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

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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 computational tools have improved cask vendors' ability to perform non-linear impact analysis, the need for a code-based method to interpret the results of this type of analysis has increased, and in 2006 the NRC encouraged ASME to develop strain-based criteria for energy-limited events. The ASME Section III Working Group on Design of Division 3 Containments has been working with the Section III Division 1 Working Group on Design Methodology to develop such a strain based criteria to use within the ASME Code Section III, Division 3 for energy limited events.

An important aspect of the strain-based criteria is that it can only be applied to a "Quality Model:" where a Quality Model is defined as 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 Task Group on Computational Modeling for Explicit Dynamics), or has been developed with the use of convergence and sensitivity studies. This paper will briefly discuss the proposed ASME Strain-based criteria, detail the advantages of using strain-based criteria, and discuss the problem areas associated with establishing strain-based criteria.

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 (Reference 1) and guidance has been provided by U.S. NRC Regulatory Guide 7.6 (Reference 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 type of stress, and the fundamental assumption employed in the development of these allowables is that elastic analysis methods are used. 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 by elastic analysis using hand calculations and was still beneficial during the early days of finite element analysis.

As finite element calculations became more detailed, it has become possible to determine the actual 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.

To better understand the need for strain-based criteria it is helpful to divide loading events into categories. All loading events can generally be placed in one of three categories: (1) force-limited (load-controlled) events, (2) energy-limited (energy-controlled) events, and (3) displacement-limited (displacement-controlled) events. Examples of force-limited events include internal pressure and mechanical loads, such as lifting loads and dead load. Examples of energy-limited events include the 9 meter regulatory drop, the 1 meter puncture drop, the non-mechanistic tip-over, tornado missile impact and aircraft impact. The third category, displacement-limited events, is largely dominated by thermal expansion.

It is clear from this breakdown and supporting examples that the design of storage and transportation containments is controlled by energy-limited events, especially since internal pressures are low and do not control the design of the containment boundary. Even the founders of the stress-based criteria in the ASME Code recognized its limitations. To quote Bill Cooper (Reference 3):

> “It is poor practice to apply criteria developed for load-controlled conditions to energy-limited conditions when deformations do not have to be controlled…. 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.”

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, and maximum safety is assured by using materials with large capacity to absorb energy rather than by materials with maximum strength.

Stress Strain Curves

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. While the yield stress and ultimate stress (and thus the design stress intensity) of the high-strength steel is larger than that for the austenitic stainless steel, the area under the stress-strain curve up to the point of maximum load, which in a tensile test is directly proportional to the amount of energy that can be absorbed, is much larger for the austenitic stainless steel.

