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Strain Limit Criteria to Predict Failure

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STRAIN LIMIT CRITERIA TO PREDICT FAILURE

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ABSTRACT

In recent years extensive effort has been expended to qualify existing structures for conditions that are beyond the original design basis. Determiniation of the component failure load is useful for this type of evaluation. This paper presents criteria based upon strain limits to predict the load at failure. The failure modes addressed are excessive plastic deformations, localized plastic strains, and structural instability. The effects of analytical method sophistication, as built configurations, material properties degradation, and stress state are addressed by the criteria.

INTRODUCTION

The strain limit failure criteria presented in this paper were developed to predict the failure loading on steel tanks and vessels.

The strain limit failure criteria used with appropriate factors of safety are for re-analysis of steel tanks and vessels subjected to normal operating, natural phenomena hazard (NPH) and accident loading conditions. The criteria are applicable to tanks constructed to ASME B&PV Code[6] rules and materials.

The strain limit criteria addresses possible failure resulting from the following failure modes and conditions:

Failure Modes:
- Excessive plastic deformation - Global Strain
- Concentrated plastic strain - Local Strain
- Structural Instability - Plastic and Elastic Buckling

Conditions:
- Material degradation
- As Built Configuration

The acceptance criteria is separated into two categories; plastic failure, and structural instability. The effects of material degradation and as-built configurations are included in each category. It is noted that these criteria do not apply to existing cracks and weld defects.

PLASTIC FAILURE

The failure mode associated with plastic failure is produced by the primary plastic strains which produce gross structural distortions or peak plastic strains that do not produce significant distortions. The acceptance criterion for plastic failure is based on a combination of two methods; the first was developed by Miller [1] for steel tank rupture, and the second was developed by Connelly [2] and Manjoine [3] for ductility reduction due to triaxial loading conditions. Since the Miller, Connelly and Manjoine criteria produce the strain limit for failure, a section is included on factor of safety to address the specific safety function and loading frequency of the component. The combined failure criterion is expressed as:

$$\varepsilon_c \leq \frac{\varepsilon_u}{KF_T} \qquad (1)$$

Where:

ε_c = Maximum calculated equivalent strain
ε_u = Maximum uniform strain from uniaxial test data
$K = K_1K_2K_3$: Combined knockdown factor
K_1 = Knockdown factor for analysis sophistication
K_2 = Knockdown factor for as-built configuration
K_3 = Knockdown factor for material considerations
F_T = Triaxial ductility reduction factor

The requirements for the individual factors are discussed in the following sections.

KNOCKDOWN FACTOR QUANTIFICATION METHOD

Knockdown factors to account for strains which are not calculated by the FEM or for conditions which reduce the material strain at failure can be quantified as shown below. An example of a condition which produces a K_1 knockdown factor is a local structural discontinuity which is not included in the FEM. An example of a condition which produces a K_2 knockdown is the ductility reduction produced by post weld heat treatment of components which have significant cold work fabrication strains. Since these two conditions affect different parameters, the equations which produce the values of the knockdown factors are different.

Quantification of the K_1 factor for strain which is not included in the FEM is based upon the calculated strain value (ε_c) and the increase in strain produced by the local effect ($\varepsilon_{\rho\ell}$) as shown in the following equation:

$$K_1 = \frac{\varepsilon_c + \varepsilon_{\rho\ell}}{\varepsilon_c} \qquad (2)$$

Where:
K_1 = Knockdown factor for FEM sophistication
ε_c = Maximum calculated equivalent strain
$\varepsilon_{\rho\ell}$ = Local peak strain increment

When the combined knockdown factor (K) is divided into the uniform strain limit ε_u to calculate the allowable strain limit, the uniform strain will be reduced by the ratio of the maximum local strain to the FEA calculated strain.

Quantification of the K_2 factor is demonstrated by an example where ductility reduction is produced by post weld heat treatment of components which have significant cold work fabrication strains. The K_2 factor is based upon the ratio of the reduction in strain (ε_r) and the uniform strain (ε_u) from the uniaxial tensile test data as shown in the following equation.

$$K_2 = \frac{\varepsilon_u}{\varepsilon_u - \varepsilon_r} \qquad (3)$$

Where:
K2 = Knockdown factor for as-built configuration
ε_u = Uniform strain from uniaxial test data
ε_r = Ductility reduction due to post weld heat treatment

When the combined knockdown factor (K) is divided into the uniform strain limit (ε_u) to calculate the allowable strain limit, the uniform strain at failure is reduced by the amount of strain (ε_r) produced by the ductility reduction.

