematically this integration is carried out in the usual fashion. If the curves are defined by a series of data points the integration can be carried out numerically. The failure criteria based on one half of the strain-energy density at a conservative estimate of the true strain at ultimate load in a tensile test (40% used here for 304 stainless steel) results in an allowable plastic strain of 24.94% using the power law hardening model and 26.39% using the linear hardening model.

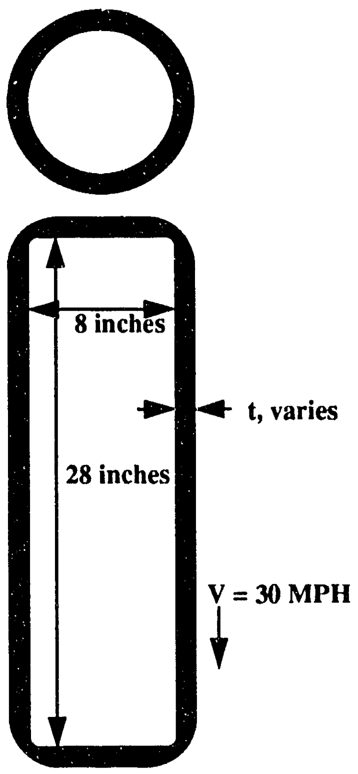
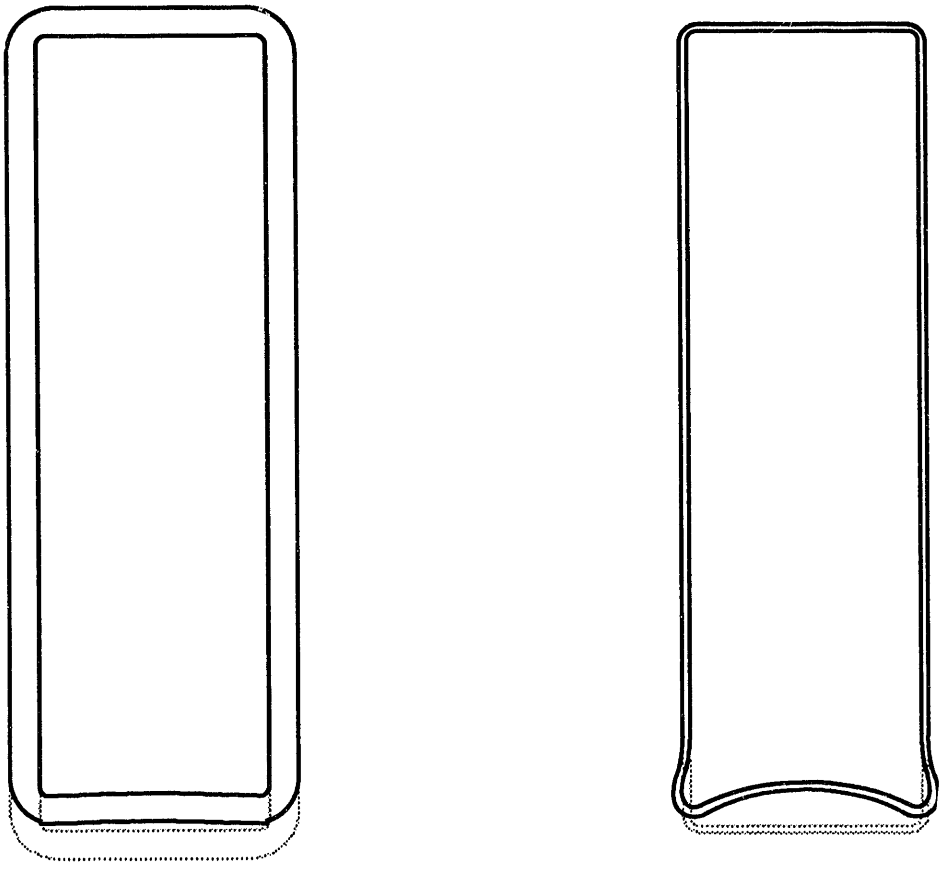


