INELASTICITY AND THE ASME CODE

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SUMMARY

The ASME Boiler and Pressure Vessel Code sets rules that constitute requirements for the Construction of nuclear power plant items. The term construction includes material, design, fabrication, testing, inspection, etc. These requirements are necessary but may not be sufficient for compliance with the Code. The manufacturer has the responsibility for the structural integrity of the completed item for the conditions stated in the Design Specifications. Thus in addition to meeting the rules of the Code, the manufacturer must take other measures to assure the structural integrity of the component.

In terms of design and analysis, it is here shown that the primary stress limits are set such that the stress intensities in essence remain elastic. This is true even though the related safety factor for various combinations of primary membrane and primary membrane plus primary bending stress is set by limit analysis and varies from 1.27 to 1.67. This is also true of austenitic stainless steel in which the allowable S_m is thirty-five percent higher than for ferritic steels. These primary stress limits are intended to prevent plastic deformation and to provide a nominal factor of safety on the ductile burst pressure. By virtue of the fact that the multiaxial calculations to meet these limits are done in the elastic range, they lead to results in which we can place a high degree of confidence. The reasons for this based on the applicable material parameters, constitutive equations and computation methods are discussed.

The peak stress limits are intended to prevent fatigue failure as a result of cyclic loadings. These limits are set from a large number of uniaxial tests with a substantial factor of safety. They are actually strain controlled tests in which there are large plastic strains from which stresses are obtained by an arbitrary multiplication by the elastic modulus. The validity of the use of these limits for multiaxial pressure vessel behavior has been demonstrated by means of many full scale tests. The implementation of these limits is generally done by an analysis and a stress concentration factor. If component fatigue testing is necessary, its validity must be justified in the Stress Report.

The potential failure mode that is perhaps most difficult to consider in terms of inelastic analysis is the prevention of excessive plastic deformation leading to incremental collapse which is generally done by means of limits on primary plus secondary stress. These limits are discussed and some specific items in inelasticity reviewed. These include:

A review of some newly developed inelastic terminology. Included are definitions of inelasticity, plasticity, plastic hinge, ratcheting and shakedown.

Some background and discussion of the new rules for tests for determination of collapse loads including the criterion of collapse loads and the possible use of a similar criterion for plastic analysis collapse load.

An evaluation of the use of $1.5\,S_m$ in the Thermal Stress Ratchet calculations in NB-3222.5 by means of pertinent experimental information for austenitic stainless steels.

Some suggestions in the light of current analytical and experimental capabilities conclude the paper.

1. INTRODUCTION

The ASME Boiler and Pressure Vessel Code has various Sections that deal with the construction of different types of components. Section III deals with nuclear power plant construction. As stated in NA-1110 of [1], the rules constitute requirements for the construction of these nuclear power plant items. As used herein construction is an all inclusive term that includes material, design, fabrication, testing, inspection, etc. Thus the rules cover such things as mechanical and thermal stresses due to static or cyclic operation. They do not, however, generally cover deterioration or radiation.

The manufacturer must therefore meet the numerical requirements as a necessary condition for acceptance. However, meeting the explicit numerical requirements is not a sufficient condition for acceptance. The manufacturer has the responsibility for the structural integrity of each item using the Design Specification as the basis for design. Thus based on the information relative to loading conditions that are supplied by the owner, the manufacturer must show that the structure is in accordance with the stress limits and design rules. He must also supplement this numerical compliance with additional information where necessary in order to insure the required integrity of the structure. He must use his engineering experience, tests, applicable information from prior tests and all other means at hand.

Computations based on elastic behavior are well established. By measurement, manufactured components can be shown to behave within narrow limits as predicted by analysis in the elastic range. On the other hand, inelastic calculations are of various types and have been used for many purposes. The degree of established methods, repeatability, and information on different materials is varied. When using inelastic methods or using other methods to predict inelastic behavior one must be aware that the Code requirements are necessary but must be used with an understanding of the material variability and other uncertainties in the calculations.

