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STRAIN-BASED ACCEPTANCE CRITERIA FOR SECTION III OF THE ASME BOILER AND PRESSURE VESSEL CODE

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ABSTRACT

Modern finite element codes used in the design of nuclear material transportation and storage casks can readily calculate the response of the packages beyond the elastic regime. These packages are designed to protect workers, the public, and the environment from the harmful effects of the transported radioactive material following a sequence of hypothetical accident conditions. Hypothetical accidents considered for transport packages include a 9-meter free drop onto an essentially unyielding target and a 1-meter free fall onto a 30-cm diameter puncture spike. For storage casks, accident conditions can include drops, tip-over, and aircraft impact. All of these accident events are energy-limited rather than load-limited, as is typically the case for boilers and pressure vessels. Therefore, it makes sense to have analysis acceptance criteria that are more closely related to absorbed energy than to applied load. Strain-based acceptance criteria are the best way to meet this objective.

As cask vendors' ability to perform non-linear impact analysis has improved, the need for a code-based method to interpret the results of this type of analysis has increased. The ASME Section III Working Group on Design of Division 3 Containments is working with Section III Working Group Design Methodology to develop strain based acceptance criteria to use within the ASME Code for energy limited events. This paper will briefly discuss the efforts within the ASME, detail the advantages of using strain-based criteria, discuss the problem areas associated with establishing strain-based criteria, and provide insights into inelastic analyses as applied to radioactive material transportation and storage casks in general. The views expressed represent those of the authors and not necessarily those of their respective organizations or the ASME.

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[1] and guidance has been provided by U.S. NRC Regulatory Guide 7.6 [2]. For the past decade, the section of the Code that is most relevant to the design has been Section III, Division 3. This section of the Code is based upon the concept of stress intensity, which is twice the maximum shear stress. The allowable stress intensities vary according to loading case and

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type of stress. For some of these, the allowable stress intensity is larger than the yield stress of the material, a tacit approval for a limited amount of plasticity. This approach was necessary when stresses were determined with hand calculations and was still beneficial during the early days of finite element analyses. As finite element calculations became more detailed, it has become possible to determine the stress state at any point in the package and the associated strains. Since the Code has allowed limited plasticity, modern package designers would prefer to use inelastic analysis techniques to calculate the stresses and strains that result from the required loading conditions. There are two ways to implement inelastic analysis: continue using stress-based acceptance criteria, or; develop strain-based acceptance criteria. Other parts of the Code (Section III, Division 1, Appendix F) allow the use of inelastic analysis, but these sections are not approved for the design of transportation packages except on a case-by-case basis. The acceptance criteria in Appendix F are stress-based, and the allowable stresses are a function of yield stress and/or ultimate stress. The major focus of this paper will be strain-based acceptance criteria, but some reference to the stress-based acceptance criteria of Appendix F will be included.

MATERIAL BEHAVIOR

The ductile materials that are used for structural parts of radioactive material packages exhibit the capability of absorbing large amounts of energy via plastic deformation. Because the accident conditions that generally govern the designs, such as the 9-meter drop test and the 1-meter puncture drop, are energy-limited events instead of load-limited events, maximum safety is assured by using materials with large capacity to absorb energy rather than by materials with maximum strength. Figure 1 shows the engineering and true stress strain curves of two materials, one an austenitic stainless steel and the other a high-strength carbon steel. The engineering stress-strain curves are shown because these are the curves that have been traditionally used to develop the allowable stresses in the ASME Code. The true stress-strain curves are shown because modern finite element programs calculate stresses and strains based on the current geometry instead of the initial geometry and therefore compute true stresses and strains. The design stress intensity (S_m) of the high-strength steel is larger than that for the austenitic stainless steel, but the area under the stress-strain curve up to the point of maximum load in a tensile test (directly proportional to the amount of energy that can be absorbed) is larger for the austenitic stainless steel. The point of maximum load in a tensile test is also the limit of uniform elongation, beyond this point there is localization of strain and the tensile test specimen becomes unstable. Although there is considerable amount of energy absorption capacity beyond this point, the onset of instability is generally avoided, and it is prudent in design to not use this reserve capacity. Another important factor to notice from the stress-strain curves in Figure 1 is that in the region of maximum load from the tensile test, both the engineering and true curves are increasing in strain much faster than they are increasing in stress. This implies that inaccuracies in calculated strain are much less important than inaccuracies in calculated stress.

