# Development of Inelastic Analysis Acceptance Criteria for Radioactive Material Transportation Packages*

*D.J. Ammerman, J.S. Ludwigsen*
*Sandia National Laboratories*

## INTRODUCTION

The response of radioactive material transportation packages to mechanical accident loadings can be more accurately characterized by nonlinear dynamic analysis than by the "equivalent dynamic" static elastic analysis typically used in the design of these packages. This more accurate characterization of the response can lead to improved package safety and design efficiency. For nonlinear dynamic analysis to become the preferred method of package design analysis, an acceptance criterion must be established that achieves an equivalent level of safety as the currently used criterion defined in NRC Regulatory Guide 7.6 (NRC 1978). Sandia National Laboratories has been conducting a study of possible acceptance criteria to meet this requirement. In this paper nonlinear dynamic analysis acceptance criteria based on stress, strain, and strain-energy-density will be discussed. An example package design will be compared for each of the design criteria, including the approach of NRC Regulatory Guide 7.6.

## BACKGROUND

Traditional design-by-analysis techniques have followed the requirements of NRC Regulatory Guide 7.6 to determine the adequacy of the design. This guide requires elastic analysis of the structural portions of the package and sets limits for maximum stresses in the containment boundary. The guide does not require elastic treatment of the nonstructural portions of the package, such as impact limiters and shielding. Also, the guide does not allow designs where structural instability may occur and post buckling strength is relied upon to achieve the packaging safety, so if the designer wishes to follow the guide it must be demonstrated that instabilities do not exist.

This analysis procedure does not predict the real behavior of the package, since plasticity generally occurs in the nonstructural elements, and is allowed even in the structural elements due to allowable stresses greater than the yield stress. For this reason many

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administrative controls are placed on the designs to ensure safety, such as limiting stresses in the closure region to below the allowable stress and limiting containment boundary materials to those with high ductility. It is also impossible to use this technique to determine the response of the package to the puncture accident, which generally causes inelastic deformation to the containment boundary.

For these reasons it is desirable to have a more robust design methodology based on nonlinear dynamic analysis techniques. Nonlinear dynamic analysis provides a better understanding of package behavior, leading to more uniform factors of safety and weight savings. The major drawback to this analysis technique is the lack of an acceptance criterion ensuring equivalent package safety to that of the current analysis techniques. The work reported in this paper is aimed at establishment of such an acceptance criterion.

## NONLINEAR DYNAMIC ANALYSIS ACCEPTANCE CRITERIA

It is desired to have a nonlinear dynamic analysis acceptance criterion that results in package designs similar to packages currently being designed. This will alleviate concerns that use of nonlinear dynamic analysis will result in packages having lower safety factors than current packages. Acceptance criteria may be based on: (1) maximum allowable stress relative to yield stress and ultimate stress, (2) maximum allowable strain relative to strain-to-failure, and (3) maximum allowable strain-energy-density relative to strain-energy-density at maximum load in a tensile test. Each of these acceptance criteria can be altered by adjusting the ratio between allowable values and material data. The acceptance criterion based on stress was chosen because there is a stress-based acceptance criterion for nonlinear analysis as part of Section III, Part 1, Appendix F of the ASME Boiler and Pressure Vessel Code (ASME 1992). The acceptance criterion based on strain was chosen because, for most metals, there is a large change in strain for a small change in stress when the stress is above the yield point stress, and a strain-based acceptance criterion may provide more uniform margins of safety than the stress-based one. The acceptance criterion based on strain-energy-density was chosen because radioactive material package structural accident events prescribed by U.S. and international regulations are energy limited instead of force (stress) or deformation (strain) limited. Therefore an acceptance criterion based on strain-energy-density should provide a more uniform factor of safety for all materials.

The most widely used material for containment boundaries in radioactive material transportation packages is austenitic stainless steel, such as Type 304L. For nonlinear dynamic analysis it is important to have an accurate depiction of the material stress-strain relationship. For 304L stainless steel the true stress vs. true strain curve can be expressed by the following two equations:

For strains less than the strain at the limit of proportionality:

$$\sigma = E\varepsilon \tag{1}$$

and, for strains larger than the limit of proportionality:

$$\sigma = \sigma_p + A\,(\varepsilon - \varepsilon_p)^n \tag{2}$$

where:

