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STRAIN-BASED ACCEPTANCE CRITERIA FOR ENERGY-LIMITED EVENTS

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ABSTRACT

The American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel (B&PV) Code is primarily a stress-based acceptance criteria code. These criteria are applicable to force, displacement, and energy-controlled loadings and ensure a factor of safety against failure. However, stress-based acceptance criteria are often excessively conservative for one time energy-limited events such as accidental drops and impacts. For several years, the ASME Working Group on Design of Division 3 Containments has been developing the Design Articles for Section III, Division 3, "Containments for Transportation and Storage of Spent Nuclear Fuel and High-Level Radioactive Material and Waste," and has wanted to expand the design articles to include strain-based acceptance criteria for accidental drops of containments. The Division 3 Working Group asked the Working Group on Design Methodology (WGDM) to assist in developing strain-based acceptance criteria. This paper discusses the current proposed strain-based acceptance criteria, associated limitations of use, its background development, and the current status.

INTRODUCTION

The ASME B&PV Code is primarily a stress-based acceptance criteria code. This stress-based approach is appropriate for sustained loads such as pressure and temperature, and occasional loads such as seismic. However, these criteria are often conservative for one time energy-limited events such as accidental drops (e.g., 30-foot drop [9m]) and impacts (e.g., puncture post). Additionally, stress criteria do not provide a good indication of the actual margin to failure and the related damage for energy-limited problems.

The Working Group on Design of Division 3 Containments has been developing the Design Articles for ASME Section III, Division 3, "Containments for Transportation and Storage of Spent Nuclear Fuel and High-Level Radioactive Material and Waste," [1] and has wanted to expand the design articles to include strain-based acceptance criteria for accidental drops of containments. The Working Group recognized the advances achieved in the finite element analysis area associated with nonlinear evaluations. The Working Group developed a white paper that discussed the problem facing the transportation and storage industry regarding analysis of accidental drop events. Based on industry input, suggestions were made in this white paper regarding the strains to be considered, proposed limitations on the types of loads to be considered, materials, desired temperature ranges, and asked a number of questions related to a viable strain criteria for Division 3 containments. In the context of this paper, the containment is an enclosure that serves as a barrier for spent nuclear fuels or high level radioactive material waste within a prescribed volume for transportation and storage. The Division 3 Working Group then asked the Working Group on Design Methodology

(WGDM) to assist in developing strain-based acceptance criteria. This paper discusses the current WGDM proposed strain-based acceptance criteria.

The goal of the strain-based acceptance criteria is to establish plastic strain levels that maintain the allowable leakage rate identified in the Design Specification, during and after energy-limited events. To achieve this goal, ASME must establish strain limits that provide sufficient margins of safety to ensure that any resulting damage maintains the desired leakage rate.

PROPOSED STRAIN-BASED ACCEPTANCE CRITERIA

It is currently proposed that ASME Section III, Division 3 Subsection WB (for packagings with weight greater than 1100 pounds) and Subsection WC rules incorporate the following strain-based acceptance criteria for the evaluation of containments subjected to accidental drop or impact events. The criteria are applicable to loadings that have been specified to satisfy Level D Service Limits.

The strain-based acceptance criteria are specified for two distinct locations on the containment.

Criteria Away from a Gross or Local Discontinuity

For material at least $3 \cdot t_n$ (t_n = nominal wall thickness) away from a gross or local discontinuity, the following must be met:

- Average through the thickness equivalent plastic strain

  $\leq (0.67 \times \varepsilon_{uniform}) / TF$

  [where <u>average</u> equivalent plastic strain is being evaluated, the allowable strain must be based on the average triaxiality factor (TF – see Definitions) also]
- Maximum surface equivalent plastic strain

  $\leq [\varepsilon_{uniform} + 0.25 \times (\varepsilon_{fracture} - \varepsilon_{uniform})] / TF$

Criteria at a Gross or Local Discontinuity

At a gross or local discontinuity, only the following must be met:

- Average through the thickness equivalent plastic strain

  $\leq (0.85 \times \varepsilon_{uniform}) / TF$

  (where <u>average</u> equivalent plastic strain is being evaluated, the allowable strain must be based on the average TF also).