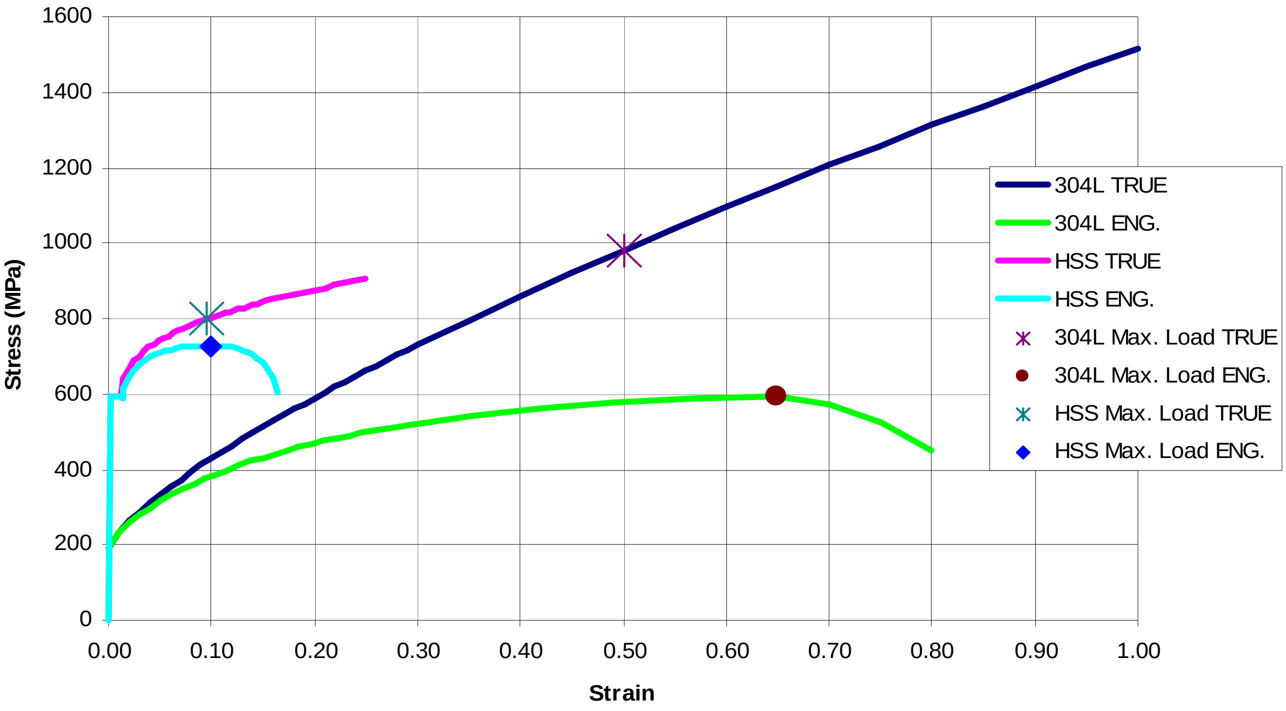


Figure 1 - Stress-strain curves for an austenitic stainless steel and a high strength carbon steel

The point of maximum load in a tensile test is also the limit of uniform elongation, also called the uniform strain limit, and beyond this point there is localization of strain and the tensile test specimen becomes unstable. Further deformation beyond the uniform strain limit occurs in a relative small volume of material as the specimen cross-sectional area is reduced ("necks"). Even though a typical stainless steel true stress-strain curve shows a large area under the curve from the onset of necking to fracture, the volume of material associated with that necked region is smaller than the volume of material in the specimen's gage length - resulting in a relatively small additional amount of energy absorbed (compared to the energy absorbed in the entire gage length) prior to the specimen failing. Therefore, it is prudent in design to not use this reserve energy capacity, and the onset of tensile instability is generally avoided, except perhaps in highly localized regions at the surface of a component.

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.

Effect of State of Stress

A complication to the development of strain-based acceptance criteria is the relationship between strain to failure and stress state. The familiar uniaxial 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.

The equivalent plastic strain correctly calculates the strain on the Von Mises yield surface in the absence of damage (crack initiation or flaw propagation). However, real materials experience damage under plastic deformation, which is accelerated when multi-axial tensile stress conditions exist. To address this issue, the concept of a stress triaxiality factor was first proposed by Davis and Connelly (Reference 4), and has been widely discussed since (e.g., References 5, 6 and7).

The Triaxiality Factor (TF) is defined as:

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

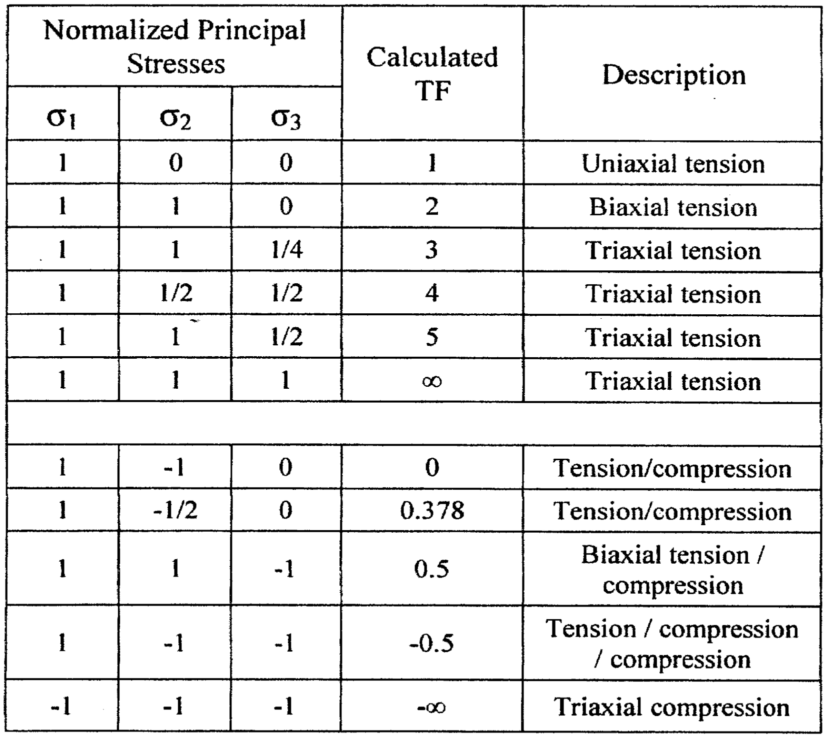
where σ_1, σ_2, and σ_3 are principal stresses at the location under evaluation.