$\sigma$ = the true stress in the material,
E = Young's modulus, 193,000 MPa
$\varepsilon$ = the true strain in the material
$\sigma_p$= the stress at the limit of proportionality, 193 MPa
$\varepsilon_p$ = the strain at the limit of proportionality, 0.001
A = the hardening modulus, 1328 MPa
and
n = the hardening exponent, 0.7482

In addition, this material has ASME Boiler and Pressure Vessel Code material values of $S_y$ = 30 ksi (207 MPa), $S_u$ = 75 ksi (517 MPa), and $S_m$ = 18.8 ksi (130 MPa). These stresses are engineering stresses, so they are not directly comparable to the stresses from equation 2 above. The stress-based acceptance criteria from Appendix F of Section III, Division 1, of the ASME code gives allowable stresses as the greater of $S_y+1/3(S_u-S_y)$ or $0.7S_u$ for primary membrane stress intensity and $0.9S_u$ for primary membrane plus bending stress intensity. These criteria are based on the Tresca failure surface, which defines stress intensity as the maximum difference between principal stresses, or alternatively, as twice the maximum shear stress. For 304L stainless steel, these limits equate to 362 MPa for membrane and 465 MPa for membrane plus bending stresses. Converting these limits to true stress levels gives 392 MPa for membrane and 555 MPa for membrane plus bending stress. These stresses occur at true strains of 8.0% and 17.7%, respectively, corresponding to engineering strains of 8.3% and 19.3%.

Type 304L stainless steel has a failure strain (true strain) in excess of 70%, but material instability (necking in a tension test specimen) starts to occur at a true strain of about 40%. For the acceptance criteria developed in this report this value will be used as the maximum strain the material can withstand. The strain-based acceptance criteria will be expressed as a ratio of this strain and the strain-energy-density-based acceptance criteria will be expressed as a ratio of the strain-energy-density at this level of strain. Integration of the stress-strain curves to a strain of 40% gives a maximum strain-energy-density of 230 MPa.

To determine nonlinear dynamic analysis acceptance criteria that result in designs similar to current packages, an example package designed using traditional techniques is compared to packages designed using nonlinear dynamic analysis techniques.

## EXAMPLE PACKAGE

The example package designed using traditional methods is a small Type B package with typical design details. The cross-section of the package is shown in Figure 1. The inside dimensions are 15.2 cm in diameter and 61 cm long. The cylindrical wall of the inner container is 6.35 mm thick and the ends have a thicknesses of 12.7 mm. Along the sides of the cylinder there is 8.25 cm of impact limiting foam with a crush strength of 1 MPa. On the end of the package the thickness of foam is increased to 16.5 cm. The foam impact limiter is encased in a 24 gauge (0.61 mm thick) 304L stainless steel skin with flanges to facilitate disassembly of the package. Details of the inner cylinder closure mechanism are not included in the model.

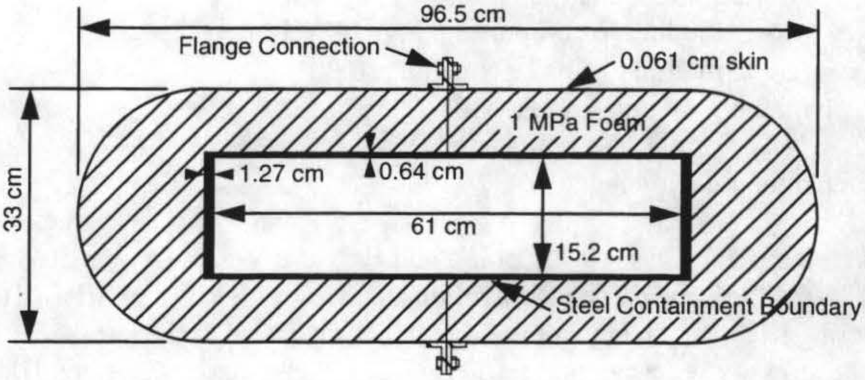

**Figure 1.** Cross-section of the package used for comparison between elastic and various nonlinear dynamic analysis acceptance criteria.