These strain-based criteria **shall not** be applied to the following:

- Regions of the containment where deformation is detrimental to maintaining the desired leakage rate (e.g., the sealing region of a bolted closure),
- Structural or non-structural attachments to the containment,
- Containment boundary fillet welds or partial penetration welds, including such welds of attachments to the containment boundary,
- Threaded connections to the containment, even if seal welded,
- Regions of the containment where significant material ductility has been lost due to fabrication, heat treatments, etc. (i.e., true fracture strain must be at least two times the true uniform strain limit).

LIMITATIONS OF CRITERIA USE

A number of limitations were identified that must be satisfied before using the strain-based acceptance criteria.

Limited Loadings

Only energy-limited loadings, such as accidental drops for storage and transportation containments, shall be considered. Such loadings are limited to one-time events. This includes impacts of non-sharp (i.e., blunt) objects (e.g., 6-inch diameter post with rounded edges, jet engine shafts, etc.).

Limited Materials

Materials are currently limited to 304/304L and 316/316L stainless steels. The proposed ASME material specifications to be covered (as restricted by Table 2A in Section II, Part D) include:

SA-182	(forgings)
SA-240	(plate, sheet, and strip)
SA-312	(seamless and welded pipe)
SA-336	(forgings)
SA-376	(seamless pipe)
SA-479	(bars and shapes)

If certain products from these specifications subject the material to cold working or lack a proper heat treatment afterwards and result in significant loss of ductility (true fracture strain approaching the true uniform strain limit), then these products should not have the strain-based acceptance criteria applied to them. Therefore, as stated above, all materials shall have a true fracture strain that is at least two times the true uniform strain limit, including those materials in compliance with the above stated specifications.

Limited Temperatures

The applicable material temperature range shall be limited to -40°F to 800°F (-40°C to 425°C).

Limited Welded Joints

The applicability of these strain-based acceptance criteria to welded joints is limited to full-penetration welds only. (See Section III, Division 3, Subsections WB & WC for weld categories and inspection requirements.) Note that the uniform strain limit for the weld material and heat-affected zone can be lower than that of the base material.

Limited Fabrication Strains

Any process may be used to hot or cold form or bend containment boundary material including weld metal provided that the requirements of the following bulleted paragraphs below are met [2]:

- Maximum fabrication-induced strains do not exceed 5%. The percent strain shall be established by the following formulas:
- For cylinders:
  $\%\ \text{strain} = (50\ t / R_f)\ (1 - R_f / R_o)$
  For spherical or dished surfaces:
  $\%\ \text{strain} = (75\ t / R_f)\ (1 - R_f / R_o)$

  where:
  R_f = final radius to center line of the curved surface
  R_o = original radius (equal to infinity for a flat part)
  t = nominal thickness
- For other shapes:
  Fabrication-induced strains for other shapes may be established by classical or computer-based methods.
- Fabrication strains that exceed 5% shall be minimized by way of post-fabrication heat treatment or deducted from the material's true uniform strain limit value (prior to any triaxiality reduction).

Residual stresses and the associated strains in welds resulting from fabrication are not of concern (negligible). Therefore, post-fabrication heat treatment is not required for welded joints.

MATERIAL PROPERTIES FOR ANALYTICAL EVALUATIONS

Appropriate consideration of the materials is vital to the effective implementation of strain-based acceptance criteria. Obviously, material properties in an aged condition (potential material degradation through use) shall be considered, if appropriate. Another issue that must be properly addressed when codifying these strain-based acceptance criteria rules is recognizing that the different material heats used in fabrication could have wide ranges of yield and tensile strengths, as well as uniform and fracture strain limit values. This complicates the determination of the maximum strain response of the containment when subjected to an energy-limited event. It is anticipated that multiple analytical evaluations that vary material property input values may need to be performed.