It is noted that since some knockdown factors are local, there will be different values for the knockdown factor at different locations.

ANALYSIS SOPHISTICATION KNOCKDOWN FACTOR (K_1)

The K_1 knockdown factor is developed to account for the level of sophistication of the finite element model (FEM). This is done by identifying the detail and completeness of the geometry, element refinement, appropriateness of boundary conditions, and other assumptions made or implied in the FEM. Any differences between the FEM and the actual geometry are quantified and related to the calculated strain to produce the value for K_1.

Finite Element Model Review

The review of the finite element model is divided into four sections: model geometry, finite elements, boundary conditions, and assumptions.

Geometry The geometry of the model is reviewed with respect to the structural components shown by the drawings and design information. The review should include the overall structural components for global structural characteristics and structural connections for local structural discontinuities.

Finite Elements The finite elements are reviewed with respect to type and size. The major focus of the review is the element mesh refinement and element type in areas of large strain gradients.

Boundary Conditions The boundary conditions of the model at the support locations, connection with adjacent structural components, or at lines of symmetry are reviewed with respect to the constraints of the actual design. Included in the review are the effects of friction interface, gaps at support points, or gaps with adjacent structures. In addition, the local effects of finite element modeling techniques, excessive constraint and connections with rigid stiffeners, should be reviewed.

<u>Assumptions</u> The basic assumptions used in the compilation of the FEM are reviewed. This review includes items such as idealization of structural components, connection with minor structural components, and the use of effective static analysis for dynamic loading.

<u>Combined K_1 Factor</u>

The items identified by the review of the FEM, where the FEM does not adequately address the actual structural characteristics, are quantified and included in the K_1 factor, as previously discussed. It is noted that the knockdown factors may have local effects and in some case knockdown factors may combine. Thus the K_1 factor for the model may not be uniform for all locations.

<u>Range of K_1 Knockdown Factor</u>

The range of the knockdown factor associated with FEM sophistication is 1 to 5 [1]. This range is based upon refinement of the FEM and how well it addresses global strains as well as strain gradients and strain concentrations due to structural discontinuities. The factor of 1 applies to a model which accurately represents the global strain state as well as the local strain concentration effects. The factor of 5 applies to a model which only represents the global strain state. It is noted that the upper limit of 5 is in agreement with the ASME Code Criteria [5] which states that 5 is the largest concentration factor to be used for any configuration designed and fabricated to the ASME Code design rules.

AS-BUILT CONFIGURATION KNOCKDOWN FACTOR (K_2)

The as-built configuration knockdown factor (K_2) is based on the difference between the structural information available to the analyst and actual construction configuration. In order to quantify the value for K_2, the important parameters related to the knockdown factor are evaluated by using the original design drawings as the basis. The parameters that contribute to the value of the knockdown factor are:

- Materials Used in Construction
- Weld Quality
- Fabrication Tolerances
- Post Weld Heat Treat
- Fabrication Residual Stresses
- Fabrication Details
- Plate Thickness and Thickness Transitions

The evaluation of these parameters is based on information from the Quality Assurance (QA) records prepared during construction. Any structural deviation from the original design configuration is either included in the FEM or quantified and included in the K_2 factor.

The range of the knockdown factor, K_2, is from 1 to 1.25 [1]. This range applies to structures constructed to the ASME code rules.

MATERIAL DEGRADATION KNOCKDOWN FACTOR (K_3)

The material degradation knockdown factor (K_3) is based upon the effect of material property degradation on the strain at failure and the structural loading of the component. Parameters which contribute to the value of the knockdown factor are:

- Corrosion, Pitting and Cracking
- Aging
- Hydrogen Embrittlement
- Radiation Damage

The effects of any material degradation are either included in the FEM or quantified and included in the K_3 factor.

The range of knockdown factor which accounts for variations in material properties is from 0.85 to 1.15 [1]. The factor of 1.0 represents the mean value of material properties.