For implementation of inelastic analysis in finite element codes a representation of the stress-strain curve is needed. This representation can be either continuous or piece-wise linear. The true stress-strain curve shown for 304L stainless steel in Figure 1 can be represented by the power law equation:

$$\sigma=\sigma_y+A\varepsilon^n,$$

where:

σ_y is the yield strength (more accurately the limit of proportionality) and is equal to 192 MPa;

A is the hardening constant and is equal to 1323 MPa, determined from curve fitting to test data; and n is the hardening exponent, which is equal to 0.74819, also determined from curve fitting.

For Code approved analyses a method must be developed to define this curve for any material that is used. The effect of both temperature and strain rate on the curve must also be considered. In the analysis community the preferred method for obtaining material data is to conduct an actual tensile test at the strain rate and temperature of interest. In the design community this is not possible, because the material to be included in the article being designed has not yet been delivered. ASTM material specifications do not specify stress-strain curves, and there can be considerable variability within a material type.

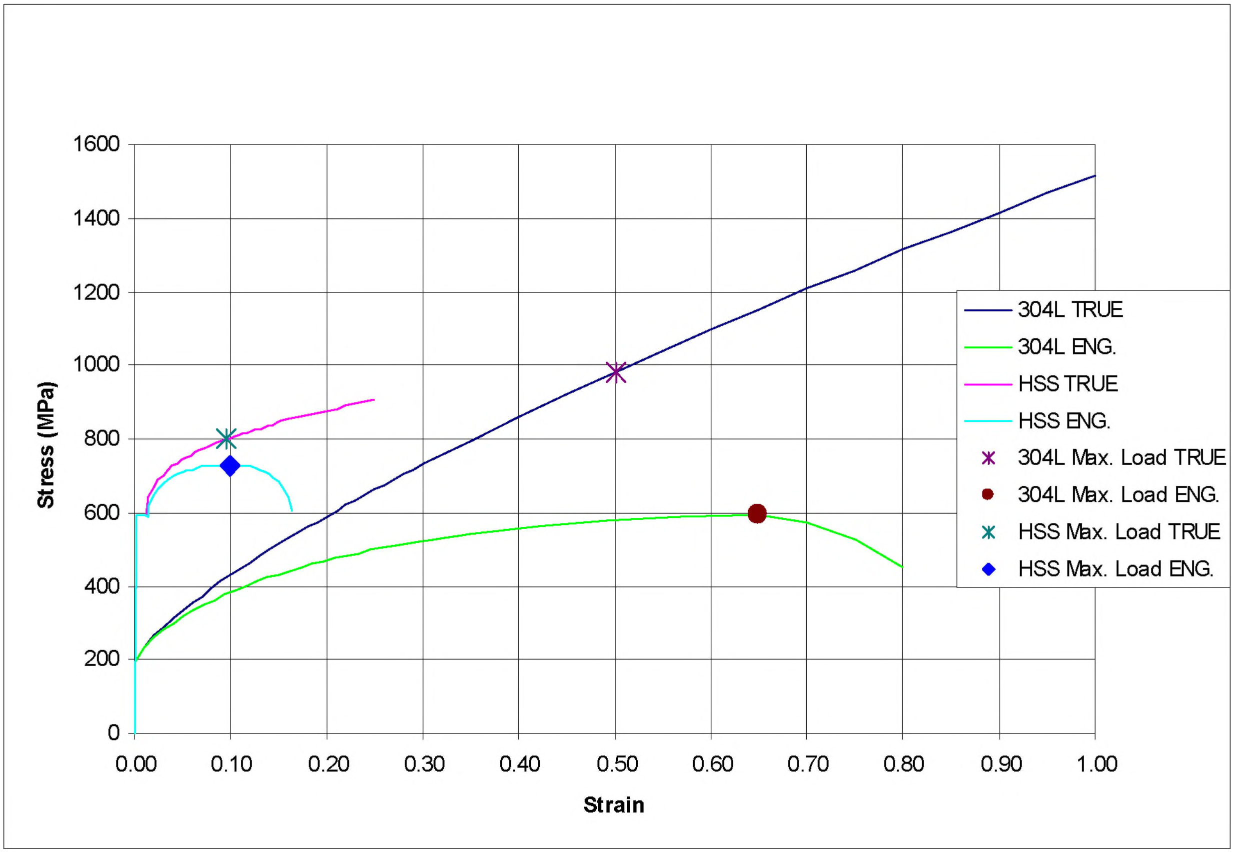

Figure 1 - Stress-strain curves for an austenitic stainless steel and a high strength carbon steel

A complication to the development of strain-based acceptance criteria is the relationship between strain to failure and stress state. The familiar uni-axial tensile test that generates the stress-strain curves shown in Figure 1 represents only one stress state. The actual strain to failure could be higher or lower than the value shown in these curves. If the loading is primarily compressive (the extreme being tri-axial compression) the strain to failure is higher. If the loading is primarily tensile (the extreme being tri-axial tension) the strain to failure is lower. Figure 2 shows the dependence of strain to failure on the stress triaxiality factor for an aluminum alloy [3]. Stress triaxiality is defined as the ratio of the mean stress to the deviatoric stress. For a normal tension test, the stress triaxiality is about 0.4 after necking has started (the triaxiality at failure is dependent on the degree of necking). All points to the right of this in Figure 2 represent tension in more than one axis, such as is the case in a biaxial tension test. The failure mode in these regions is by void formation. For a pure shear test there is no mean stress and the stress triaxiality is zero. Points with negative triaxiality have at least one component of compression. Failure in these regions is by generation of slip planes. Between these two regions (the shaded area of Figure 2) there is mixed-mode failure. Curves like that shown in Figure 2 are not currently available for many of the metals used in package design, so the exact relationship between stress triaxiality and strain to failure is not known.

