LM-03K006

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REPORT NO. TDA-19193
APRIL, 2003

ELASTIC-PLASTIC STRAIN ACCEPTANCE CRITERIA FOR STRUCTURES SUBJECT TO RAPIDLY APPLIED TRANSIENT DYNAMIC LOADING

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NOTICE

ABSTRACT

Rapidly applied transient dynamic loads produce stresses and deflections in structures that typically exceed those from static loading conditions. Previous acceptance criteria for structures designed for rapidly applied transient dynamic loading limited stresses to those determined from elastic analysis. Different stress limits were established for different grades of structure depending upon the amount of permanent set considered acceptable. Structure allowed to sustain very limited permanent set is designed to stress limits not significantly greater than yield stress. Greater permanent set in structure under rapidly applied transient dynamic loading conditions is permitted by establishing stress limits that are significantly greater than yield stress but still provide adequate safety margin (with respect to failure).

This paper presents a strain-based elastic-plastic (i.e., inelastic) analysis criterion developed as an alternative to the more conservative stress-based elastic analysis stress criterion for structures subjected to rapidly applied transient dynamic loading. The strain limits established are based on material ductility considerations only and are set as a fraction of the strain at ultimate stress obtained from an engineering stress/strain curve of the material. Strains limits are categorized by type as membrane or surface and by region as general, local, or concentrated.

The application of the elastic-plastic criterion provides a more accurate, less conservative design/analysis basis for structures than that used in elastic stress-based analysis criteria, while still providing adequate safety margins.

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1.0 INTRODUCTION

A variety of analysis methods have historically been used to design structure to withstand rapidly applied transient dynamic loads with allowable stress as the basis using linear elastic analysis methods. The static "G" method, in which rapidly applied transient dynamic loads are derived from multiples of deadweight loads, was the first such method. Limitations of this method, including the disregard of system flexibility in determining rapidly applied transient dynamic loads, led to development of elastic-based dynamic analysis computer programs. Structural interaction, response phasing, and nonlinear behavior were not explicitly included in these original programs. These limitations lead to conservative assumptions that add weight and cost to structures.

Advances in numerical methods and computing resources fostered development of more advanced dynamic, transient analysis programs. Since the rapidly applied transient dynamic event can be more closely simulated, less conservative assumptions and criteria may be employed to produce more optimized and cost effective structural designs. Additionally, computer programs have been developed which can evaluate structure for stress conditions beyond the static yield stress of the material. These nonlinear analysis programs are capable of evaluating dynamic as well as static loading conditions.

The elastic-plastic analysis criterion presented in this paper, in conjunction with inelastic analysis methods, offers a more accurate, less conservative basis for determining structural adequacy under rapidly applied transient dynamic loading when structure is designed to stress allowables greater than yield stress. Application of this criterion is cost effective from a construction standpoint since it maximizes the use of lower strength steels which have higher strain limits because they typically have a higher value of strain at ultimate stress. Additionally, accounting for inelastic behavior of the structure under dynamic loading results in lower predicted structural accelerations and resultant loads.

Application of the elastic-plastic criterion will permit the determination of the actual structural deflection and permanent set. Therefore, stress limits do not have to be set arbitrarily low for structures that may be deflection limited. Strain limits may be established based solely on ductility considerations with deflection requirements being evaluated on a case by case basis.

Section 2.0 of this report presents definitions of some of the terms used in the elastic-plastic analysis criteria. The requirements associated with satisfying the criteria are contained in Section 3.0. The engineering rationale used to develop the criteria requirements contained in Section 3.0 is contained in Section 4.0.

In Sections 4.3 and 4.4, the initial strain limits are developed based on ductility considerations of the material as reflected on an engineering stress vs. engineering strain diagram. In Section 4.5, the initial strain limits developed in Sections 4.3 and 4.4 are reduced by an overall factor of safety. The reduced limits developed in Section 4.5 reflect the strain limits contained in Section 3.0 of the report.

2.0 DEFINITIONS

Definition of several key terms used in the elastic-plastic analysis criteria are provided below.

2.1 ELASTIC-PLASTIC ANALYSIS

Elastic-plastic analysis refers to a class of structural computational methods that account for the inelastic (non-recoverable) as well as the elastic (recoverable) behavior of the structural material. That is, once the material deformation exceeds a specific limit (the elastic limit), the stress in the material is no longer directly (linearly) proportional to the strain in the material. The terms *elastic-plastic* and *inelastic* are considered synonymous in these criteria.

The additional nonlinearity represented by large displacements must be included in computational algorithms when displacements are large relative to certain characteristic dimensions of the structure. However, the term *elastic-plastic analysis* used in these criteria and the corresponding strain limits established by the criteria do not necessarily imply large displacement analysis.

2.2 STRESS AND STRAIN

Stress is a force divided by an undeformed cross-sectional area, and *strain* is a change in length divided by the corresponding original length. These are more commonly referred to as *engineering stress*, σ, and *engineering strain*, ε.

2.3 ULTIMATE STRAIN

Ultimate strain, ε_u, is the engineering strain, corresponding to the maximum value of engineering stress (i.e., ultimate stress) as determined from an engineering stress vs. engineering strain diagram representative of the material in question. In other words, the ultimate strain is the strain at which the slope of the engineering stress-strain curve is zero at the maximum load. At this point, "neck-down" of the material begins and the structure's capacity to sustain load becomes unstable. It therefore reflects, from an analytical standpoint, the maximum permissible strain in a structure. For conservatism in establishing design strain limits, the ultimate strain, ε_u, should be based on minimum material properties.

2.4 TRUE STRESS AND TRUE STRAIN

True stress, σ_T, is defined as the load divided by the corresponding deformed cross-sectional area. It differs from the more conventional definition of stress because of the change in area due to the loading itself. In a similarly defined manner, *true strain*, ε_T, is the integral over the length of a finite extension of each infinitesimal elongation divided by the corresponding infinitesimal length of the integration.

For the elastic-plastic analysis criteria:

$$\varepsilon_T = \ln(1+\varepsilon) \qquad (2\text{-}1)$$

$$\sigma_T = \sigma(1+\varepsilon) \qquad (2\text{-}2)$$

These relationships are considered valid up to the material ultimate strain, ε_u. These criteria are intended to deal with the more traditional quantities of engineering stress and engineering strain. Criteria formulated on the basis of engineering strain may be converted using the above relationships to establish a limit on true strain. A true stress vs. true strain curve is generally required to perform elastic-plastic analysis. For design calculations, a curve based on mean material properties should be used. The criteria in this report are based on the use of engineering stress and engineering strain.

2.5 PLASTIC STRAIN MAGNITUDE

Elastic-plastic analysis criteria strain limits are established as functions of the material ultimate strain. Computed plastic strain magnitudes are to be compared to these limits. The *plastic strain magnitude*, ε^P, is a scalar term reflecting the maximum plastic strain related to the inelastic strain tensor at a given location.

Specifically, using tensor notation:

$$\varepsilon^P = \{\, 2/3\ \varepsilon_{ij}^{\ P}\, \varepsilon_{ij}^{\ P} \,\}^{0.5} \qquad (2\text{-}3)$$

where repeated indices denote tensor summation, and:

ε^P = plastic strain magnitude

$\varepsilon_{ij}^{\ P} = \varepsilon_{ij} - \varepsilon_{ij}^{\ E}$

ε_{ij} = total tensor strain component i,j

$\varepsilon_{ij}^{\ E}$ = elastic tensor strain component i,j

$\varepsilon_{ij}^{\ P}$ = plastic tensor strain component i,j.

Expanding equation (2-3) into cartesian strain components yields:

$$\begin{aligned}\varepsilon^P &= \{\, 2/3\ \varepsilon_{ij}^{\ P}\, \varepsilon_{ij}^{\ P} \,\}^{0.5} \\ &= 1/3\ \{2((\varepsilon^P_{\ x} - \varepsilon^P_{\ y})^2 + (\varepsilon^P_{\ y} - \varepsilon^P_{\ z})^2 + (\varepsilon^P_{\ z} - \varepsilon^P_{\ x})^2 + 6(\varepsilon^{P\ 2}_{\ xy} + \varepsilon^{P\ 2}_{\ yz} + \varepsilon^{P\ 2}_{\ zx}))\}^{0.5} \qquad (2\text{-}4)\end{aligned}$$

2.6 MEMBRANE STRAIN

Membrane strain is defined as average strain through the thickness of a shell, plate, or beam. The averaging should be performed on a strain component level including all components of strain and then combined to determine the average plastic strain magnitude.