FIGURE 2: VESSEL FOR EXAMPLE 1



1.00 inch wall thickness

0.25 inch wall thickness

FIGURE 3: DEFORMED SHAPES FOR 1.00 INCH AND 0.25 INCH WALL THICKNESSES

Example Problems

The effect of the differences between the failure criteria and material models discussed above will be demonstrated via two example problems. In the first problem the vessel shown in Figure 2 is subjected to an impact of 44 feet/sec. onto an unyielding target in the orientation shown. The baseline wall thickness is 1.0 inches. This yields a total weight for the vessel of 254 pounds. All redesigns of the vessel adjust the density of the wall material to maintain this same weight. Using the power law hardening model for the stress-strain relationship results in a required wall thickness of 0.95 inches to meet the ASME Boiler and Pressure Vessel Code allowable stress and a wall thickness of 0.33 inches is required to meet the allowable plastic strain at one half the strain-energy density of 40% plastic strain. Using the linear hardening model for the stress-strain relationship results in a required wall thickness of 1.05 inches to meet the ASME Boiler and Pressure Vessel Code allowable stress and a wall thickness of 0.27 inches is required to meet the allowable plastic strain at one half the strain-energy density of 40% plastic strain. These results show that the model used to represent the stress-strain relationship has a much lower influence on the results than the acceptance criteria that is chosen. Figure 3 shows the final deformed shape of vessels with 1.00 inch and 0.25 inch wall thicknesses using the power law hardening material model. These deformed shapes suggest the vessel with the 0.25 inch wall has gross deformations that are unacceptably large, even though the failure criteria indicates that this vessel is not close to material rupture of the stainless steel. For this reason it is recommended that any set of acceptance criteria for inelastic analysis not rely entirely on the level of stress or strain in the material, but also have a limit on the acceptable amount of deformation, based on the planned application of the vessel. It is also interesting to note that the point with maximum strains for all of these analyses is near the corner between the impacting end and the side wall. In the construction of many vessels this would be the location of a weld. If heat treatment of the weld region is not possible then it is necessary to determine the allowable strains based on the material in this weld region, instead of the parent 304 stainless steel.

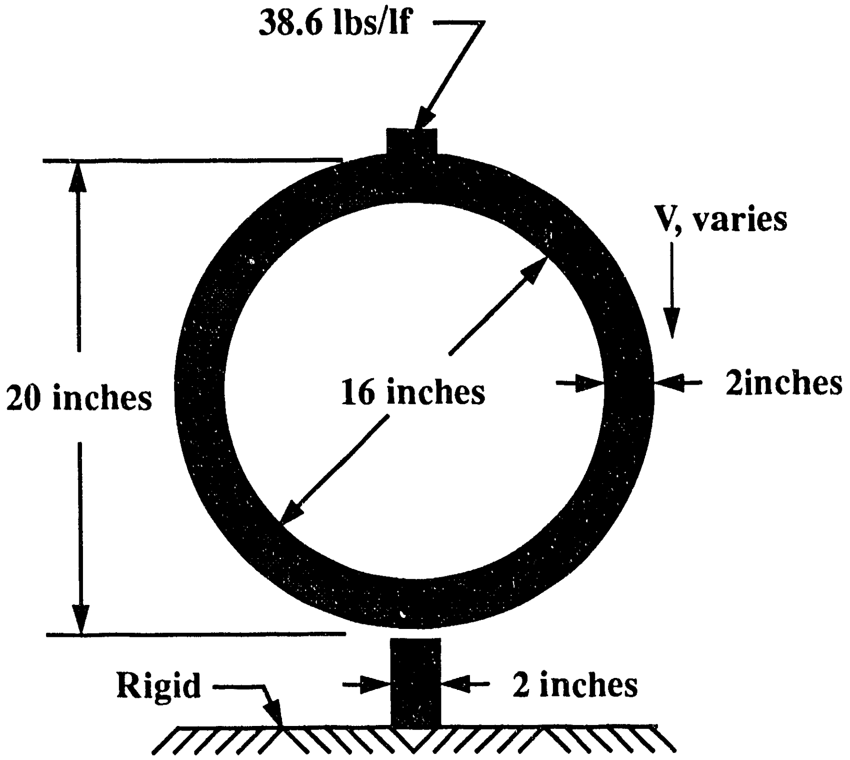
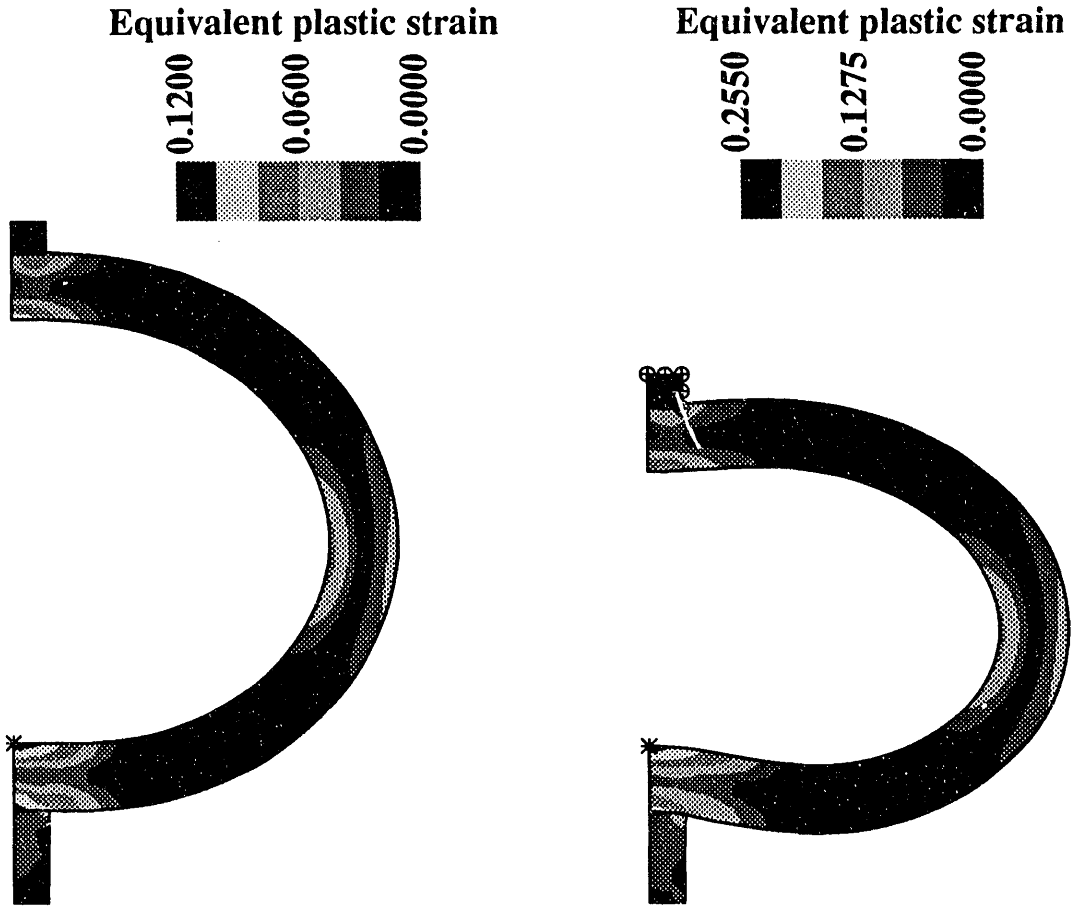