## Quasi-Dynamic Elastic Analysis

For this package the 9-meter side-drop onto an unyielding target provides the highest loads to the package because in this orientation there is more backed area of impact limiter than in either the end or corner drops. The calculated accelerations based on the crush strength of the impact limiter, the area backed by the containment vessel, and the mass of the package is 203 Gs. This impact orientation also results in the highest stresses. Therefore, for comparisons with nonlinear dynamic analysis based designs, only the side-drop orientation will be considered and the only variable will be the thickness of the cylinder wall. Figure 2 shows the stress distribution from the quasi-dynamic elastic analysis of this drop configuration. The figure shows one-quarter of the containment boundary due to quarter symmetry of the package and inertial loading. The maximum stress from this analysis, 448 MPa, occurs at the center of the bottom of the cylinder, and is clearly a bending stress. This stress is only slightly lower than the allowable membrane plus bending stress of 467 MPa (3.6 $S_m$). Since the yield stress for this material is 207 MPa, this level of stress implies there will be some local yielding of the containment boundary at this location.

## Nonlinear Dynamic Analysis

The nonlinear dynamic analysis of the package includes the impact limiter foam, stainless steel skin, and flange connection. For this reason no assumptions need to be made about how the load from the impact limiter is applied to the package. The calculated peak acceleration from the finite element model was about 230 Gs, which is fairly close to the 203 Gs assumed in the elastic analysis. It should be noted the analysis overpredicts the stiffness of the bolted flange connection because the symmetry boundary condition applied at the center of the package does not allow the flange to buckle. Elimination of this conservative assumption would cause a slight decrease in the accelerations and loads on the

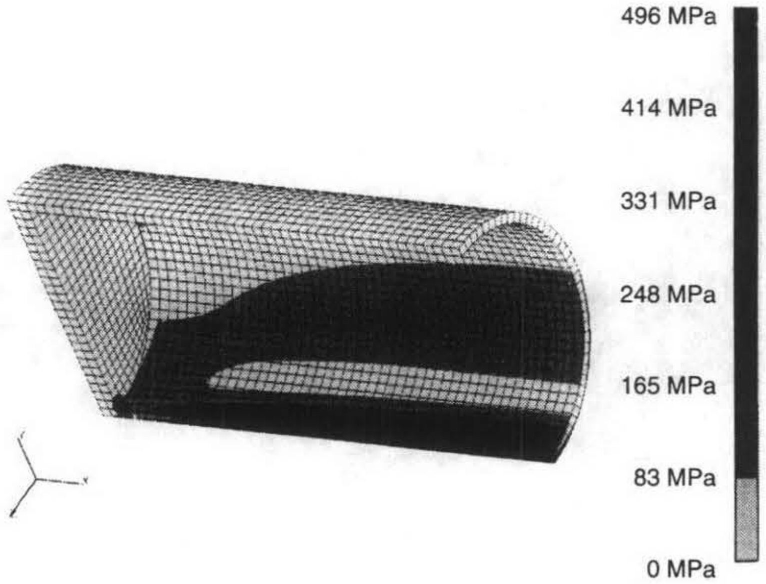

**Figure 2.** Stresses in the containment boundary calculated from pseudo-dynamic elastic analysis of the test package.

package. The strain distribution in the side walls of the containment boundary for this analysis is shown in Figure 3. The maximum plastic strain occurs at the top center of the package and is 0.89% (total strain of 0.99%). This corresponds to a maximum stress of 229 MPa and a strain-energy-density of 1.7 MPa. The stress is 41% of the ASME allowable stress for membrane plus bending using inelastic analysis, the strain is 2.2% of the strain to failure, and the strain-energy-density is only 0.73% of the maximum strain-energy-density. This analysis shows how a small amount of yielding can significantly reduce the predicted stresses in the containment boundary and result in a redistribution of stresses. The elastic analysis predicted the maximum stress to be at the bottom mid-length centerline of the package and the nonlinear dynamic analysis predicts the highest stress at the top mid-length centerline.

## Design of Package with Ferritic Steel

A type of ferritic steel frequently used for pressure vessel forgings is ASTM A508. This steel has higher strength than 304L stainless steel, but lower ductility. Comparison of inelastic analysis acceptance criteria for this steel will illustrate the difference between stress-based, strain-based, and strain-energy-density-based acceptance criteria.

This steel is available in several different designations. The type used for this study is Grade 2 Class 2. This material has ASTM code properties of 448 MPa yield strength, 621 MPa tensile strength, 18% minimum elongation for a 2-inch test specimen, and 35% minimum reduction in area. These material properties would give the material an $S_m$ value of 155 MPa. For the stress-based acceptance criteria from the ASME code, the allowable engineering stresses are 505 MPa for membrane stresses and 558 MPa for membrane plus bending stresses. These correspond to true stresses of 514 MPa and 574 MPa, respectively, and occur at true strains of 1.6% and 2.8%, respectively.