The chosen methodology employed in the ASME strain-based criteria uses the triaxiality factor in a simple formulation. The strain at failure in a general state of stress is related to the uniaxial tension failure strain by:

$$\varepsilon_{\text{general failures case}} = \varepsilon_{\text{uniaxial tension failure}} / \text{TF}$$

A triaxiality factor of 1.0 represents uniaxial tension, a factor of 2.0 represents biaxial tension, and greater than 2.0 represents a triaxial tension stress state. Triaxiality factors of less than 1.0 are due to compressive principal stresses in one or more directions. A triaxiality factor of 0.0 represents a state of pure shear. Examples of triaxiality factors for various principal stress states are shown in Table 1.

Table 1: Triaxiality Factors for various principal stress states.



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	1/4	3	Triaxial tension
1	1/2	1/2	4	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

STRAIN-BASED ACCEPTANCE CRITERIA

The ASME Code stressed-based criteria were developed for load-controlled (force-limited) events. The stress allowables are based on the use of minimum strength properties for yield stress and ultimate stress with a safety factor or reduction factor applied to these values. For a design basis accident event using elastic analysis techniques, allowable stress intensities are given in ASME Appendix F and are based on the ASME minimum yield stress. For a design basis accident event using plastic analysis techniques, calculated primary membrane stresses must remain below the ASME minimum ultimate stress reduced by a factor of 0.7.

Strain-based criteria for energy-controlled (energy-limited) events must be based on the fundamental strain properties of a stress-strain curve, which are the true uniform strain and the true failure strain, and must employ the same strategy as stress criteria of using minimum strain properties and an appropriate factor applied to the minimum values. In addition, strain-based criteria must account for the effect of the state of stress on ductility. Thus, strain-based criteria contains three essential components: (1) the use of minimum material properties for uniform strain and failure (rupture) strain, (2) a Triaxiality Factor applied to the minimum strain properties from a uniaxial tensile test to account for potential loss in material ductility due to the constrain of plastic flow caused by the state of stress, and (3) a safety factor applied to the minimum strain properties appropriate for the component and service level of the event. Two distinct location evaluations are required for evaluation.

Locations Not at a Local or Gross Structural Discontinuity

For material at least $3t_n$ (where t_n is the nominal containment wall thickness) away from a gross or local structural discontinuity, the following shall be satisfied:

(a) The average (through containment wall thickness) equivalent plastic strain $(\varepsilon^p_{eq})_{avg}$ shall be:

$$(\varepsilon^p{}_{eq})_{avg} < (0.67\varepsilon_{uniform})/TF$$

(b) The maximum equivalent plastic strain (ε^p_{eq}) at any containment surface shall be:

$$(\varepsilon^p{}_{eq}) < [\varepsilon_{uniform} + 0.25(\varepsilon_{fracture} - \varepsilon_{uniform})]/TF$$

Where $\varepsilon^p{}_{eq}$, $\varepsilon_{uniform}$, and $\varepsilon_{fracture}$ are true strains, and the material properties are such that $\varepsilon_{fracture} > 2\,\varepsilon_{uniform}$.