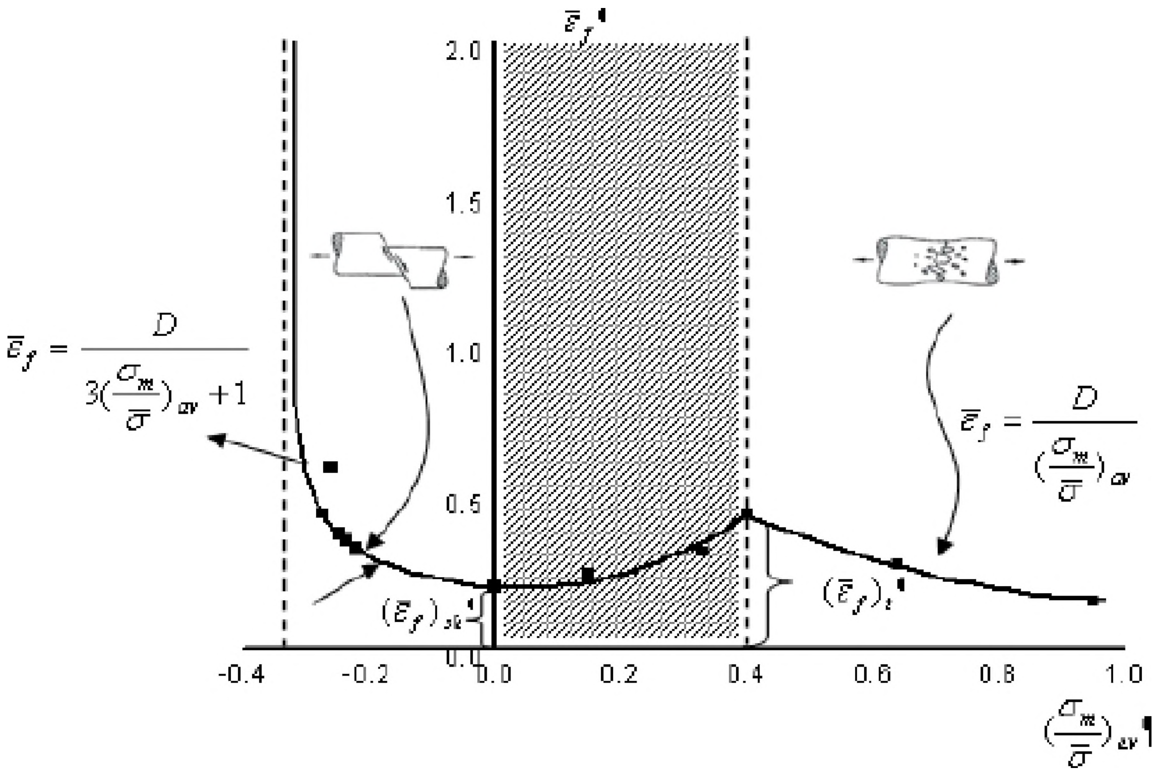

Figure 2 - Relationship between strain to failure and stress triaxiality

ASME PROBLEM STATEMENT

The Section III Working Group on Design of Division 3 Containments of the ASME has recognized the need for strain-based acceptance criteria to satisfy Level D Service Limits. The working group has developed a problem statement to define initial considerations for strain-based criteria for energy limited events. The development of the specific criteria will evolve from the initial problem statement. The goal of the problem statement is to provide a framework for the development of inelastic criteria that will be used in conjunction with an inelastic analysis. While there are many energy limited events that could potentially benefit from the application of strain-based acceptance criteria, the initial effort of Section III, Division 3 is the application to the 9-meter drop event of the hypothetical accident conditions for the transport of radioactive materials. The goal of the strain-based criteria is to maintain the allowable leakage rate as identified by the user's Design Specification for the containment. The strain-based acceptance criteria will not be applied to regions of the containment where deformation is detrimental to maintaining the desired leakage rate (e.g., the sealing region of a bolted closure). To reduce the material uncertainty, the initial focus of the criteria is on a very narrow range of materials, namely Types 304/304L and 316/316L austenitic stainless steel and will consider incorporating material strain rate. Although the range of materials is narrow, the materials proposed for incorporation into the criteria are by far the most widely used steels within the radioactive material transportation package industry.

The current ASME design philosophy includes different limits for the various types of stresses in the package that result from the hypothetical accident conditions calculated using elastic analysis techniques. There is a limit for average primary membrane stress ($P_m < 2.4S_m$ or $0.7S_u$), a limit for the maximum primary membrane plus bending stress ($P_m + P_b < 3.6S_m$ or S_u), and a limit for the maximum localized stress ($P_L < S_u$). The reason for this design philosophy is to have lower limits for types of stresses that are more likely to lead to abrupt or catastrophic failure. A similar design philosophy should be implemented for inelastic analysis and strain-based acceptance criteria. The ASME Problem Statement proposes a similar type of approach considering (1) average (through the thickness), (2) localized (through the thickness at discontinuities), and (3) average or localized (through the thickness) plus peak (surface) strains.