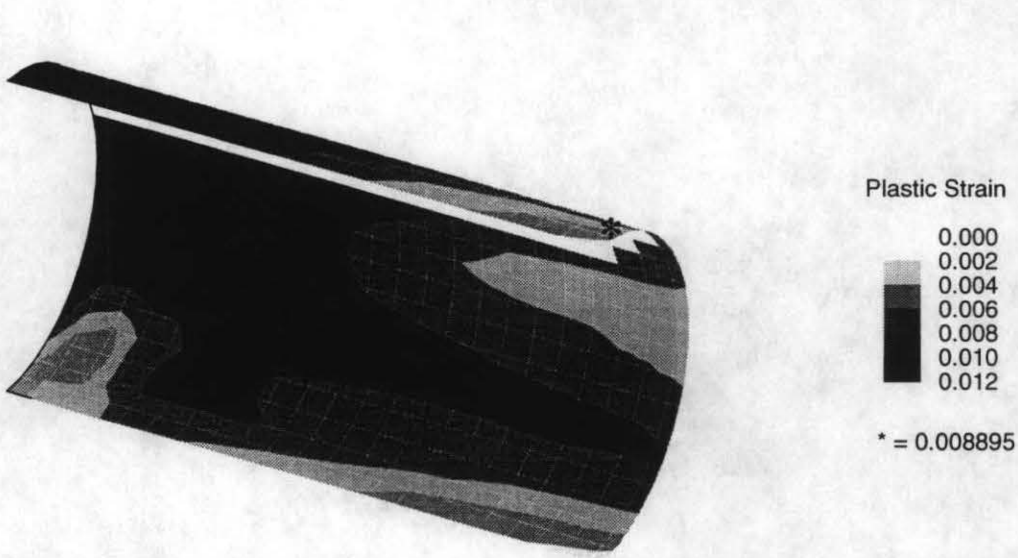

**Figure 3.** Strains predicted from nonlinear dynamic analysis of the stainless steel package with 0.25 inch thick wall.

This information is not sufficient to establish a stress-strain relationship for the material. Tensile tests have been used to develop the following power-law hardening model for the postyield material behavior:

$$\sigma = \sigma_y + A\langle \varepsilon - \varepsilon_l \rangle^n \qquad \text{(EQ 3)}$$

where:

$\sigma$ = the true stress in the material,
$\varepsilon$ = the true strain in the material
$\sigma_y$ = the yield stress, 483 MPa
$\varepsilon_l$ = the luders strain, or the plastic strain at the onset of strain hardening, 0.015
A = the hardening modulus, 570 MPa
n = the hardening exponent, 0.42
and
the brackets <> indicate the Heaviside function where the expression enclosed takes on the value of the expression when positive and zero when negative.

An additional point needed for the proposed acceptance criteria is the strain at the onset of material instability. This is the point at which necking starts and the maximum load is reached in a tensile test. From the tensile test data, this is at an engineering strain of 13%, or a true strain of 12.2%. Integration of the above equation to a strain of 12.2% gives a strain-energy-density at maximum load in a tensile test of 76.1 MPa.

Using the same example package as above, the elastic analysis is identical, because the modulus of elasticity for the two steels is the same. The resulting maximum bending plus membrane stress of 448 MPa is about 80% of the allowable stress of 558 MPa (3.6 $S_m$).

The plastic strains in the side walls from the nonlinear dynamic analysis of this package in the side-drop orientation are shown in Figure 4. The maximum plastic strain is 0.56% (total strain of 0.81%) and occurs at the top centerline of the package. Comparison of this figure with the results for the 304L stainless steel package shown in Figure 3 shows lower strains, as expected, and very similar distribution. The 0.56% strain is less than the luders strain, so the material is in the range of constant stress (483 MPa). The strain-energy-density at this level of strain is 3.3 MPa. These levels correspond to stress of 86.4% of the ASME allowable stress for inelastic analysis, strains of 4.6% of the strain at maximum load, and strain-energy-density of 4.3% of the strain-energy-density at maximum load. This design has a larger design margin for elastic analysis than the 304L stainless steel design, but a lower design margin for all of the inelastic analysis acceptance criteria.