2.7 SURFACE STRAIN

Surface strain is defined as the value of the strain component in the extreme fibers of a shell, plate, or beam. The surface strain may reflect either a linear or non-linear distribution of strain through the thickness or depth of an element or cross-section. The depth of a section may be that of a beam or a composite section made up of effective plate elements of a finite element model or the thickness of a single plate element.

2.8 GENERAL STRAIN

General strain is strain in regions of a structure not influenced by geometric discontinuities, attachments, penetrations, or sources of concentrated loads from displacement-induced interferences.

2.9 LOCAL STRAIN

Local strain is the strain that occurs in regions of a structure influenced by geometric discontinuities, attachments, penetrations, or sources of concentrated loads. Strains that exceed the general strain allowables may be considered local if the area over which the strain exceeds the general strain allowables does not exceed 10% of an effective area. The effective area is a function of the geometry of the structure being analyzed.

2.10 CONCENTRATED STRAIN

Concentrated strain is the highest value of plastic strain computed in a region. Concentrated strains occur in regions of load application or structural discontinuity. Strains that exceed the local strain limits for membrane and surface regions may be considered concentrated if the area over which the strain exceeds the local limits does not exceed 5% of the effective area. The limits established on concentrated strain account for the effect of strain concentrations due to joint geometry, inherent flaws in materials, and inherent geometry-based discontinuities in partial penetration welds and fillet welds not specifically modeled.

2.11 BUCKLING

Buckling, as used in the context of structural design and analysis, refers to a threshold of load-carrying capability where the structure may take on another kinematically admissible state. It is generally associated with membrane compressive stresses but can be induced by shear and bending stresses as well.

The limits established by the criterion presented in this paper allow a structure to approach the onset of buckling while maintaining a less conservative factor of safety than would be used in a traditional elastic-based approach. It is required that the designer account for differences between theoretical buckling values and those that are to be expected for the actual material and actual as-constructed geometry. However, the means by which the effects of geometric imperfections and non-linearities are considered can be difficult to establish. Where the designer cannot accurately determine the effects of geometric imperfections and non-linearities, the use of current, more conservative, design approaches should be used.

2.12 DISPLACEMENT-INDUCED EFFECTS

Displacement-induced effects due to rapidly applied transient dynamic inputs include effects such as interference or contact between attached or adjacent structures, piping systems, and foundationed components and equipment. To the extent that interferences produce loads (possibly concentrated loads) on the structure being evaluated, those loads must be considered in the application of these criteria.

The displacement that the structure experiences when subjected to dynamic loadings will result in stresses and strains. These resulting stresses and strains are the subject of specific and detailed criteria. However, the resulting displacements in and of themselves can also be a concern to the designer. These issues are characterized in these criteria as *displacement-induced effects*.

Although these effects are not explicitly addressed in these criteria, they should be considered by the designer when evaluating structures subjected to dynamic loading.

2.13 STRESS MEASURE

The term *stress measure* is used to denote the equivalent total of combined stress (Reference 11). The Octahedral Shear Stress Theory is used to combine the orthogonal stress components. The stress measure (S) is defined as follows:

$$S = \{((\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 + 6(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{zx}^2))/2\}^{0.5} \quad (2\text{-}5)$$

Where,
σ_x, σ_y, σ_z are the normal stress components, and
τ_{xy}, τ_{yz}, τ_{zx} are the shear stress components.

3.0 ELASTIC-PLASTIC CRITERIA

The strain limits and other design requirements of the criteria are contained in this section of the report. Material property requirements are presented in Section 3.1. Strain limits on structure, bolts, and welds are contained in Sections 3.2, 3.3, and 3.4, respectively. Requirements for the consideration of buckling and displacement-induced effects are addressed in Sections 3.5 and 3.6, respectively.

3.1 MATERIAL PROPERTIES REQUIREMENTS

An appropriate material stress versus strain curve that extends beyond the range of linear elastic material behavior must be used when performing inelastic analysis. The allowable strains are established for the materials at the corresponding service metal temperature. It is appropriate to use material stress-strain relationships at room temperature if the material yield and ultimate stress at the design temperature are the same as room temperature values. Stress-strain relationships for design must be based on the stress-strain curve or test data at the design temperature.

Computer programs used in performing elastic-plastic analysis require the use of a true stress vs. true strain curve. The strain limits in the criteria in this report are based on an engineering stress vs. engineering strain curve. If appropriate data is not available, these curves must be developed from tensile tests.

For design calculations, a true stress vs. true strain curve based on mean material properties should be utilized to accurately reflect structural performance and dynamic behavior. For establishing strain limits, minimum material properties, that are conservative for strain calculation, should be used. An engineering stress-strain curve for the material of construction may be determined by collecting a series of load-deflection data pairs in accordance with the rules of ASTM E8 ("Standard Methods of Tension Testing of Metallic Materials"). The ultimate strain should be taken as the strain calculated at the value of deformation just before the maximum load decreases. Mathematical procedures that may be used to determine the ultimate strain are described in the Appendix.

The criteria in this report are limited to structural steels with an ultimate stress to yield stress ratio not less than 1.20 (e.g., HY-80) for the reasons defined in Section 4.2.

3.2 ELASTIC-PLASTIC ANALYSIS STRAIN LIMITS

When structures subjected to dynamic loadings are qualified using inelastic analysis, the strain limits for elastic-plastic analysis must be satisfied. The requirements on buckling and displacements must also be satisfied.

Except for threaded fasteners (bolts), strain limits are limits on the plastic strain magnitude expressed as a fraction of the ultimate strain of the material. As defined earlier, the plastic strain magnitude at a point in the structure is a scalar quantity computed from the total strain tensor. Components of the total strain tensor may be calculated using thin plate or thin shell methods, but computation of the plastic strain magnitude must take into account the strain normal to the surface of the plate or shell.

Continuous operating loads on a structure must be included in the dynamic analysis when performing inelastic analysis. Continuous operating loads are loads on the structure that are not relieved by minor initial yielding. Examples of continuous operating loads are dead weight, torsional and centrifugal operating forces and moments from rotating components and pressure loads. Non-continuous loads should not be combined with dynamic loads. Examples are thermal loads, and the effects of residual stresses. Residual stresses in welded joints are not considered.

Elastic-plastic analysis plastic strain magnitude limits are summarized in Table 1. The rationale for these limits is discussed in Section 4.0 of this report.

TABLE 1: ELASTIC-PLASTIC ANALYSIS PLASTIC STRAIN MAGNITUDE LIMITS

STRAIN CATEGORY [1]	GENERAL PLASTIC STRAIN LIMITS [3,4]	LOCAL PLASTIC STRAIN LIMITS [3,5]	CONCENTRATED PLASTIC STRAIN LIMITS [3,6]
MEMBRANE [2]	$0.20\ \varepsilon_u$	$0.30\ \varepsilon_u$	$0.50\ \varepsilon_u$
SURFACE [2]	$0.30\ \varepsilon_u$	$0.45\ \varepsilon_u$	$0.50\ \varepsilon_u$
STRUCTURE AT PARTIAL PENETRATION WELDS [7]	-	-	$0.35\ \varepsilon_u$
STRUCTURE AT FILLET WELDS [7]	-	-	$0.25\ \varepsilon_u$

Notes:

(1) Not applicable to bolting.
(2) Limits apply to base metal and weld metal in full penetration welds.
(3) ε_u is the minimum ultimate strain of the base metal or weld metal.
(4) Can be exceeded over not more than 10% of the effective cross-section.
(5) Can be exceeded over not more than 5% of the effective cross-section.
(6) Maximum value - not to be exceeded.
(7) For 100% efficient welds only - welds that are less than 100% efficient should be evaluated on the basis of allowable stress.

3.3 BOLTS:

The criteria for bolts are summarized below based on the rationale presented in Section 4.6. Bolts used as hold down devices and subjected to dynamic loads shall meet the requirements of either (1) or (2) below:

(1) Bolts shall be designed for axial and shear loads such that the stress measure is less than or equal to the static yield or proof test strength of the bolt. Where consideration for bolt bending is required, the maximum stress measure computed at the periphery of the fastener resulting from direct tension, shear, and bending, but excluding stress concentrations, shall not exceed the static yield strength of the bolt.

(2) The membrane strain on the cross-section of a bolt shall not exceed the material yield stress, S_y, divided by the bolt material modulus of elasticity, E. Where bolt bending must be considered, the surface strain on a cross-section of a bolt that results from direct tension, shear, and bending loads from all concurrent conditions shall not exceed the yield strain (i.e., S_y / E).

The computation of bolt stress or strain should be based on the minimum cross-sectional properties of the bolt. If the cross-section includes the threaded portion of the bolt, "stress-plane" section properties are typically used.