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. For this reason, it is instructive to compare several possible acceptance criteria. The first of these must be the currently approved elastic analysis method. For this comparison we will consider one loading case of the package, simple beam bending of the overall cross-section. In this example we will consider the 22,500 kg package shown in Figure 3 constructed of Type 304 stainless steel subjected to a side impact of 200G. This loading is somewhat typical for that resulting from a side drop. Material properties for the stainless steel (room temperature values) are given in Table 1. For membrane stress the allowable is the lesser of 2.4 S_m or 0.7 S_u. For this material 2.4 S_m governs and the allowable stress is 331 MPa. For membrane plus bending stress the allowable stress is the lesser of 3.6 S_m or S_u. For this material the 3.6 S_m governs and the allowable stress is 496 MPa. Figure 4 shows several possible stress-strain curves to use for the inelastic analysis of this problem. The dashed curves are true-stress vs. true-strain and the solid curves are engineering-stress vs. engineering-strain. The top curve is the true-stress vs. true-strain derived from an actual tension test. The other curves are scaled versions of this curve or the bi-linear representation of it using yield and the point of maximum load. Also shown on the graph are four limit states based upon $0.7S_u$: the lowest is from using the Code value for S_u as an engineering stress, the next up is $0.7S_{max}$ from the test-based engineering stress-strain curve, and finally the two true stress limits that correspond to the engineering stresses, based on their respective engineering stress-strain curves.

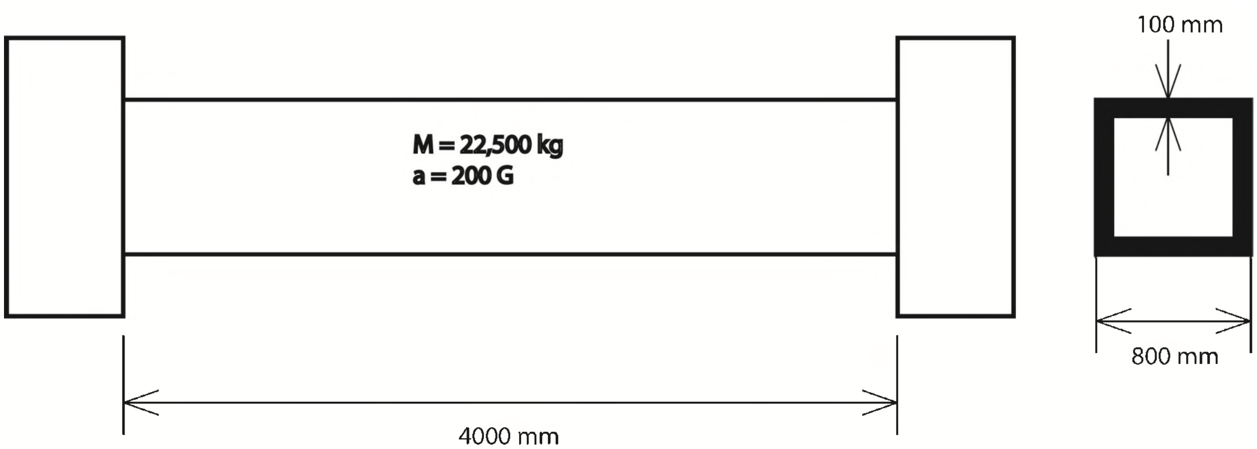

Figure 3 - Example cask for comparing acceptance criteria

Table 1 - Material properties for SA 240 Type 304 stainless steel

Property	Value
Ultimate strength, S_u [5]	515 MPa
Yield strength, S_y [5]	205 MPa
Design stress intensity, S_m [1]	138 MPa
2.4 S_m	331 MPa
3.6 S_m	496 MPa
0.7 S_u	361 MPa
Minimum % elongation [5]	40