FIGURE 4: CONFIGURATION FOR EXAMPLE 2

The second example problem is an infinitely long 304 stainless steel tube with a 38.6 pounds/linear foot mass fixed to its top impacting onto a two inch wide stainless steel rail (Figure 4 shows the geometry). The ring has a 20 inch outside diameter and a two inch wall thickness. For this example the impact velocity is adjusted to reach the desired level of strain. Using the power law hardening model the strain level corresponding to the ASME Boiler and Pressure Vessel Code Appendix F allowable stress is reached when the impact velocity is 83 feet per second and the strain level corresponding to one half the strain-energy density at 40% plastic strain is reached when the impact velocity is 136 feet per second. Using the linear hardening model the strain level corresponding to the ASME Boiler and Pressure Vessel Code Appendix F allowable stress is reached when the impact velocity is 82 feet per second and the strain level corresponding to one half the strain-energy density at 40% plastic strain is reached when the impact velocity is 152 feet per second. Figure 5 shows the deformed shape and the plastic strain contours for impacts of 80 feet per second and 132 feet per second using the power law hardening model These results are similar to those from example 1, and indicate that the response is much more sensitive to acceptance criteria than it is to the method of modelling the post-yield behavior of the material. The results also indicate large deformations may result from plastic strains at the levels indicated by these acceptance criteria. This reinforces the contention that a stress or strain based limit is not sufficient to assure safety for inelastic analysis. These limits are adequate to assure no material failure, but a requirement for compatibility of deformations is also necessary.

CONCLUSIONS

The results of the work presented in this paper have shown the acceptance criteria chosen for design by inelastic analysis has a profound effect on the results of that design. This result is not extremely surprising, in that the two acceptance criteria chosen for this study resulted in large differences in allowable strains for the 304 stainless steel material used in the designs. This result would not necessarily be obtained for a material with similar strength properties but lower ductility. For such a material the allowable stress from the ASME Boiler and Pressure Vessel Code would not change, but the allowable strain determined from the strain-energy density based acceptance criteria would be reduced. This brings up the major issue behind the development of any acceptance criteria: "What is the behavior you are trying to achieve or assure with the acceptance criteria?" In the case of radioactive material transportation packages it is the authors' belief that the desired behavior is no release of radioactive material or loss of shielding for accidents less severe than the regulatory hypothetical accident defined in 10CFR71 (NRC, 1983) and a predictable and gradual failure mode for any accidents more severe than the regulatory hypothetical accident. This behavior can best be achieved by an



80 feet per second impact

132 feet per second impact

FIGURE 5: DEFORMED PIPE FROM 80 FPS AND 132 FPS IMPACTS

acceptance criteria that takes into account the energy limited nature of impact accidents. In this regard, the most logical acceptance criteria is one that is based on strain-energy density with a secondary limit on deformations. Further investigation is required to determine what level of strain-energy density provides for adequate safety and how to implement the secondary limit on deformations. It is the purpose of this paper to indicate the problems associated with choosing an acceptance criteria for inelastic analysis and to stimulate discussion and research into strain-energy density based acceptance criterion for inelastic analysis. It is not intended to provide an absolute answer to this very involved question.

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