3.4 WELDS

Welds should be sized to develop 100% of the capacity of the connection based upon the ultimate tensile strength of the base metal and the ultimate shear strength of the weld metal. An engineering evaluation must be performed when welds cannot be sized to develop 100% of the capacity of the connection. This evaluation must be based on a computed stress in the weld calculated from the load on the weld divided by the effective area of the weld.

The criteria in this report require that welding electrodes will have stress/strain characteristics similar to the base metal and material strength properties equal to or greater than the weaker of the materials being joined based on traditional fabrication requirements. The structural characteristics of the electrode material must "match" the base material to assure that the inelastic behavior of the weld can be characterized by the stress/strain diagram of the base material. Base metal and weld metal in full-penetration welds must satisfy the strain limits for general strain, local strain, and concentrated strain. The criteria do not require that welds be uniquely modeled as part of the engineering evaluation. Rather, the maximum strain in the structure at the welded joint is limited such that:

(1) At structural joints attached by full penetration welds, the concentrated plastic strain shall not exceed 0.50 ε_u, where ε_u is the minimum ultimate strain in the base metal or weld metal, as applicable.

(2) At structural joints attached by 100% efficient, partial penetration welds, the concentrated plastic strain in the structure at the weld shall not exceed 0.35 ε_u, where ε_u is the minimum ultimate strain in the base metal or weld metal, as applicable.

(3) At structural joints attached by 100% efficient fillet welds, the concentrated plastic strain in the structure at the weld shall not exceed 0.25 ε_u , where ε_u is the minimum ultimate strain in the weld metal or base metal, as applicable.

Fillet and partial penetration welds that are not 100% efficient must be evaluated on the basis of allowable stress. Stresses in fillet and partial penetration welds may be determined from the inelastic analysis at the junction of the part being welded. The average stress in these welds may be computed by dividing the load per inch of the weld by the minimum effective throat dimension of the weld, t_w, in inches. The average stress in the weld is limited to 0.55 S_y, where S_y is the yield stress of the weaker of the materials being joined. The limits for fillet and partial penetration welds are not applicable to single-sided welds. Single-sided fillet and partial penetration welds should not be evaluated using the criteria of this report.

3.5 BUCKLING

Buckling is not permitted in structures subjected to rapidly applied transient dynamic loads. The maximum compressive load (i.e., produced by forces and moments on the structure) determined from the dynamic analysis may be applied statically in the assessment of buckling. All structures evaluated to these criteria must have a minimum factor of safety of 1.5 applied to the maximum compressive load unless otherwise specified. The allowable buckling stress values to be used for the evaluation of instability may be the value determined from either:

(1) Analysis that considers all relevant effects such as geometric imperfections, deformations due to applied load, and non-linearities, or

(2) Tests that represent the actual loading and geometry.

Other, more conservative methods of determining the allowable buckling stress are also acceptable.

3.6 DISPLACEMENT - INDUCED EFFECTS

When displacements are computed from an inelastic analysis, the following requirements apply:

(1) Displacements and permanent set of the structure shall be accounted for to ensure that the function of the structure and supported equipment is maintained.

(2) Displacements of the structure shall be limited such that interference or contact with any unattached adjacent structure is prohibited. Displacement limiting devices such as snubbers may be used to limit deflection; however, loads resulting from such contact must be accounted for to meet criteria limits.

(3) Displacement under dynamic loadings shall be accounted for in the design of structures attached to or supported by the structure evaluated by an inelastic analysis.

(4) Displacement-induced loads on the structure imposed by attached equipment, piping, components, snubbers, etc., shall be included with dynamic loads when computing strains.

4.0 RATIONALE

This section presents the rationale for the elastic-plastic analysis strain magnitude limits presented in Section 3.0 and summarized in Table 1. In this section, the strain limits are developed based on ductility considerations. These strain limits are summarized in Table 2, Elastic-Plastic Analysis Plastic Strain Magnitude Limits Based on Material Ductility. To obtain the strain limits for design in Table 1, the strain limits in Table 2 are multiplied by a Design Reduction Factor (DRF) of approximately 0.75 as discussed in Section 4.5.

4.1 INTRODUCTION

Strain limits are not specified in current design codes such as Section III, Division 1 of the ASME Boiler and Pressure Vessel Code. However, some guidance can be obtained from ASME Code Case N-47-28, "Class 1 Components in Elevated Temperature Service, Section III, Division 1."

The engineering rationale for the proposed strain limit on structures is based on material behavior characteristics as reflected by a stress vs. strain diagram developed from static tensile tests of material specimens loaded to fracture. These tests serve as a consistent, reasonable expression of a material's capacity beyond yield stress which may be used to conservatively define acceptable strain limits.

The criteria in this report provide strain limits structures under dynamic loading conditions. The allowable strain is presented as a fraction of the ultimate strain. The strain limit varies according to category (membrane or surface) and the extent of the affected areas (general, local, or concentrated) of the structure. This strain limit is compared to the computed strain defined as the "plastic strain magnitude". The plastic strain magnitude is the inelastic portion of the total strain and neglects the elastic strain component which is small relative to the strain limits established. Residual strains in welded joints are neglected because tensile testing of as-welded specimens have demonstrated that residual stresses have minimal impact on as-welded specimen strength.

The strain limits are based on ductility and consider the ultimate strain and the strain at fracture of the material. The proposed strain limits in these criteria include factors of safety to account for anticipated variations in material performance, construction related geometric discontinuities, and analytical results. There is particular concern that time dependent inelastic analysis may have other, as yet unquantified, uncertainties associated with modeling assumptions and inherent calculational inaccuracies. As such, an additional reduction factor is applied.

In nonlinear analysis, factors are more appropriately applied to loads rather than strain limits because in the inelastic region, small increases in load can result in relatively large increases in strain. This condition does not exist in these criteria since the existing limits are set at a fraction of the strain at ultimate stress which results in "controlled" inelastic behavior. Additionally, there is no practical way to apply load factors to dynamic loads. Therefore, factors are applied to strain to provide an appropriate margin of safety.

The results of an inelastic analysis will provide to the designer the total deflection envelope and permanent set of the structure being evaluated. These values cannot be specifically limited within these criteria because limits will vary based on the requirements of the structure.

4.2 DISCUSSION

Section III, Division 1, of the ASME Code does not set strain limits. In Section III, Subsection NE, NE-3228.2 of the ASME Boiler and Pressure Vessel Code (1989 Edition with 1990 Addenda), a factor of safety of 1.5 is required on the "lower bound collapse load" for a limit analysis.

Figure 1 shows typical stress vs. strain curves for high yield (HY-80) and high tensile (HSS) material. The curves are typical of the materials, and it is reasonable to expect that the conclusions drawn using these curves should hold true for all samples of the material.

From Figure 1, the strain at fracture of HSS steel plate is approximately 36%. The ultimate strain for HSS steel is approximately 16%. Large, uncontrollable strains can result from small increases in stress once "necking down" of the structure begins beyond the ultimate strain of the material. Therefore, factors such as adverse material tolerances, construction related defects, and material flaws require a more prudent limit than the ultimate strain for design purposes. Through the use of appropriate "knockdown factors," (i.e., factors of safety) a more appropriate limit of the maximum permissible strain may be developed.

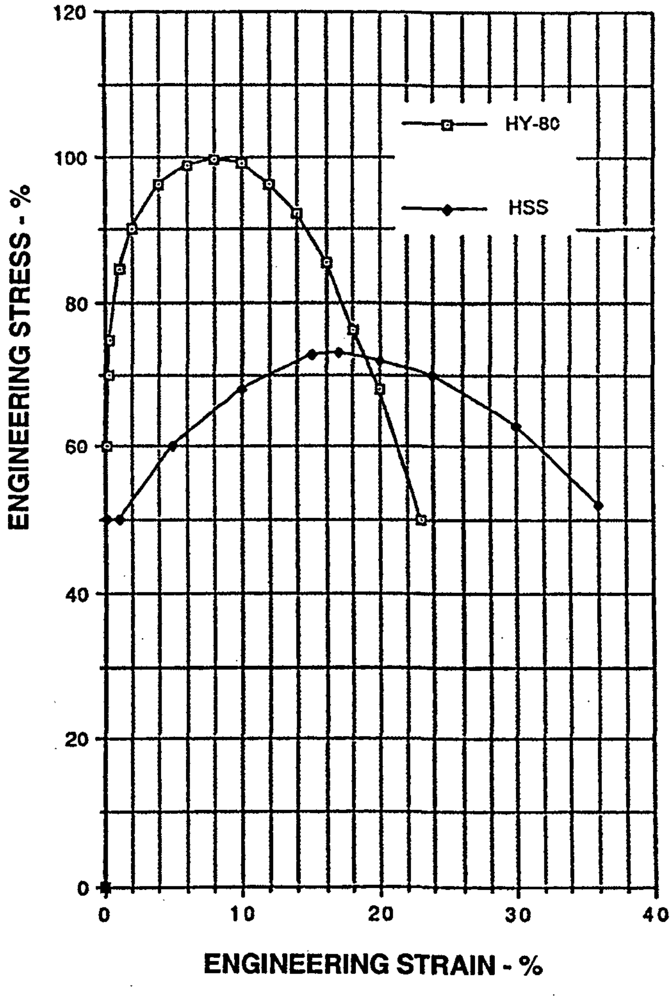
ASME Code Case N-47-28, "Class 1 Components in Elevated Temperature Service, Section III, Division 1", contains strain limits for steels similar to HSS at temperatures from 900°F to 1200°F. The following strain limits are specified in Appendix T of ASME Code Case N-47-28:

(1) Average strain through the thickness, 1%;
(2) Surface strain, due to an equivalent linear distribution of strain through the thickness, 2%; and
(3) Local strain at any point, 5%.