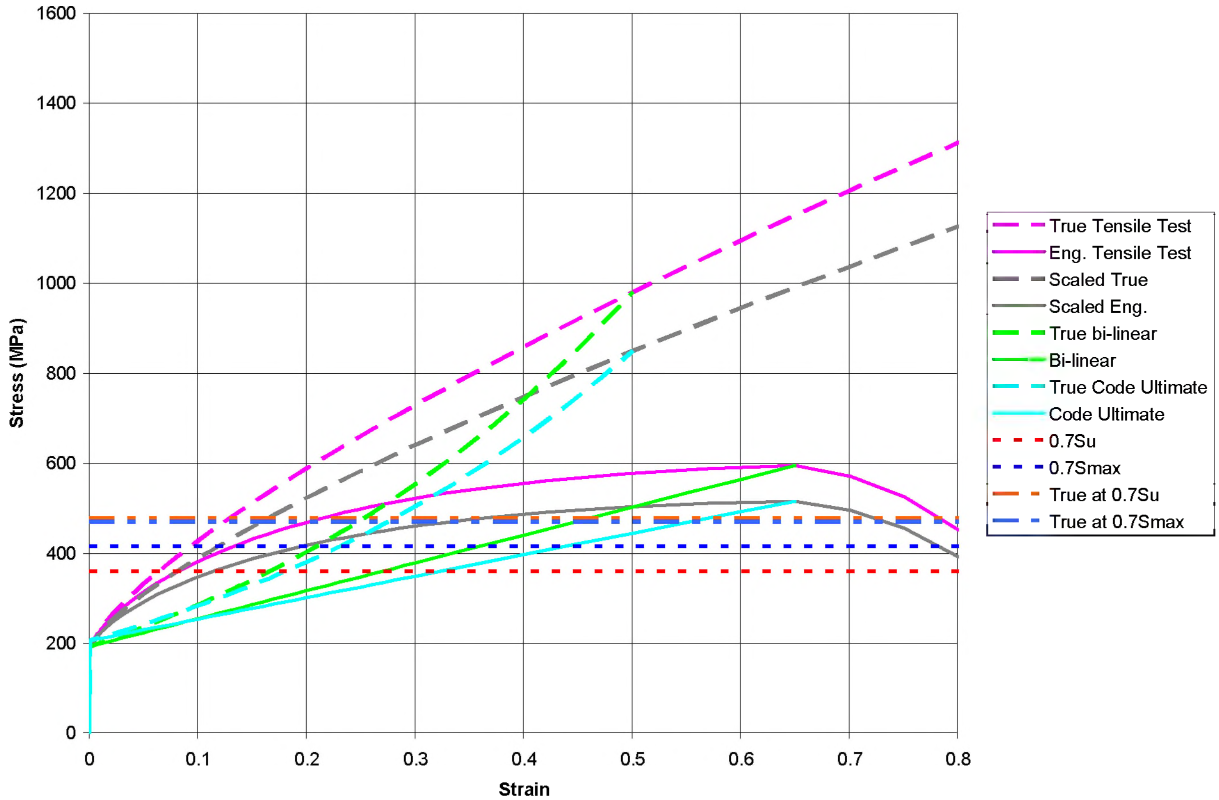

Figure 4 - Stress-strain curves for 304 stainless steel

For simple beam bending the maximum membrane stress using elastic analysis is 331 MPa. This is exactly the allowable stress. The maximum membrane plus bending stress is 378 MPa, compared to an allowable of 496 MPa. For illustration, the problem was constructed so the design would have no margin of safety against the design allowable stress. If we assume the package behaves as a Bernoulli beam (plane sections remain plane) for the inelastic analysis we obtain a maximum membrane stress of 306 MPa, a maximum membrane plus bending stress of 318 MPa, and a maximum engineering strain of 5.3%. The Appendix F allowable stress (currently this analysis technique is not accepted in Section III, Division 3, but is being considered by the ASME to be included in Division 3) is 361 MPa (0.7 S_u) for membrane stress, giving a design margin of 15%, and 464 MPa (0.9 S_u) for membrane plus bending stress. The maximum strain is 13% of the percent elongation.

To further illustrate the difference in package designs that come from the use of inelastic analysis consider the increase in deceleration on the package so the inelastic analysis stress is at the allowable stress levels from Appendix F. The maximum membrane stress resulting from a 234G deceleration would be 361 MPa, the allowable membrane stress. Alternatively, if the thickness of the wall of the package is reduced to increase the inelastic analysis computed stress. keeping the original 200G deceleration, a wall thickness of 81 mm results in a maximum membrane stress of 361 MPa. In both of these adjusted designs the maximum strain is less than 9.5%, still well below the minimum percent elongation.