2. ELASTIC BEHAVIOR

First consider design based on elastic behavior and the Code. Material property values are set for each material at various temperatures. As shown in Article II-1000, the design values for design stress intensity (twice the maximum shear stress at a point), and stress are obtained by the application of factors to the mechanical properties of the materials. Consideration is given to the minimum properties specified and the properties at various temperatures as determined by uniaxial tests on representative specimens of the material.

In this paper the specifications of Class 1 nuclear components will be considered. In Article III-2000 [1], the method by which the design stress intensity values for Class 1 components are determined from uniaxial specimen tests is described. There are two groups of materials. For ferritic steels and most non ferrous metals and alloys the allowable stress intensity, S_m, is the lowest of the following:

(1) 1/3 of the specified minimum tensile strength at room temperature

(2) 1/3 of the tensile strength at temperature

(3) 2/3 of the specified minimum yield strength at room temperature

(4) 2/3 of the yield strength at temperature

For austenitic steels, and some other materials the design stress intensity is the lowest of (1), (2), and (3) above and for (4) instead of 2/3 of the yield strength is 90% of the yield strength at temperature but not to exceed 2/3 of the minimum yield strength at room temperature. This loosening of the requirement for austenitic steels to 90% of the yield strength at temperature is based on the idea that austenitic steels have no well defined yield point and rapidly work harde Thus it is assumed that even if some local areas had stress intensities which exceed yield under design load such that plastic flow occurred, the subsequent behavior would be "safely" elastic and comparable to that obtained with ferritic materials. As pointed out in the Criteria Document [2], "The S_m value in the Code Tables regardless of material can be thought of as being no less than 2/3 of the design yield strength for the material". This point will be discussed in more detail later in the paper.

The above determination of material behavior both quantitative and qualitative is essentially the province of the metallurgist. He has defined numerican values and other important material parameters such as composition limits, heat treatment, ductility, etc. It is then assumed that this uniaxial information is indicative of the behavior of complex structures under complex loads with the maximum stress intensity being the connection between uniaxial and equivalent multiaxial behavior.

The primary evaluation of safety is made with stress intensities basically limited to the elastic range. This is done by the use of limits on primary stress. Primary stresses are those necessary to satisfy the laws of equilibrium. The basic characteristic of primary stresses is that they are not self limiting. The primary stress limits are set so as to prevent plastic deformation and to have some factor of safety relative to a generally conservative estimate of the ductile burst pressure (or perhaps more basically the plastic instability load). Figure 1 herein is taken from Figure 2 of the Criteria Document [2]. It is based on the limit analysis of a rectangular cross section in combined tension and bending. The curve shown is the limit analysis-collapse load which is determined from uniaxial stress behavior. The design limits are shown for uniaxial behavior. However, the membrane design limit, S_m, may be extended to the multiaxial stress case. It is assumed that the uniaxial concepts can be applied so that the average stress intensity through the thickness is limited to S_m. Similarly, the membrane stress intensity plus the linearized bending stress intensity is set so as to remain elastic, i.e. within 1.5 S_m.

The Criteria Document [2] indicates that the intent of the code is to base the primary stress limits on a fraction of the limit analysis-collapse load and that the current design limits were chosen to avoid undue complication in the definition of the design limits. "The safety factor is not constant for all combinations of tension and bending, but a design rule to provide a uniform safety factor would be needlessly complicated". The actual factor of safety indicated varies from about 1.27 to 1.67. One might now go further and develop a limit analysis-collapse load picture based on a more complete set of stress resultants. These might include various combinations of bending, shear, radial and membrane stress. The various yield hypersurfaces would then have to be represented. This is the task of those who develop background information for Code bodies. The calculations that would then be required to meet these limits would also be somewhat complex. However, the safety factors could be set so that basically elastic calculations could be performed for which the capability is now generally available.