Another pertinent issue recognized by the Working Group is that material property data and associated rules must be developed before users can apply the proposed strain-based acceptance criteria. The material property data and rules are currently under development (e.g., developing appropriate rules to address strain rate effects) but certain approaches have been discussed and agreed upon at the WGDM level.

Two design evaluation options are currently being considered. The first option (when designs are finalized prior to knowing specific material heat data) is that ASME would specify necessary minimum properties for both base and weld materials. In addition, actual material yield or ultimate strengths exceeding the ASME Code specified minimums by 25% or more would also have to be considered. This recognizes that stronger materials may alter the strain response. The second option is to permit the user to perform the design evaluation using the material properties from the actual material heats used in the component fabrication, provided the appropriate data [true stress-strain curves, true uniform strain limits (mean value), true fracture strain limits, etc.] is obtained. Additional material property details are provided below.

ASME-Specified Material (Base and Weld) Properties

- True stress-strain curve definitions based on ASME Code minimum specified yield and ultimate strengths at temperature (under development),
- True Uniform strain limit and true fracture strain at temperature (under development). [ASME-specified minimum fracture strain shall meet a 98% probability of exceedance, and the uniform strain limit shall be the mean value. (True fracture strain shall be at least two times the mean true uniform strain limit for material acceptability.)].

Actual Material (Base and Weld) Strength Properties

- Actual material yield or ultimate strengths exceeding the ASME-specified minimum values by 25% or more, at the range of operating temperatures, shall also be considered (yield or ultimate material strengths incorporated into the actual material true stress-strain curves). These higher strengths may be estimated at specific values or a range of values at the time of design, but must be later verified through Certified Material Test Reports on the actual material.

MODELING REQUIREMENTS FOR ANALYTICAL EVALUATIONS

Another issue that has been discussed at the Working Group is the need for the users to calculate the correct strain values. These 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 Task Group on Computational Modeling and Code Evaluation), or using a model with demonstrated suitable convergence and sensitivity studies.

DEFINITIONS

- Equivalent (true) plastic strain (ε^{p}_{eq}) is defined as :

$$\varepsilon_{eq}^{p} = \int_0^t \left(\frac{2}{3} \dot{\varepsilon}_{ij}^{p} \, \dot{\varepsilon}_{ij}^{p} \right)^{1/2} dt$$

  or (in another format)

$$\varepsilon_{eq}^{pl} = \int_0^t \left(\frac{2}{3} \dot{\varepsilon}^{pl} : \dot{\varepsilon}^{pl} \right)^{1/2} dt$$

- $\varepsilon_{uniform}$ is:
  True uniform strain limit or the true strain just prior to the onset of necking in a uniaxial tension test [the true strain at the maximum load (ultimate stress)] at the coincident average thru-wall temperature of the base or weld material.

- $\varepsilon_{fracture}$ is:
  True strain at fracture in a uniaxial tension test at the coincident average thru-wall temperature of the base or weld material.
- Triaxiality Factor (TF) is:

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

  (σ_1, σ_2, & σ_3 are principal stresses at a location)
  However, for TF < 1.0, a value of **1.0** shall be used in the above strain acceptance criteria.
- Discontinuity:
  Gross Structural Discontinuity: Gross structural discontinuity is a geometric or material discontinuity that affects the strain distribution through the entire wall thickness of the containment. Examples of gross structural discontinuity are head-to-shell junctions and flange-to-shell junctions, nozzles/openings, and junctions between shells of different diameters or thicknesses.
  Local Structural Discontinuity: Local structural discontinuity is a geometric or material discontinuity that affects the strain distribution through a fractional part of the wall thickness. The containment response associated with a local discontinuity is only a localized deformation and strain. Examples are small fillet radii and structural or non-structural attachments. (Note that these strain-based acceptance criteria only apply to the containment nominal thickness and not to a structural attachment or any attachment welds on the surface of the containment.)