The strain limits are explained in Reference (3). Membrane strains are limited to 1% to ensure the applicability of small deflection theory. Surface strains, due to an equivalent linear distribution of strain through the thickness, are limited to 2% for the same reason.

The limit on local strain, 5%, is based primarily on a concern for the detrimental effects of creep at elevated temperatures. Tests have shown that the creep strain at fracture can be very low, well under 10%; hence, it was deemed prudent to limit creep strain to a value under 5%. However, because of the practical difficulties that occur in trying to divide strain between plastic strain and creep strain, the limit of 5% was used for total local strain.

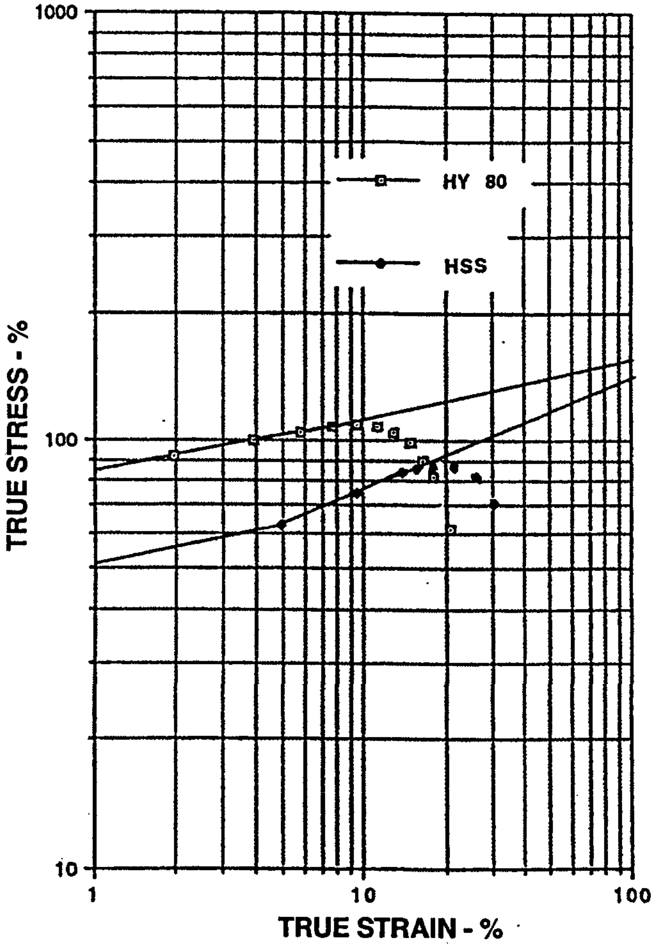
FIGURE 1 Engineering Stress-Strain Curves for HY-80 and HSS (Reference (2))



The effects of creep are not a concern under temperatures up to 700°F provided that the elevated temperature does not continue for an extended period of time. Therefore, for materials like HSS similar to those pertaining to ASME Code Case N47-28, an acceptable limit on total local strain as defined by the Code Case could be 10%. Local regions are sufficiently reinforced by adjacent material such that this strain level can be accepted without concern. If the surrounding material cannot support the high load levels associated with the high stress, this material will also contain high strains. Then a "general" strain condition will exist, and the proposed lower limits on general strain will apply in lieu of the proposed local strain limits which are higher.

However, the stress-strain characteristic of higher yield strength materials with lower margin between yield and ultimate stress, like HY-80, must be addressed. Stress-strain curves in Figures 1 and 2 are used to compare the relative behavior of HSS and HY-80 steels. Figure 1 shows typical engineering stress vs. engineering strain curves for the two materials. Figure 2 shows the same data calculated as true stress vs. true strain based on the relationships defined by equations 2-1 and 2-2 of Section 2.4, up to the ultimate strain and extrapolated out to 100% strain.

FIGURE 2 True Stress-Strain Curves for HY-80 and HSS (Reference (2))



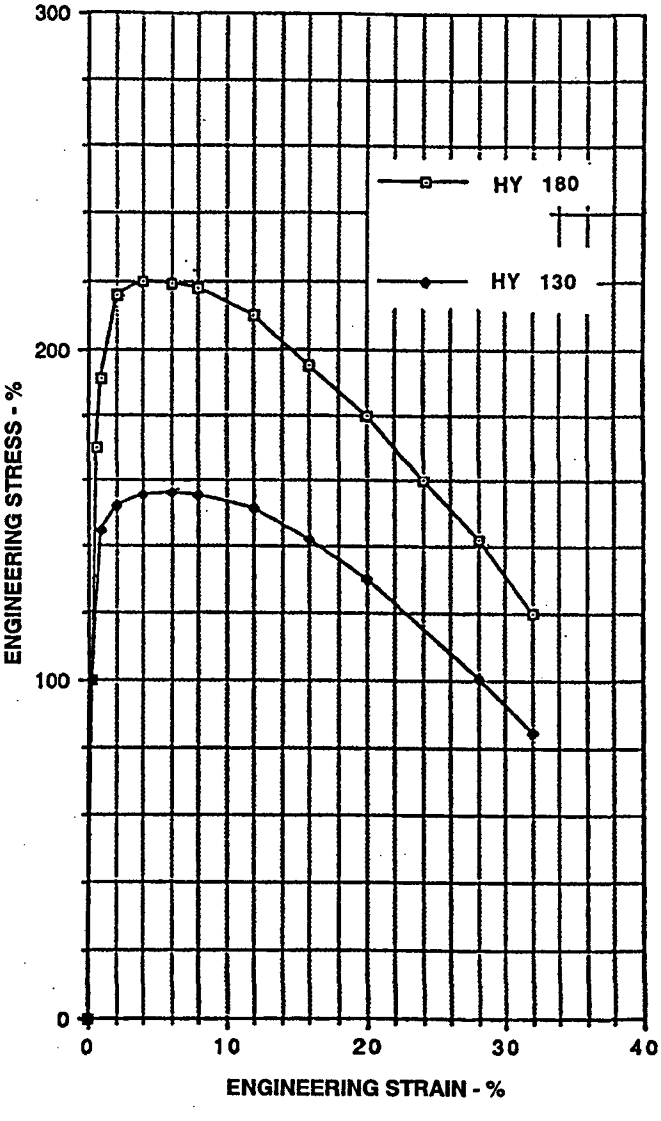
Based on the definition of ultimate strain as the strain at the maximum value of engineering stress (i.e., ultimate stress) of a material taken from the engineering stress-strain curve, the ultimate strain for HSS steel is approximately 16% and the strain at fracture is about 36%. The ultimate strain of HY-80 steel is approximately 8% and the strain at fracture approximately 23%. Therefore, strain limits must be set as a fraction of ultimate strain for each material in order to account for the difference in material inelastic behavior.

Note that these values of ultimate strain reflect the approximate point where necking of the specimen begins. When these values are plotted on the true stress vs. true strain curves (Figure 2), they reflect a realistic strain limit for the purpose of analysis and design.

The inelastic strain criteria in this report are limited to materials with an ultimate stress to yield stress ratio not less than 1.20 (e.g., HY-80). The purpose of inelastic analysis is to take advantage of a material's capacity beyond its initial yield point and to maximize its potential to absorb energy under dynamic loads, thereby mitigating component accelerations and consequently permitting the use of lower strength materials. Figure 3 shows typical engineering stress-engineering strain curves for HY-130 and HY-180 steels. Conservative engineering analysis and design practice dictates that the useful strain of a material be limited to the ultimate strain. Beyond that point, small changes in stress result in very large strains and the material cannot sustain a constant load without uncontrolled necking.