The design conditions are generally chosen for a component in a conservative manner. The structure is analyzed for these design conditions so as to meet primary stress intensity limits in the elastic regime. Even though the material properties were determined by means of uniaxial specimens, and the primary membrane plus primary bending stress intensity limits are determined from uniaxial considerations, the multiaxial analysis of the actual structure under complex loads by means of linear elastic analysis is valid to a high degree of confidence. The reasons for this fortunate situation were discussed in [3]. Briefly they are as follows: In terms of the material properties, the parameters utilized in elastic analysis for multiaxial conditions are the elastic modulus and Poissons ratio. The "book values" that are used are valid to within 10% for a wide range of material conditions including weld material and heat affected zones. If some plastic flow does take place due to residual stresses or due to momentarily high loads above the design loads, the subsequent values of elastic modulus and Poisson's ratio do not significantly change.

The constitutive equations (mathematical expressions of multiaxial behavior) for elastic analysis are clear and have been verified innumerable times by means of clear and careful experiments. Accurate results may be obtained regardless of the loading sequence and for very complex loads. Thus stress determination with modern methods of analysis is essentially reduced to computation that is frequently done by the use of available special purpose or general purpose computer programs. Designers and stress analysts may thus translate the results of the metallurgists work with uniaxial specimens into valid solutions which are consistent for complex structures

3. SHORT TERM INELASTIC BEHAVIOR

It is instructive to consider in more detail the situation of excursions of load such that the stresses exceed the yield stress. This can occur in various cases in the Code especially for the austenitic steels in which the allowable stress intensity S_m may be 90% of the yield strength at temperature. This for various situations in the normal and upset or emergency or test conditions, the initial yield stress may be exceeded. In order to assess the importance of this behavior first consider a uniaxial stress-strain curve of an austenitic stainless steel. A curve for type 304 stainless steel at 300°F (170°C) is shown in Figure 2. What can be seen is that up to some value the strain is a linear function of stress. With further increase in stress there is a more than linear increase in strain. The 0.2% yield stress is determined by means of a 0.2% offset from initial linear behavior. If the stress were reduced from the 0.2% yield stress the material behaves linearly between zero stress and that value. Similarly if the specimen were loaded to a higher than the 0.2% yield stress and then the load is reduced the material returns to a linear behavior with a "higher" current yield strength. This procedure in which the yield stress is exceeded is permissible for austenitic steels and other such materials if the strains are acceptable. This is so because its ductility is high so that only a small portion of its elongation to failure is used up and the material has a tensile strength that is sufficiently greater than its new yield strength. Thus, for one or a few loads which do not involve fatigue or large cyclic load excursions, we can accept the idea that austenitic steel "work hardens" to a higher yield strength. Consider this acceptance a bit further. Shown in Figure 3 is a three dimensional principal stress space. Since it is assumed that hydrostatic states of stress do not affect the yielding of a material, the yield surface may be represented by the yield curve in the plane of stress states for which the hydrostatic component of stress is zero. If one assumes the validity of the Mises yield surface, then the circle shown for which the zero stress state in the center represents the initial yield surface. Next, consider the work hardening of materials, i.e., the subsequent yield surfaces of an element after plastic flow has taken place. There are two mathematical models of work hardening that have been generally used, namely kinematic hardening and isotropic hardening. They are assumed to bracket the realities of hardening behavior. This last assumption is saying alot because a current yield surface depends in a complex manner on prior plastic flow.