If TF < 1.0, a value of 1.0 shall be used in the strain-based acceptance criteria. Where the average equivalent plastic strain is being evaluated in (a) above, the allowable strain must be based on the average (through the thickness) triaxiality factor.

Locations at a Local or Gross Structural Discontinuity

At a gross or local structural discontinuity, the following shall be satisfied:

(a) The average (through containment wall thickness) equivalent plastic strain $(\varepsilon^p_{eq})_{avg}$ shall be:

$$(\varepsilon^p{}_{eq})_{avg} < (0.85\varepsilon_{uniform})/TF$$

(b) The maximum equivalent plastic strain (ε^{p}_{eq}) at any containment surface shall be:

$$(\varepsilon^{p}{}_{eq}) < [\varepsilon_{uniform} + 0.25(\varepsilon_{fracture} - \varepsilon_{uniform})] / TF$$

Where $\varepsilon^{p}{}_{eq}$, $\varepsilon_{uniform}$, and $\varepsilon_{fracture}$ are true strains, and the material properties are such that $\varepsilon_{fracture} > 2\,\varepsilon_{uniform}$.

If TF < 1.0, a value of 1.0 shall be used in the strain-based acceptance criteria. Where the average equivalent plastic strain is being evaluated in (a) above, the allowable strain must be based on the average (through the thickness) triaxiality factor.

MATERIAL PROPERTY DATA NEEDS

For Code approved analyses a method must be developed to define the true stress-strain 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 and ASME Section II do not specify all of the material date necessary to implement strain criteria, such as uniform strain and reduction in cross-sectional area at failure. ASME and others are working to obtain such data.

The ASME Code minimum material properties for yield stress and ultimate stress are based on exceedance probabilities (EP) of between 95 and 98 percent, which is to say that there is a 95 to 98 percent probability that the actual material yield and ultimate stress will exceed the ASME minimum value. Minimum strain properties must be based on the same exceedance probability range. Currently, the 98% EP is currently specified in the draft Strain-Based Acceptance Criteria for Section III, Division 3 of the ASME Code.

PURPOSE AND LIMITATIONS OF STRAIN CRITERIA

The purpose of the proposed strain-based acceptance criteria is to establish plastic strain limits that are capable of maintaining the allowable leakage rate during and after energy-limited events. To achieve this goal, only a limited number of proven ductile materials, which include 304, 304L 316 and 316L austenitic stainless steels, are allowed, and strain limits have been established with sufficient margins of safety to prevent through-wall crack formation, thereby maintaining the helium leakage rate down to 10^{-7} std cc/sec.

It is not the intent of the strain criteria to permit significant regions or major portions of the containment boundary to experience the higher strain limits of these criteria. Instead, these strain-based criteria were established to address the smaller localized regions of the containment that experience strains due to direct impact. Hence these strain based criteria are not to be utilized for explicit dynamic events that are moderated by external, non-integral impact limiters.

Only energy-limited events shall be evaluated using the strain-based criteria. Such loadings are limited to one-time events per location on the containment where the strain-based criteria are implemented. Cyclic and repeated incremental strain responses are not allowed. The loadings include accidental drops and impacts of non-sharp (i.e., blunt) objects [e.g., 6-inch diameter post with rounded edges, aircraft engine shafts, etc.].

ACCURATE STRAIN DETERMINATION

Significant advances have been achieved in the finite element analysis methodology associated with nonlinear evaluations. However, in order to properly implement the strain based acceptance criteria, it is imperative that accurate strains be calculated. Therefore, the strain-based acceptance criteria shall be implemented using strains calculated from “Quality Models.” A Quality Model is a finite element model of the complete containment system that adheres to the guidance set forth in the ASME Non-Mandatory Appendix “Computational Modeling Guidance for Explicit Dynamics,’ currently under development by the ASME Task Group on Computational Modeling for Explicit Dynamics. Alternatively, a model constructed with the aid of suitable convergence and sensitivity studies that demonstrate the accuracy capable of the containment system model may also be used. The explicit dynamics solution technique shall be employed for the analyses when using these acceptable models.

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