USE OF EQUIVALENT PLASTIC STRAIN

The equivalent plastic strain is a cumulative, positive scalar quantity, non-decreasing strain measure that takes into account the entire deformation history. Since the driving mechanism for plastic distortion is the transformation of externally supplied energy (for example, kinetic energy in case of impacts and drops) into plastic work, the equivalent plastic strain is intrinsically a better indication of the material condition than any instantaneous stress measure.

Analogous to the maximum distortion energy – equivalent (Mises) stress, the equivalent plastic strain cumulatively combines the strain state/history into a meaningful value for comparative purposes. This value is especially useful in reducing the voluminous strain output created by finite element and other computer solution methods commonly in use today. The fact that the equivalent plastic strain does not indicate whether tension or compression has caused the strain is appropriate and consistent with the triaxiality factor usage herein, which also conservatively ignores any strengthening effects of compression.

USE OF TRUE UNIFORM STRAIN LIMIT

Failure in stress-based acceptance criteria may be based on, for example, exceeding the specified minimum material yield strength. The acceptance criteria would then limit the stresses to a level below the material yield strength to provide a safety margin against yielding.

In this proposed strain-based acceptance criteria, large plastic deformations are expected and allowed in the structure. The goal of the acceptance criteria is to maintain the allowable leakage rate identified in the Design Specification. Therefore, failure would be defined as plastic strain levels that cause breach of the structure (i.e., higher than the allowed leakage rate).

The two materials to which these strain-based acceptance criteria are limited, 304/304L and 316/316L, are ductile austenitic stainless steels. Significant leakage of these stainless steels is not expected until the through-wall strains reach the level of material necking. In a uniaxial tensile test, a specimen experiences uniform straining along the entire gage (or reduced area) length until the maximum load is reached (at the ultimate strength). At that point, beyond this uniform strain limit, further deformation occurs in a relatively small volume of material as the specimen local cross-sectional area reduces (“necks”). Note that even though a typical stainless steel true stress-strain curve shows a large area under the curve from necking to fracture, the volume of material associated with that necked area is very small – resulting in only a small amount of energy absorption (compared to the energy absorbed through uniform straining in the entire gage length).

Therefore, the true uniform strain limit (i.e., the strain at the onset of necking) is used as the basis for these strain-based acceptance criteria.

USE OF TRIAXIALITY FACTOR

Many theories and formulations have been proposed to account for material damage under multi-axial stress and plastic strain conditions. The details of these theories and formulations will not be discussed herein. However, the chosen methodology employed in this criteria, as discussed in Reference 5 (a report written by W. E. Cooper with technical support from D. F. Landers), uses the Stress Triaxiality Factor in a simple formulation.

The equivalent plastic strain correctly calculates the strain condition on the 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. The concept of a stress triaxiality factor was first proposed by Davis and Connelly [3], and has been widely discussed since (e.g., [4] and [5]). As discussed above, the stress triaxiality factor is based on the principal stresses, and is the sum of the three principal stresses (first stress invariant) divided by the effective (Mises) stress at a location. The strain at failure in a general case is related to the uniaxial tension failure strain by:

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

Therefore, determining the allowable strain limits by accounting for stress triaxiality effects will promote damage prevention and the achievement of specified leakage rates.

A triaxiality factor of 1.0 represents uniaxial tension, a factor of 2.0 represents biaxial tension, and greater than 2.0 indicates a triaxial tension state. Triaxiality factors of less than 1.0 are due to compressive principal stresses in one or more directions. This is shown in the table of example triaxiality factors below.

Examples of Triaxiality Factor Calculations

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	$-\infty$	Triaxial Compression

Note that the triaxiality factor does not indicate that plastic straining is occurring – it merely indicates the stress state. Therefore, only the triaxiality factor calculated while plastic straining is occurring is applicable in the allowable strain equations. When plastic straining has stopped, the triaxiality factor simply indicates the elastic stress state.

The proposed strain-based acceptance criteria indicate that a minimum triaxiality factor of 1.0 must be used. Using a minimum factor of 1.0 conservatively ignores the potential strengthening/damage inhibiting effects of compressive stresses.