To demonstrate the two hardening behaviors, consider various stress points and stress paths on Figure 3. A stress point is the trace of a particular stress state and a stress path is the consecutive positions of the stress points for a material element. Consider the stress path OAB. For this stress path the proportions of the components of principal stresses, σ_1, σ_2 and σ_3 are constant with only the magnitude changing. This stress path is therefore called a radial or proportional stress path. As the magnitude is increased beyond the point A, plastic flow occurs. This flow behavior would have an effective stress vs. effective strain curve similar to that of the stress-strain curve of the uniaxial specimen shown in Figure 2. Not only does the in-rease in magnitude of stress beyond point A cause plastic flow it also causes a change in the entire surface for further material yielding. If one assumed kinematic hardening, the diameter of the yield curve which is twice the initial yield stress remains constant. However, the yield curve moves as long as the stress point is on its surface and is "increasing". For isotropic hardening on the other hand, the yield curve increases uniformly about its origin. The yield curves under the assumptions of kinematic hardening and isotropic hardening are both shown in Figure 3 with the stress point at B. This position indicates flow such that the new stress point is 50% above the initial stress value.

Consider now a "reduction" of the stress point so that the stress path remains radial. There would not be any plastic flow until the stress point reached point C based on the kinematic hardening assumption. If the stress point on the radial stress path reached D, the initial yield surface would again apply. If the stress reduction from point B were non radial but went to a point such as E, we see that there is a large stress state region for which no further plastic flow would take place for that element even for kinematic hardening. This means that for relatively small local plastic flow that may occur when analyzing for the primary stress limits, residual stress patterns would develop such as to cause subsequent elastic behavior.

4. DEFINITIONS

Before the consideration of additional inelastic behavior in the Code it would be valuable to review some definitions. There are definitions of some terms given in Article NB 3200. However, one of the difficulties that has occurred is that inelastic behavior has been evaluated by various Code groups that have different points of view due to different needs. Different terms have therefore been used to mean the same thing and in some cases terms may apply in one usage and not another. These questions have been considered over a period of years by the SubGroup Design Analysis. After discussion with some other Code groups, a few tentative new or modified definitions have been proposed. One idea for which two different words seem to be used is that of deformation. The word distortion is also used interchangeably with deformation, i.e., in II-1220 it reads, "Either strain or distortion tests may be used for the determination of collapse load". Also in NB-3222.5 it reads "It should be noted that under certain combinations of steady state and cyclic loadings there is a possibility of large distortions developing as the result of ratchet action; that is, the deformation increases by a nearly equal amount for each cycle." It was suggested that the word deformation be used and defined as:

Deformation of a component part is an alteration of its shape or size.

Some of the other terms that have already been used herein or that will be subsequently used herein are now listed:

Inelasticity is a general characteristic of material behavior in which the material does not return to its original shape and size after removal of all applied loads. Plasticity and creep are special cases of inelasticity.

Plasticity is the special case of inelasticity in which the material undergoes time-independent non-recoverable deformation.

Creep is the special case of inelasticity that relates to the stress-induced time-dependent deformation under load. Small time-dependent deformations may occur after the removal of all applied loads.

Plastic analysis is that method which computes the structural behavior under given loads considering the plasticity characteristics of the materials including strain hardening and the stress redistribution occurring in the structure.

The plastic instability load is defined as that load at which unbounded plastic deformation can occur without an increase in load. At the plastic tensile instability load the true stress in the material increases faster than strain hardening can accomodate.

Limit analysis is a special case of plastic analysis in which the material is assumed to be ideally plastic (non-strain hardening). In limit analysis the equilibrium and flow characteristics at the limit state are used to calculate the collapse load. Two bounding methods are used in limit analysis, v.z., the lower bound approach which is associated with a statically admissible stress field and the upper bound approach which is associated with a kinematically admissible velocity field. For beams and frames the term "mechanism" is commonly used in lieu of "kinematically admissible velocity field".

Limit analysis - collapse load - The methods of limit analysis are used to compute the maximum load a structure made of ideally plastic material can carry. The deformations of an ideally plastic structure increase without bound at this load, which is termed collapse load.

Ratcheting is a progressive incremental inelastic deformation or strain which can occur in a component that is subjected to variations of mechanical stress, thermal stress, or both.