The ultimate strain is approximately 6% for HY-130 and approximately 4% for HY-180. Comparison with Figure 1 for HY-80 reveals that the working strain range, i.e., up to the ultimate strain, is much smaller in HY-130 and HY-180. Therefore, these materials are not recommended for use in relatively high inelastic environments. Higher strength steels such as HY-130 and HY-180 act as elastic-perfectly plastic materials and are better suited to elastic analysis methods involving lower strains.

FIGURE 3 Engineering Stress-Strain Curves for HY-130 and HY-180 (Reference (2))



Furthermore, the use of very high strength steels provides for more elastic behavior, reducing the potential for inelastic energy absorption. Therefore, HY-80 is the highest strength material for which the elastic-plastic criteria should be used. This provides an additional margin of safety for the establishment of appropriate strain limits because of the increased ductility in the steels.

4.3 STRAIN LIMITS: STRUCTURE UNDER DYNAMIC LOAD

Design analyses of structures for dynamic loads are conducted using the maximum design loading condition. Under these conditions, a structure is subjected to a small number of cycles of load. Under high frequency dynamic loading, the initial cycle is the largest, followed by a few, less severe load cycles. Under low frequency dynamic loading, a few cycles of relatively high load can exist before leveling out. The strain limits established by these criteria are to be applied to the maximum plastic strain magnitude produced by the dynamic loading.

Transient loads are used for design assuming that the structure experiences the maximum design loading condition only once. Although it is recognized that these conditions produce multiple load cycles of varying magnitude, current design methods evaluate each condition as a single application of the maximum load, conservatively limiting stresses to static stress limits.

There is no requirement to demonstrate a structure adequate for fatigue under dynamic load of short duration, even though existing criteria currently permit stresses induced by dynamic loading to exceed yield stress on some grades of structure. Since the number of significant load cycles for a short duration dynamic event is small (e.g., about 10 cycles), it is reasonable to conclude that fatigue is not a concern for the maximum strain limits specified in the criteria.

This conclusion is corroborated from the data in Reference (4) which demonstrates that the effect of a relatively few cycles of inelastic strain does not adversely affect the load-carrying capacity of a structure designed for a single dynamic load event. Reference (4) presents data on various steels relating the plastic strain range to the number of cycles required to produce failure. Per Reference (4), for HTS and HY-80 smooth steel specimens, the steels under consideration could be cycled to about 3% strain over 100 times before failure. The data from Reference (4) is based on membrane strain conditions such that comparisons should be made based on the general membrane strain limits. If material can be cycled to a plastic strain range of 3% 100 times before failure, the maximum acceptable strain range for 10 times is undoubtedly much greater.

Additionally, extrapolation of the limited data in Reference (4) indicates that for low numbers of cycles, there is not much difference in the maximum plastic strain range versus cycles to failure between smooth and V-notched specimens (Stress Concentration Factor (SCF)@3.0 reflected in data). Application of the limits of this criteria assumes that the dynamic event may be treated on the basis of a single event, and the number of load cycles associated with each event is low. Therefore, the strain limits can be established on the basis of single load tests and safely applied to the maximum strain pertaining to one dynamic event. The effect of accumulated strain on fatigue may be safely neglected.

4.3.1 GENERAL MEMBRANE STRAIN

The limit on general membrane strain is based on the strain at the ultimate stress of the material as determined from a simple tensile test. In limiting general membrane strain, it is therefore appropriate to consider that:

- The strain at ultimate stress is unambiguous and can be accurately determined,
- General membrane strain is relatively simple to calculate - there are no hidden conservatisms, and
- The consequences of failure would be catastrophic.

The consequences of failure require that general membrane strains be more severely limited than other strains. Knockdown factors (i.e., factors of safety) are established in Reference (5) and Reference (6) to account for various design/analysis considerations. Knockdown factors are established for:

(1) Design confidence in construction,
(2) Level of analysis sophistication, and
(3) Material properties.

The factors were developed for use in the evaluation of commercial nuclear plant containment vessels to determine their maximum internal pressure capacity. The factors account for uncertainties associated with a design which cannot be totally accounted for by the analysis methods used in the structural evaluation. As such, they reflect a reasonable attempt to qualify the ability of an analyst to predict or determine a specific result, in this case, the pressure capacity of a containment vessel.

The knockdown factor associated with construction from References (5) and (6) ranges from 1.0 to 1.25 with a mean estimate of 1.1. Analysis sophistication refers to the variables associated with analysis tools, modeling techniques, and design assumptions. The mean knockdown factor for analysis sophistication in References (5) and

(6) is 1.25. The mean knockdown factor associated for material properties in Reference (6) is 1.0. This is conservative since minimum material properties should be used for design purposes.

For a structure loaded in tension, the knockdown factor for analysis sophistication is taken as 1.0 because the computed stress is an axial or membrane stress which can be accurately predicted by existing analysis methods. The limit set on general membrane strain should correlate to membrane stress computed from simple elastic analysis method. This is in recognition of the fact that failure could occur prior to reaching ultimate stress due to actual construction related conditions. Therefore, the limit for general membrane strain is based on an equivalent membrane stress of $S_u/1.1 = 0.90S_u$, accounting only for construction effects. Using Figure 1, the strain at the elastic stress limit is tabulated as shown below.

MATERIAL	$S = 0.9S_u$ (ksi)	ε @ $0.9S_u$ (in./in.)	ε_u	$f = \varepsilon / \varepsilon_u$
HSS	66	0.07	0.16	0.44
HY-80	88	0.02	0.08	0.25

Hence, an appropriate membrane strain limit ranges from 0.25 ε_u to 0.44 ε_u for the two materials. The lower value of 0.25 ε_u was chosen for the general membrane equivalent plastic strain limit and provides a factor of safety of 4.0 on the ultimate strain. This results in a general membrane strain limit of 2% for HY-80 steel and approximately 4.0% for HSS steel, which is consistent with the data presented in Reference (4) such that fatigue can be neglected. This approach provides some margin for fabrication considerations while still permitting some inelastic behavior. Higher knockdown factors would essentially reduce the membrane limits in HY-80 to elastic response.

The sensitivity of strain to relatively small changes in stress in HY-80 for the general membrane condition is typical of material behavior in the higher yield strength steels. This substantiates the conclusion that elastic-plastic analysis methods are best suited to materials like HSS which possess greater ductility. Therefore, care must be used in establishing membrane strain limits which require the application of relatively large factors of safety.

Also, the general membrane equivalent plastic strain limit established is greater than the limits in ASME Code Case N-47-28 and higher than typical membrane strains observed during pressure tests to failure of containment vessels constructed from SA-516, grade 70 steel (similar to HSS). The vessel test results are described in References (7), (8), and (9). The tested vessels did not fail in the region of membrane stress. The failures generally occurred at discontinuity regions and areas of high stress concentration when membrane strains in the shell were generally in the 2% to 3% range. Since membrane strain will produce the most significant structural deformation and the ultimate strength of the structure will most likely be controlled by local conditions, there is no apparent reason for, or benefit to, establishing a higher limit on general membrane strain.

4.3.2 GENERAL SURFACE STRAIN

General surface strains are the strains at the extreme fibers of a section resulting from a linear or non-linear distribution of stress through a section. For equal values of strain, the deformation will be less under a surface strain than under a membrane strain. Therefore, general surface strains should be permitted higher limits than general membrane strain.

Although not as clearly relevant to strains as it is for stresses, the plastic shape factor of a section is a reasonable measure of the relative capacity of the section in bending. The shape factor of a section ranges from 1.2 for "I" sections, to 1.5 for solid rectangular sections, to 1.7 for solid circular sections, and to 1.8 for "T" sections. The uniform factor of 1.5 was selected because the categorization of strain will most likely be based on element data from a finite element model based on plate/shell elements with rectangular cross sections. The effect of a beam section comprised of finite elements will probably be neglected (this would be conservative). In any case, where beams or beam elements are used, the use of 1.5 as a factor is a reasonable simplification to streamline the application of these criteria. For sections with a shape factor less than 1.5, the inherent conservatism based on minimum ductility properties, dynamic vs. static loads, and the margin of safety on the general membrane stress will outweigh the lack of conservatism of the uniform factor.