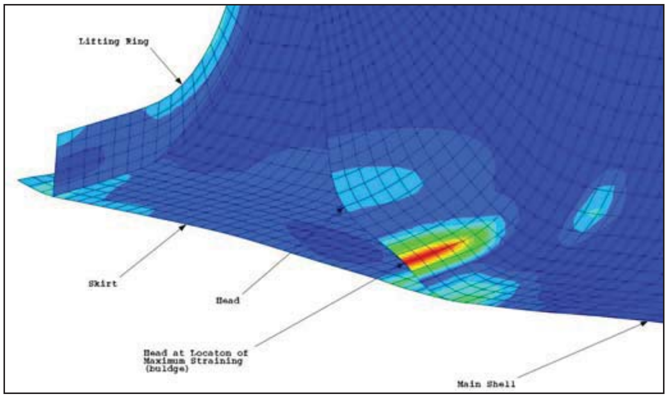
EXAMPLE USAGE OF CRITERIA

Several years ago, the Idaho National Laboratory performed drop testing [6] on an 18-inch [457mm] diameter canister, ½-inch [13mm] wall thickness, 15 feet [4.5m] in length, weighing about 6,000 lbs [26.7KN]. The canister was made of SA-312, 316/316L stainless steel and material testing was performed (to verify yield strength, tensile strength, and elongation values only). Uniform and fracture strain values were not determined (not of interest at that time). Typically, 316/316L material has a true uniform strain limit range of 40 to 48 %, with a true fracture strain range of 150 to 200% at room temperature [e.g., Ref. 7]. This canister was dropped from 30 feet [9m] onto a rigid, flat surface, impacting at an angle of 10 degrees off-horizontal. Because of the shallow impact angle, most of the deformation occurred not in the initial (bottom end) impact but in the secondary (top end) slapdown. After the drop test, the canister was helium leak tested and found to have a leakage rate of less than 10^{-7} std cc/sec., which is considered leaktight [8].

Finite element (FE) modeling was employed to simulate the drop test. FE results of deformations matched closely with those of the actual canister. During Working Group deliberations, the model was then enhanced (by way of 9 integration points through the thickness) to predict the plastic straining; the largest strains occurring in the top end head due to the secondary slapdown.

Using the proposed strain-based acceptance criteria, the actual strains compared to the allowable strains, using the lower typical values (40% true uniform strain, 150% true fracture strain) as follows:

- Average through thickness equivalent plastic strain of **29%** slightly exceeded the allowable strain limit of **27%** (average triaxiality factor of 1.0),
- Maximum outside surface equivalent plastic strain of **60%** was slightly below the allowable strain of **68%** (triaxiality factor of -1, so a value of 1.0 was used),
- Maximum inside surface equivalent plastic strain of **29%** was slightly below the allowable strain of **34%** (triaxiality factor of 2.0).



Strain Contours of Canister Slapdown Drop Event (canister sectioned at the center)

Therefore, this canister/drop event would not have satisfied the strain-based acceptance criteria because the average through-wall strain exceeded the allowable level. However, the post-drop helium leak testing indicated that leaktightness had been maintained. This gives an indication that the average through-wall allowable equivalent strain being 67% of the true uniform strain limit does indeed maintain specified leakage rates, up to and including leaktight conditions.

During this drop testing effort, another canister of the same geometry was also dropped from 30 feet [9m] with the integral skirt experiencing significant deformation (see figure below). The analytical peak strain prediction was 107% on the outside surface. Non-destructive examination was performed on this surface of the test canister and no indications were identified, indicating that no cracks initiated even at these high strain levels.

Canister Skirt Deformation for Off-Vertical Drop Event

CONCLUSIONS

The strain-based acceptance criteria discussed in this paper is not approved by all of the appropriate ASME Committees and is considered to be only a proposal at this time. These proposed criteria are expected to be a valuable step forward for the transportation and storage industry that can also be acceptable to the regulator for the analysis of energy-limited events. The Working Group on Design of Division 3 Containments is proceeding with the formal codification of these proposed rules along with other associated supporting development work.

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