Shakedown of a structure occurs if, after a few cycles of load application, ratcheting ceases. The subsequent structural response is elastic, but may have local elastic-plastic behavior. Elastic shakedown is the case in which the subsequent response is elastic.

5. CYCLIC BEHAVIOR

This last definition of shakedown is modified from the proposed committee definition. It is different than that given in NB 3213.18 of the Code. This term for shakedown would permit localized elastic-plastic behavior. The definition currently in the Code is in accord with the generally accepted definition in structural mechanics. It implies that the structure reaches a state of residual stress such that subsequent structural response is elastic. Consider cyclic behavior further. In the Code it is the limitation on the elastically calculated primary plus secondary stress limits for normal and upset conditions that are intended to prevent excessive plastic deformation leading to incremental collapse. The secondary stresses are those developed by the self constraint of adjacent material or by self constraint of the structure. The basic characteristic of a secondary stress is that it is self limiting. The primary plus secondary stresses are limited to $3S_m$. For materials limited to 2/3 of the yield strength at temperature this means that $3S_m$ is equal to twice the yield strength. As shown in Figure 3, this means that the stresses are limited to the diameter of the initial yield surface which is the same as the diameter of the kinimatic hardening yield surface. For materials in which 90% of the yield strength at temperature is permitted, the $3S_m$ limit may be 2.7 times the initial yield strength. Thus it is implicitely assumed that some kind of hardening, possibly isotropic, takes place until the diameter becomes 2.7 times the initial yield strength. As may be seen from Figure 2, there is some additional hardening that is assumed to take place so as to reach the 0.2% yield strength from the initial proportional behavior.

In the discussion of potential failure modes in the criteria document [2] the second mode indicates that the primary plus secondary stress limits are intended not only to prevent excessive plastic deformation leading to incremental collapse but also to validate the application of elastic analysis when performing the fatigue evaluation. Peak stresses in addition to primary and secondary stresses are used to make this fatigue evaluation.

Peak stresses are defined as that increment of stress which is additive to the primary plus secondary stresses by reason of local discontinuities or local thermal stress including the effects, if any, of stress concentration. The basic characteristic of a peak stress is that it does not cause any noticeable distortion and is objectionable only as a possible source of a fatigue crack or a brittle fracture. A local structural discontinuity is defined as a geometric or material discontinuity which affects the stress or strain distribution through a fractural part of the wall thickness. The stress distribution associated with a local discontinuity causes only very localized types of deformation or strain, i.e., small fillet welds, and has no significant effect on the shell type of discontinuity deformations. "Local thermal stress is associated with almost complete suppression of the differential expansion and thus produces no significant distortion" (i.e. small hot spot). Such stresses shall be considered only from a fatigue standpoint. ."

With the primary plus secondary stresses held within elastic bounds peak stresses are used to evaluate possible fatigue failure. The fatigue evaluation that is made in the Code is based upon tests in which strain rather than stress is the controlled variable. These strain values even though they may be in the plastic strain range are multiplied by the elastic modulus so as to give a ficticious stress value. For each class of material, a curve of S_a (allowable elastic stress) vs. allowable number of cycles has been developed.

The peak stress intensity in a structure to be analyzed is derived from the highest value at any point through the thickness of a section of the combination of all primary, secondary and peak stresses. Although the peak stress intensity is evaluated in an elastic manner, the local areas in which there are peak stresses may continue to cycle into the plastic range. In order to account for the fact that there may be acceptable repeated contained plastic behavior in peak areas when a structure shakes down, the proposed definition of shakedown was made more inclusive and the definition of "elastic shakedown" was included.