The limit of 0.40 ε_u chosen for general surface equivalent plastic strain corresponds to 1.5 times the membrane limit of 0.25 ε_u. The limit on surface strain is still well below the limit established for concentrated strain, 0.70 ε_u, which is appropriate. The limit applies to all general surface strains and is not restricted to linearized strain. The general surface strain includes some strains which could be classified as concentrated strain, but the separation into general and concentrated components would be difficult. Therefore, the general limit is imposed as an unavoidable conservatism.

4.3.3 LOCAL STRAIN

Local strains may be allowed higher limits than general strains because they are restricted to a smaller region of the structure and tend to occur at regions of structural discontinuity. The limit placed on local strains must be less than that established for concentrated strains. A local strain limit set at 1.50 times the membrane and surface strain limits previously established is consistent with the limits in Section III of the ASME Code for local membrane stress, which is set at 1.5 times the general membrane stress.

Therefore, the limit on local membrane equivalent plastic strain becomes:

$$1.5(0.25\ \varepsilon_u) = 0.38\ \varepsilon_u \quad \text{(Approx } 0.40\ \varepsilon_u\text{)}$$

The limit for local surface equivalent plastic strain is therefore:

$$1.5(0.40\ \varepsilon_u) = 0.60\ \varepsilon_u$$

Very highly strained regions are found in most complex structures. Some of these strains are the result of discontinuities and mathematical approximations of the finite element process. Nevertheless, conservatism requires that the area over which these high strains occur must be limited such that significant plastic deformation cannot adversely affect the behavior of the structure and invalidate the analysis or lead to localized failure.

Determination of the effective area of a structure over which local strain limits should be applied relies as much on engineering judgment as it does on analysis. The technical rationale and judgment used in evaluating local stresses are considered applicable to local strain. Paragraph NE-3213.10 of the Section III, Subsection NE of the ASME Boiler and Pressure Vessel Code defines the limit of local membrane stress in the meridional direction in a pressure vessel as $1.0\ (rt)^{0.5}$, where "r" is the minimum midsurface radius of curvature and "t" is the minimum thickness in the region considered. That is, the area which can be considered local increases with the physical parameters of the structure. Based on experience and judgment, strain may be categorized as local if the area over which it exceeds the general strain limit is less than 10% of the effective or "relevant" load carrying area.

4.3.4 CONCENTRATED STRAIN

Conditions arise within regions designated as local where computed finite element strains at nodes due to local introduction of load or structural discontinuities are very high. Therefore, strains within local regions in excess of the local strain limits are considered to be concentrated strains. They are limited to an area of not more than 5% of the effective load carrying area and are limited in magnitude to the limits established for concentrated strain.

Concentrated strain is the largest strain permitted anywhere in the structure. The basis for the limit on concentrated strain is the realization that failure will probably occur at localized regions of relatively high strain which contain potential crack-like defects. Therefore, differentiation between membrane and surface strain is considered unnecessary, and a single strain limit may be established which is applicable to both types of strain.

Therefore, the limit established on concentrated strain encompasses more than one design consideration. The first consideration is to provide reasonable assurance against ductile failure by applying a reasonable factor of safety on ε_u. Knockdown factors are used to determine a cumulative, reasonable factor of safety to set the limit to the left of the peak of the stress-strain curve. Second, a considerable factor of safety is required on failure strain such that failure in a localized region does not occur from any defect in base material.

In establishing the limit for concentrated strain based on material ductility, consideration must be given to the uncertainties of analysis, design, and construction that are beyond the abilities of testing to predict. Based on the initial definition of ultimate strain as the strain at ultimate stress, and using the knockdown factors previously discussed, a design value for concentrated strain can be established. The total knockdown factor, K', for the analysis becomes:

$$K' = \underset{\text{construction}}{(1.1)} \times \underset{\text{analysis}}{(1.25)} \times \underset{\text{material}}{(1.0)} = 1.375 \quad \text{(Approx. 1.4)}$$

Therefore, $\varepsilon_{conc} = \varepsilon_u/1.4 = 0.71\ \varepsilon_u$. The limit for concentrated strain is established at .70 ε_u.

The analysis of a structural element that contains an unspecified geometric feature (e.g., the radius at the toe of a fillet weld and the root opening of a partial penetration weld) must consider the possibility that geometric discontinuities may be involved. Such discontinuities cannot be modeled using finite elements without either:

(1) recognizing that results will be model dependent (i.e., strains will increase without bound as element size decreases), or
(2) using elements that model the crack tip singularity.

The first option would be exercised by establishing limits on strains in the region of the defect based on reasonable factors (as, for instance, the deep notch strength reduction factors of Reference (3)). The second option would require calculation of the fracture mechanics parameter J (or some other fracture mechanics characteristic) and comparison to an allowable. However, fracture mechanics analysis would not be practical in the context of these design criteria due to the nature of the structures involved (welded steel members with multiple connections). Hence, the criteria limit strains only.

The idea of using a single factor for the limit on concentrated strain is much more attractive than using a library of factors. Since it is very difficult to consistently predict inelastic peak strains at discontinuities, criteria limits are established that can be readily and safely applied to the current finite element analysis methods and techniques.

Based on these considerations and concerns, the limit established on concentrated strain must consider the strain at fracture of the material. From Figure 1, the strain at fracture for HSS steel is approximately 36% and for HY-80 steel, approximately 23%.

The curves shown are generally typical of the materials, and it is reasonable to expect that the conclusions drawn using these curves should hold true for all samples of the material.

The uniform concentrated strain limit, established at 0.7 ε_u, based on knockdown factors, provides a factor of safety (FS) on failure strain of approximately 4.1 for HY-80 and 3.2 for HSS as shown below.

MATERIAL	ε_f	ε_u	$\varepsilon_c = .7\, e_u$	$FS = \varepsilon_f / \varepsilon_c$
HSS	36%	16%	11.2	3.2
HY-80	23%	8%	5.6	4.1

Since HSS is a more ductile material than HY-80, the lower factor of safety is considered acceptable and desirable to take full advantage of a materials properties. The approach applies the highest factor of safety to the least ductile material.

This factor of safety is considered reasonable since the typical fatigue stress concentration factor for fillet welds is about 4.0. The factor of safety contained in the "concentrated plastic strain" limit for base material and full penetration welds is used to "design around" the concerns for fracture from geometric discontinuities within the structure. It is based on the assumption that conditions could be no worse in the base metal than that observed in a fillet weld, and recognizes the fact that strains in peak regions cannot become unstable (i.e., the regions are supported by surrounding material with greater residual strength). This is a conservative basis for base metal since tensile tests of 100% efficient fillet welded joints, with the tests run to failure, indicate that welds are designed to develop the full strength of the base metal such that failure occurs beyond the capacity of the base metal.

Also, additional conservatism is employed by limiting the region over which such a strain can be considered acceptable. Strains in excess of allowable local stress but less than allowable concentrated stress are limited to an effective area one-half as large as the effective area permitted for local strain. Therefore, strains that exceed the local strain limit for membrane and surface conditions may be considered concentrated only if the area over which the strain exceeds the local limits does not exceed 5% (i.e., 1/2 x 10%) of the effective area.

4.4 FILLET AND PARTIAL PENETRATION WELDS

Structures evaluated to these criteria are required to have welds that have stress/strain characteristics similar to the base metal and develop the capacity of the connection based upon the ultimate strength of the base metal and the ultimate shear strength of the weld metal. Hence, welds that are 100% efficient need not be uniquely analyzed as part of these criteria. Fillet and partial penetration welds sized as 100% efficient are sized such that under static tensile tests, the weld joints fail (i.e., fracture) in base metal outside the welded area. Therefore, it is reasonable to assume that the inelastic behavior of welded structures can be characterized by the stress/strain diagrams of the base materials. Where welds cannot be sized to be 100% efficient, an engineering evaluation of the welded joint shall be performed based on the loads at the joint and the effective area of the weld.

This requirement is imposed to prevent welds from becoming weak links in the structure. Because stresses are permitted to go beyond yield stress, redistribution of stress within the structure is permitted. Since welds less than 100% efficient cannot be effectively and efficiently represented in the finite element analysis, welds should possess adequate strength to preclude localized failures, excessive distortion or gross structural deflections due to the behavior at welded joints.

There are no restrictions on the types of welds used (i.e., full penetration, partial penetration, or fillet welds), except that single-sided fillet welds or single-sided partial penetration welds that must react to bending loads across the weld are unacceptable. These criteria do not require that welds be uniquely modeled in the finite element representation of the structure. The effect of the weld type is accounted for by lowering the concentrated strain limit in the structure at the welded joint where partial penetration and fillet welds are used.