MULTIAXIAL STRAIN DUCTILITY REDUCTION FACTOR (F_T)

The ductility reduction in the material, or decrease in the strain level at failure, due to multiaxial loading effects is addressed by using the triaxiality factor approach. The triaxiality factor (F_T) was originally proposed by Davis and Connelly [2], and is expressed as

$$F_T = \frac{\sqrt{2}(\sigma_1+\sigma_2+\sigma_3)}{\sqrt{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2}} \qquad (4)$$

Where:
F_T = Triaxiality Factor
σ_i = Principal Stresses(i=1,2,3)

It has been empirically determined by Manjoine [3] that the maximum principal strain at failure under a multiaxial load can be approximated as the maximum principal strain at failure under a uniaxial load divided by the triaxiality factor, as shown below.

$$\varepsilon_f = \frac{\varepsilon_u}{F_T} \qquad (5)$$

Where:

ε_f = Equivalent strain at failure for multiaxial loading

ε_u = Maximum uniform strain for uniaxial loading

It is noted that for a uniaxial tensile test, the F_T is unity and the failure strain is equal to the maximum uniform strain from the test. However, this method will over-predict the failure strain for small values of F_T. For example, the F_T is zero for a torsion test ($\sigma_1 = \tau/2$ and $\sigma_2 = -\tau/2$), and the method predicts infinite failure strain. To ensure a reasonable limiting value, Manjoine [4] proposed the following formulation.

$$\varepsilon_f = \varepsilon_u(2^{1-F_T}) \qquad (6)$$

In addition, Manjoine [4] proposed the use of the minimum strain limit from Equations 5 and 6, as shown below.

$$\varepsilon_f = MIN[\tfrac{\varepsilon_u}{F_T};\varepsilon_u(2^{1-F_T})] \qquad (7)$$

Thus the failure strain is controlled by Equation 5 for F_T values between 1 and 2, while Equation 6 will control outside this range.

To combine these equations into one which produces the triaxiality factor for use with the previously developed knockdown factors, Equation 7 is rearranged as follows:

$$F_T = MAX[F_T;\frac{1}{2^{1-F_T}};1] \qquad (8)$$

ELASTIC AND PLASTIC INSTABILITY

Structural instability of components subjected to compressive loads is a function of the geometric configuration, loading and strain level. The failure mode is not necessarily dependent upon plastic strain since the failure can be due to elastic instability. Structural instability must be addressed with a criterion which is based upon overall structural collapse, and not on local instability.

Therefore, the acceptance criterion for structural instability is based upon the maximum collapse load adjusted by a factor of safety. The maximum collapse load is determined by a comprehensive analysis which addresses the effects of geometric imperfections, deformations due to existing loadings, nonlinearities, large deformations, material degradation, residual stresses, and inertial loads. The factor of safety is included to address the safety function of the structure and the frequency of the conditions which produce the loading conditions.

To address the accuracy of the finite element model, as-built configuration, and material property variation and degradation, the knockdown factor method, outlined for the plastic failure criterion, may be applied. The instability acceptance criterion is expressed as follows:

$$P_A \le \frac{P_C}{K} \qquad (9)$$

Where:

P_A = Applied loading

P_C = Collapse load from analysis

$K=K_1K_2K_3$: Combined knockdown factor

FACTOR OF SAFETY (F_S)

The factor of safety for a given loading shall address the mean failure strain, the variation in failure strain, the probability of load application and the target performance goals.

For normal operating conditions, the factor of safety shall be chosen to limit the probability of failure to less than 1%.

The factor of safety for seismically induced loadings shall reflect the mean failure strain, the variation in failure strain, the seismic performance category and the seismic hazard at a given site. Additionally, the factor of safety shall be chosen to be consistent with target seismic performance goals specified in DOE-STD-1020-94 [8]. Reference [7] contains a basic seismic criterion and a general approach to compliance which derives factors of safety for capacities with a failure probability of 10%.

CONCLUSION

Strain limit criteria identifies the failure mode and maximum capacity of new and existing structures. When applied to indeterminant structures, the strain limit criteria more accurately accesses structural capacity than elastic methods due to load redistribution in the plastic analysis. Strain values required for the use of limit criteria are directly obtained from current engineering analysis methods and material test data. Thus the use of strain limit criteria is computationally practical and cost effective.

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