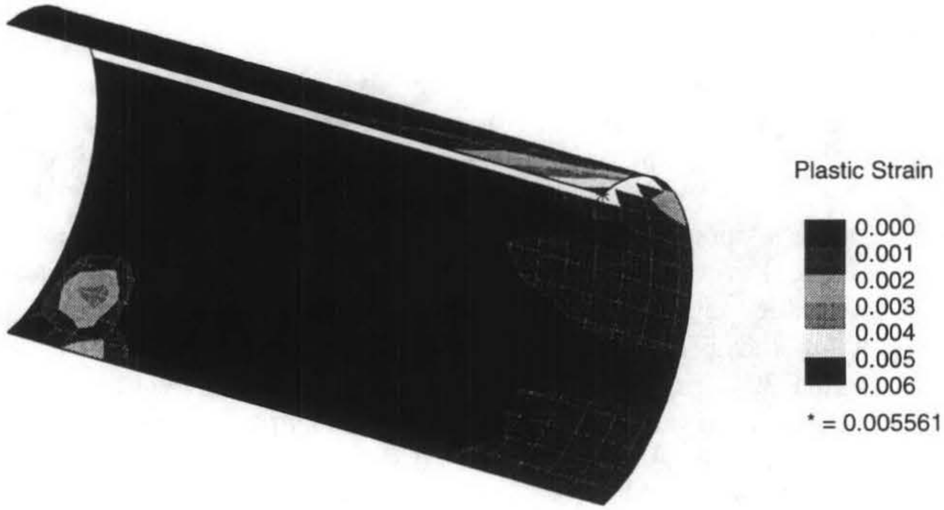

**Figure 4.** Strains predicted from nonlinear dynamic analysis of the ferritic steel package with 0.25 inch thick wall

## Summary of Results

The results from these three analyses are presented in Table 1. For the nonlinear dynamic analyses the maximum stress, strain, or strain-energy-density is compared to the allowable stress from the ASME Boiler and Pressure Vessel Code for inelastic analysis, a conservative estimate of the failure strain, or the strain-energy-density at maximum load in a tensile test, respectively. These results show the package with 304L stainless steel containment boundary designed using traditional analysis techniques has a large margin of safety when analyzed using nonlinear dynamic analysis techniques. The results for the package with A508 ferritic steel containment boundary are significantly different. For this package the stress-based inelastic analysis acceptance criteria has a lower design margin than the elastic analysis. Even for this case, the percentage of the available strain-energy in the material used is very small.

**Table 1: Summary of Analysis Results**

| Analysis | Max. Stress (MPa) | % of allow. stress | Max. Strain (m/m) | % of failure strain | Max. Strain-Energy (MPa) | % of failure strain energy |
|---|---|---|---|---|---|---|
| Elastic, 304L | 448 | 96 | 0.0023 | - | 0.5 | - |
| Elastic, A508 | 448 | 80 | 0.0023 | - | 0.5 | - |
| Nonlinear, 304L | 229 | 41 | 0.0089 | 2.2 | 1.7 | 0.73 |
| Nonlinear, A508 | 483 | 86 | 0.0056 | 4.6 | 3.3 | 4.3 |

## CONCLUSIONS

The goal of this work was to establish a nonlinear dynamic analysis acceptance criterion that resulted in package designs that are similar to those from traditional analysis techniques. This acceptance criterion should allow only a slight amount of plasticity, as is seen in the example design. All of the proposed inelastic analysis acceptance criteria can be calibrated to offer this behavior and all show the margin against material failure more clearly than elastic analysis. However, none of the proposed acceptance criteria can result in designs similar to the elastic analysis acceptance criteria for both the 304L and A508 packages considered in this study. This is due to the very different behavior of these two steels in the inelastic regime. 304L stainless steel has very high ductility and relatively low strength, while A508 steel has high strength and relatively low ductility. The current philosophy of regulatory agencies, especially in the United States, is to favor materials with high ductility. This philosophy leads to the recommendation for an acceptance criterion based on the results for the 304L package, such as limiting the maximum strain-energy-density to 1% of the strain-energy-density at the maximum load in a tensile test. Using this acceptance criterion the package with the A508 containment boundary would not be acceptable as configured in the example. Use of this level of strain-energy-density as an acceptance criterion will provide packages with the highest safety. Further work needs to be conducted to determine if this conclusion is valid for other accident events, such as puncture, and other package types.

## REFERENCES

ASME Boiler and Pressure Vessel Code, Section III, Division 1, Appendix F, ASME, New York, NY (1992).

US Nuclear Regulatory Commission, *Design Criteria for the Structural Analysis of Shipping Cask Containment Vessels*, Regulatory Guide 7.6, Washington, DC (1978).