The nature of fillet and partial penetration welds create concern regarding flaws in the toe and root of the weld. Per Section III, Subsection NB, NB-3123.2, of the ASME Boiler and Pressure Vessel Code, for fillet welded attachments, the limit for primary and secondary stress intensities in the weld are one-half of the allowable primary and secondary stress intensities. Cyclic loading is evaluated using a fatigue strength reduction factor of four. Clearly, a reduction in stress (i.e., strain) in the structure at fillet welded joints is required. Strain limits at joints attached by fillet welds are reduced to account for the effects of the weld. The maximum strain limit of the base material, 0.70 ε_u, is used as the basis of the weld strain limit since it is based on a consideration of geometric discontinuities that can exist in the structure and are more likely to exist in non-full penetration welds. For fillet welds, a knockdown factor of 2.0 is therefore used to establish the strain limit "in the structure" at fillet welded locations. Thus, the maximum plastic strain limit in the structure at the fillet weld is $0.70\ \varepsilon_u/2 = 0.35\ \varepsilon_u$.

For partial penetration welds, a lesser knockdown factor of 1.50 is used to address the concern for flaws in the root of the weld. This value is larger than the knockdown factor established in Reference (7) as the maximum factor relating to design confidence in construction (i.e., 1.1). Therefore, the strain limit "in the structure" at partial penetration welds is $0.70\ \varepsilon_u/1.50 = 0.47\ \varepsilon_u$.

When fillet and partial penetration welds are evaluated on the basis of load, the stress is determined based on the minimum throat dimension. The stress limit is established at 0.55 times the yield strength of the weakest material joined. The stress limit is established on the basis of shear stress using the distortion-energy theory. Based on the distortion-energy theory, shearing-yield strength is predicted to occur at 0.577 times the yield strength of the material. The factor 0.55 is selected for simplicity. No additional factor of safety is required since the stress limits are established at the yield stress of the material consistent with previous stress criteria.

4.5 DESIGN STRAIN LIMITS

The strain limits discussed in Sections 4.3 and 4.4 are based on ductility considerations. They include nominal (i.e., mean) factors of safety to account for potential variances related to material properties, construction related defects, and analytical methods. These strain limits are summarized in Table 2.

Various uncertainties related to the design process warrant consideration of a Design Reduction Factor (DRF) in addition to the factors of safety already included in the strain categories and material limitations.

The determining consideration in the selection of an appropriate DRF should be the maximum plastic strain permitted in the structure, currently limited to 0.70 ε_u. For nominal design conditions, the ASME Code, Section III, limit the maximum primary stress intensity (i.e., local membrane plus bending) to one-half the minimum ultimate tensile strength in materials whose base stress intensity limit (S_m) is controlled by ultimate stress. Therefore, an overall factor of safety of 2.0 on maximum strain is reasonable.

Based on the rationale used to establish the concentrated strain limit of 0.70 ε_u and the requirement to limit the maximum plastic strain permitted by this criteria to one-half the ultimate strain, the appropriate DRF is 0.50/0.70 = 0.714 (approximately 0.75). A DRF of 0.75 is therefore applied to the previously established strain limits in Table 2 while limiting the concentrated strain in the structure to 0.50 ε_u for the purpose of design. The resulting values are shown in Table 1.

TABLE 2 - ELASTIC-PLASTIC ANALYSIS PLASTIC STRAIN MAGNITUDE LIMITS BASED ON MATERIAL DUCTILITY (See Table 1 for Design Limits)

STRAIN CATEGORY [1]	GENERAL PLASTIC STRAIN LIMITS [3,4]	LOCAL PLASTIC STRAIN LIMITS [3,5]	CONCENTRATED PLASTIC STRAIN LIMITS [3,6]
MEMBRANE [2]	0.25 ε_u	0.40 ε_u	0.70 ε_u
SURFACE [2]	0.40 ε_u	0.60 ε_u	0.70 ε_u
STRUCTURE AT PARTIAL PENETRATION WELDS [7]	-	-	0.47 ε_u
STRUCTURE AT FILLET WELDS [7]	-	-	0.35 ε_u

Notes:

(1) Not applicable to bolting.
(2) Limits apply to base metal and weld metal in full penetration welds.
(3) ε_u is the minimum ultimate strain of the base metal or weld metal.
(4) Can be exceeded over not more than 10% of the effective cross-section.
(5) Can be exceeded over not more than 5% of the effective cross-section.
(6) Maximum value - not to be exceeded.
(7) For 100% efficient welds only - welds that are less than 100% efficient should be evaluated on the basis of allowable stress.

4.6 BOLTING

Combined axial plus shear stress in fasteners is limited to the static yield strength of the material, S_y. The load should be the sum of the externally applied load and any tension resulting from prying action produced by deformation of the connected parts.

A stress limit on fasteners of S_y is required because the ability to redistribute stress is virtually non-existent in an individual fastener without accounting for strain hardening of the material, and is difficult to quantify in bolt patterns where loads are typically "averaged out". Furthermore, for high strength fasteners, the difference between yield and ultimate stress is small, and the corresponding ultimate strain relatively low. Therefore, failure of fasteners under dynamic loading is more likely than in continuous structural elements.

Additionally, allowing fastener membrane stresses to exceed yield strain could compromise designs where bolt preloads are required to satisfy design requirements. Bolts undergoing permanent set would lose part or all of their preload.

Typically, fastener bending stresses are not considered under dynamic loading. However, where consideration for fastener bending is required, the maximum value of combined stress at the periphery of the fastener connection resulting from direct tension, shear and bending, but excluding stress concentration, is limited to Sy.

The rationale for bolting strain limits for the inelastic analysis criteria is consistent with the stress limits. The effective strain limit for bolts was selected on the basis that excessive deformations of the bolts would result in loss of functionality of the design. This is consistent with the existing analysis requirements. Bolt stresses significantly above the bolt yield stress will excessively distort and possibly fracture the bolts with catastrophic consequences. Therefore, the average strain on the cross-section of a bolt is limited to the material yield stress, S_y, divided by the bolt material modulus of elasticity, E. When bolt bending under dynamic loading must be considered, the surface plastic strain on a cross-section of a bolt that results from loads from all concurrent conditions is limited to the strain at yield stress (i.e., Sy/E). This limit is the same as the average strain limit to prevent excessive, detrimental distortion. This limit provides for sufficient margin on bolts made of higher strength steels that would typically have lower S_u/Sy ratios than would be accepted by these criteria.

Although these criteria limit bolt stress to the material yield stress, it should be noted that extreme fiber stresses may exceed the yield stress if it can be shown by separate inelastic analysis that, after dynamic loading, the remaining load in the bolt is sufficient to maintain the function of the design.

4.7 BUCKLING

Buckling is not permitted under rapidly applied transient dynamic loading conditions. This requirement applies to gross column/beam buckling as well as local plate type buckling. Buckling cannot be permitted because the resulting condition would violate the assumption of behavior on which the structural stress analysis was based, and large uncontrolled and undefinable deflection could result.

Various codes, standards and related design documents include factors of safety ranging from 1.5 to 3.0 to be applied to the actual capacity of a structural member. All structure must have a 1.5 minimum factor of safety applied to the maximum transient compressive load unless otherwise required. The term "compressive load" refers to the load resulting in compressive stresses in a finite element model. This stress results from the gross forces and moments that exist at the structural cross-section. In beam models, the term compressive load refers to the system of forces and moments on the beam element. All loads (forces and moments) must be considered when determining the minimum buckling capacity of the member.

The factor of safety on structure evaluated by this criterion provides additional assurance of performance of equipment after rapidly applied transient dynamic loading. This is accomplished by maintaining a minimum margin of safety since allowable stresses (i.e., strains) have been increased above previously established limits.

There are inherent factors of safety that arise from considerations such as the load rate, strain rate effects, inelastic buckling, post buckling strength, and the effects of load reversal under dynamic loading. Therefore, the capacity of the structure to resist compressive loads without buckling may be based on the actual buckling capacity of the structure, either gross or local, reduced only by the margin that reflects the difference between theoretical and actual load capacity. Such considerations could include geometric imperfections, deformations due to applied loads, non-linear effects, etc. The capacity of a member to resist buckling may be based on test data that reflect the actual conditions. This requirement is not intended to limit the use of other acceptable, more conservative methods of determining the allowable buckling stress.

4.8 DISPLACEMENT LIMITS

Limits on displacements are established from practical considerations:

- Displacements must be such that the structure is capable of performing its intended function. For instance, if the structure holds a component which can sustain limited displacement, then the structure must not allow greater deformation.

- The structure must not deform so as to impinge on adjacent structures. This condition would result in additional, unspecified loads on the structure and could adversely effect the performance of the impacted component or foundationed equipment.