DISCUSSION

Modern finite element analysis methods allow for the accurate depiction of the stress and strain state in the structural components of radioactive material transportation packages. However, the current design allowable stresses are not well aligned with this new capability. The purpose of analysis acceptance criteria is to prevent against rupture of the containment boundary. This purpose can be more readily accomplished with strain-based acceptance criteria. There are two areas of difficulty in establishing new acceptance criteria: 1) determining the appropriate limits, and 2) developing a method to determine if those limits have been met.

The first of these is primarily a material issue, and a new series of material tests (similar to those used to determine the current limits based upon S_m and S_u) may be required to establish these limits. For example, strain-based acceptance criteria should be tied to the uniform elongation strain (the strain at the point of maximum load in a tensile test), but this value is typically not reported. In the example above the material specification minimum percent elongation was used as a surrogate for this value. Actual tensile tests for Type 304 stainless steel typically show maximum load occurring at an engineering strain of about 65%. This corresponds to a true strain of 50%. The problem of strain limits may be alleviated by choosing an allowable strain that is sufficiently low that it is below the failure strain independent of stress state or how the material strain-to-failure is determined. However, the Code should allow the designer to choose a more accurate method of determining the strain at material failure and then have the design allowable strain as a higher percentage of the failure strain. To generate discussion, possible limits are 15% of the true strain at the point of maximum load as determined from a tensile test (uniform elongation strain) if stress triaxiallity is not considered in the analysis and 70% of the failure strain as a function of stress triaxiallity if it is considered.

The second area is determining the value to compare against the acceptance criteria. Modern inelastic analysis finite element codes produce outputs in terms of equivalent plastic strain, which is a scalar representation of the magnitude of the strain tensor. The post-processing software can display the value as a contour plot or fringe plot. The analyst can easily determine the maximum strain in any material or part. However, some amount of judgment is needed to determine if the plastic strain is the result of membrane action, membrane plus bending action, or a localized strain due to a discontinuity. If the designer chooses to use the failure strain considering stress triaxiallity a mapping of strain vs. stress triaxiallity is required. The off-the-shelf versions of current finite element analysis codes do not compute stress triaxiality and the analyst is forced to create a user subroutine for this calculation.

EXTENSION

The previous discussion and the current ASME Problem Statement are focused on the analyses associated with the 9-meter regulatory impact test. However, the ASME Problem Statement does suggest that regions of the containment remote from the impact point can be evaluated for the loads applied during a puncture event using the strain-based acceptance criteria, provided those regions were not plastically strained during any previous drop event. The reason for this current limitation is so that the ASME Code committees can focus on the development of strain-based acceptance criteria without having to address more complicating issues such as repeating strain accumulations at one location (due to the sequencing requirements of the 9-meter free drop and the 1-meter puncture drop). Additional efforts in the future are anticipated to broaden the scope of strain-based acceptance criteria as appropriate. Still, a strain-based inelastic analysis is ideal for calculating the response to the regulatory 1-meter drop onto a puncture spike. In this accident the response in the region of the impact is almost always inelastic. In a puncture test there are high stresses and strain in the immediate vicinity of the impact location and much lower stresses and strains away from this location. These stresses and strains would typically be classified as localized, and the elastic analysis method allows higher stresses for localized loads. Similarly, the strain-based acceptance criteria should allow higher strains for these localized events, perhaps 50% of the uniform elongation strain if stress triaxiallity is not considered in the analysis and 90% of the failure strain as a function of stress triaxiallity if it is considered

The use of inelastic analysis with strain-based acceptance criteria for design of packages to meet the regulatory hypothetical accident conditions places the designer in an excellent position to extend the analyses to beyond design basis accidents. To address these beyond design basis events the concept of service levels needs to be extended. The regulatory hypothetical accident conditions are service level D, so beyond design basis accidents should be service level E. At this service level the primary function of the package is to prevent gross release of material. An allowable strain limit equal to the failure strain (as a function of stress triaxiality) would be appropriate.

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