- Displacement limiting devices such as snubbers may be used to limit overall motion under dynamic load, but the additional loads resulting from the use of such devices must be accounted for in the analysis.

4.9 RESTRICTIONS

The development of this criterion has been subject to a detailed review and approval process. It was developed for specific applications related to the evaluation of structural designs using elastic-plastic analysis. Use of the criterion should be subject to the following restrictions:

a) Limited to plate and solid finite element models where failure is caused by ductile behavior of the material.
b) Extent of plasticity allowed in a structure must be limited such that structural stability is not compromised.
c) Ensure that welding is performed using electrodes of compatible strength and ductility.
d) Ensure that the finite element code adequately documented and approved for use in analysis.

5.0 ACKNOWLEDGMENTS

Development of the elastic-plastic analysis strain acceptance criteria is partially based on work performed by General Dynamics Corporation for Sandia National Laboratories under Contract No. 78-5066. This work was sponsored by the U. S. Department of Energy, Office of Heavy Water Reactor. Reference (1) is the final report for that contract. References (12), (13), and (14) are based on the work in Reference (1) and provide a concise summary of the cited work. The author of this report is responsible for the application of the work reported in Reference (1) reflected in these criteria.

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APPENDIX PROCEDURES FOR DETERMINING ULTIMATE STRAIN

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The elastic-plastic analysis strain acceptance criteria limits are based on the ultimate strain of the material, defined as the strain at ultimate stress from an engineering stress-strain curve. This information can be obtained from a design curve or determined from tensile tests of the material. In this report, two equivalent methods for determining ultimate strain are described. The first method utilizes the engineering stress-strain data to determine ultimate engineering strain, and the second method utilizes true stress-strain data to determine ultimate true strain.

METHOD 1: ULTIMATE ENGINEERING STRAIN

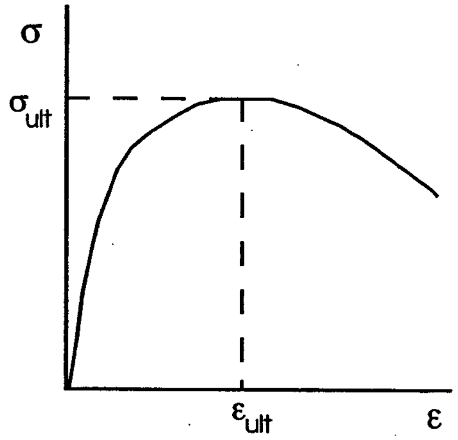
In a standard tensile test, the elongation, Δl, of the specimen (initial length l_o and initial cross-sectional area A_o) is prescribed and the required force, P, needed to accommodate this extension is recorded. Therefore, engineering stress, $\sigma=P/A_o$, and engineering strain, $\varepsilon = \Delta l/l_o$, data are directly obtained. Figure A-1 illustrates an engineering stress-strain curve typical of work hardening materials such as structural steels with an ultimate stress to yield stress ratio not less than 1.20 (e.g., HY-80).

The ultimate stress is defined as the stress at the point where the maximum force is recorded.

$$\sigma_{ult} = P_{max}/A_o$$

This represents the maximum load carrying capacity of the material. Any additional loading will result in unstable necking and ultimate failure of the material. The ultimate engineering strain, ε_{ult}, is the strain corresponding to the ultimate stress.

FIGURE A-1 TYPICAL ENGINEERING STRESS-STRAIN CURVE



The ultimate stress and strain are established by finding the stress-strain state that corresponds to the maximum load. This maximum is found by satisfying

$$\frac{d\sigma}{d\varepsilon} = 0 \quad and \quad \frac{d^2\sigma}{d^2\varepsilon} < 0 \quad at \quad \varepsilon = \varepsilon_{ult}. \qquad \text{(A-1)}$$

This condition requires expressing the stress as a function of the strain, forming the first and second derivatives, and computing the strain that satisfies Equation (A-1). After a number of stress-strain curves have been obtained from tensile tests of a specified material, a statistically determined best fit of the experimental results will be used to describe the "design" stress-strain curve. A functional form of the curve can be obtained from this data. Then, the ultimate engineering strain can be numerically determined from this curve. For use with this criteria, a worst case ultimate strain can be determined as the lowest ultimate strain taken from each curve.

Alternatively, the ultimate stress and strain can be determined graphically from the experimental results as the point where the slope of the tangent to the stress-strain curve is zero.

METHOD 2: ULTIMATE TRUE STRAIN

The ultimate stress and strain can be determined directly from the true stress, $\sigma = P/A$, and true strain, $\varepsilon = ln(l/l_o)$, data where A and l represent the deformed cross-sectional area and length of the specimen, respectively. To obtain this data from the experimental results, the cross-sectional area must be measured and then the true stress calculated. A true stress-strain curve typical of work hardening materials is shown in Figure A-2. Most often the true stress continues to increase to failure because of the reduction in cross-sectional area. For large plastic deformation, the elastic component is neglected and the material can be considered incompressible (Reference (A.1)) such that

$$Al = A_o l_o.$$

FIGURE A-2 TYPICAL TRUE STRESS-STRAIN CURVE

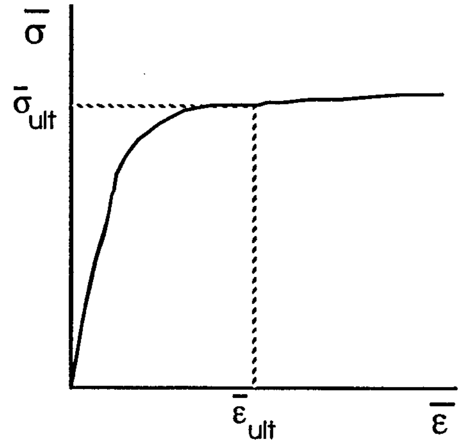


Figure 2: True Stress-Strain Curve

Therefore, the force is related to the true stress and strain by

$$P = \sigma A_o exp(-\varepsilon).$$

As discussed in the last section, the ultimate strain state is defined as the strain at the maximum load. This condition is found by satisfying

$$\frac{dP}{d\varepsilon} = 0 \quad at \quad \varepsilon = \varepsilon_{ult},$$

which reduces to

$$[\frac{d\sigma}{d\varepsilon} - \sigma] = 0, \; at \quad \varepsilon = \varepsilon_{ult}. \tag{A-2}$$

Therefore, the ultimate true strain is found by determining the point where the slope of the tangent to the stress-strain curve is equal to the stress.

In many metals, the true stress-strain relationship in the moderate range of strains ($\varepsilon_{elastic} << \varepsilon_{plastic} \bullet \varepsilon_{ult}$) can be expressed as a power law.

$$\sigma = B \epsilon^{n}$$

where B is the strength coefficient and n is the strain-hardening exponent (Reference (11)). This relationship is invalid for small plastic strains (elastic strains not negligible) and large plastic strains (greater than ultimate strain) (Reference (A.1)). When the data can be reasonably fit to the power law, the condition for determining the maximum load becomes

$$\epsilon_{ult} = n.$$

Therefore, the ultimate true strain can be determined graphically by plotting the stress strain data on a log-log scale. The ultimate strain data is then determined by using a straight line fit through the moderate plastic strain data and determining its slope.

DISCUSSION

Either of the two methods outlined above can be used to determine the ultimate strain. This holds since both methods are equivalent as shown below. The engineering stress and strain are related to the true stress and strain by

$$s = \overline{s}\ exp(-\epsilon) \quad \text{and} \quad \epsilon = ln(1+\varepsilon). \tag{A-3}$$

The condition for finding the ultimate engineering strain was given in Equation (A-1), which becomes,

$$\frac{d\sigma}{d\varepsilon} = [\ \frac{d\sigma}{d\varepsilon} - \sigma\ ]\ exp(-2\epsilon) = 0.$$

when Equation (A-3) is used.

This yields the condition to determine the ultimate strain given in Equation (A-2). Therefore, the conditions for finding the ultimate engineering and true strain are equivalent and proper use of either method should yield reasonable results.

Method 1, used to find the ultimate engineering strain, has less empiricism than Method 2, used to find the ultimate true strain. Method 1 relies only on accurate tensile test data and the ability to determine the point of maximum load. Method 2 relies on accurate measurement of the change in cross-section and the accuracy of determining the slope of the curve. Therefore, this second method may introduce more error into the calculation of the ultimate strain.

On the other hand, the numerical methods being utilized for the elastic-plastic stress analysis require true stress-strain input. If possible, ultimate strains should be calculated using both methods. This will provide a check of the data and ensure that an accurate stress-strain curve is used as input for the stress analysis.

REFERENCES

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