To this point it has been seen that the primary stress limits are met with essentially elastic analysis. The fatigue failure prevention is basically done with elastic calculations and various concentration factors. The resultant elastic peak stress intensity is compared to a ficticious stress derived from experimental strain controlled test results. These uniaxial experimental results have been modified by various "safety" factors and the resultant curves have been verified by component tests. The prevention of excessive plastic deformation leading to incremental collapse is dealt with mainly by means of the $3S_m$ limit on elastically calculated primary plus secondary stress intensity. This of course leads to the question of the justification of the use for the acceptable elastic stress range, of 2.7 times the yield strength for austenitic steels and other materials. This question may be similarly posed in the special requirement given in NB-3222.5 in which it is intended to prevent thermal stress ratchet growth of a shell subjected to thermal cycling in the presence of a static mechanical load. A footnote to NB-3222.5 states, "It is permissible to use 1.5 S_m whenever it is greater than S_y." Thus a value of 1.35 times the allowable yield strength is again permitted for austenitic stainless steels for thermal ratcheting. The use of the 0.2% yield strength rather than the proportional limit is considered in Subparagraph NB 3222.5(b) as follows:

> "Use of the yield strength, S_y, in the above relations instead of the proportional limit allows a small amount of growth during each cycle until strain hardening raises the proportional limit to S_y".

The question that is now addressed is:

> Does the existing experimental data show that the "hardening" of austenitic stainless steel take place in a manner so as to verify the higher values used?

First consider uniaxial specimens. The stress range from cyclic behavior can be seen to increase substantially. In Figure 4, taken from [4], a definite increase in the stress range may be noted for cyclic behavior of a total strain range of 0.4%. Even at this low value of strain, an increase of the total stress range of at least 35% is achieved. This does not mean that general isotropic hardening took place. It only indicates that "hardening" took place in the uniaxial direction of loading.

Additional information can be obtained from work reported by Liu & Greenstreet [5]. A number of tests were run with radial (proportional) loading in addition to uniaxial tension - compression loading into the plastic range. They used cylindrical thin walled 304 stainless steel specimens that were subjected to axial and torsional loadings of varying relative proportions. Their results showed that for the first yield, the results were in good agreement with Mises Yield Criterion based upon a deviation of the effective strain from the linear elastic response by ten microinches per inch. They loaded four of the specimens an equivalent amount in stress space into the plastic region. They then unloaded each specimen proportionally into the plastic region in the opposite direction.

Finally they reloaded each specimen into the plastic regime in the original direction.

In general, the four curves of different radial paths were in good agreement with each other in the unloading and reloading step in terms of the plot of deviatoric stress vs. effective strain. This should indicate that cyclic radial loading into the plastic range acts in a manner similar to uniaxial specimens in the direction of loading. However, the curves of segmental prestress loadings and associated subsequent yield surface (reproduced from [5] as Figure 5) do not necessarily indicate hardening in the direction of loading.

In thermal stress ratchet behavior there is a primary load (driving force) and secondary thermal load. These loads would not be applied in a proportional manner even though in many cases there would be a fairly definite sequence of application. Thus, unless there is multiaxial data that relates to the specific type of loading sequence encountered, one should look at general behavior for a series of non radial loadings into the plastic region to find out whether the subsequent yield surfaces generally increase their diameter. Some idea of more general behavior can be gleaned from Figure 6 (taken from [5]) which is a continuation of the sequence of loading shown in Figure 5. These results show that the net size of the yield surface did not change much.

The data therefore does not seem to substantiate the substitution of 1.5 S_m for S_y for austenitic steels. There is some direct test information, however, which indicates that there may be hardening in thermal ratcheting for austenitic steels. Corum [4] reports on thermal ratcheting tests that were run on a straight pipe. The analysis that was carried out was based on a hardened 304 material as shown in the 10th cycle of Figure 4 herein. The analytical results generally agreed with the experimental results. However, the test was run between 1100°F (670°C) and 800°F (480°C) with hold times for creep. Creep played a very large role in the results so that the exact relationship between the "cold" plastic flow and the corresponding analysis is unclear.

There were thermal ratcheting experiments on 304 stainless steel pipes that were recently described by Yamamoto, et. al. [6]. The tests were carried out with hot and cold sodium loops with superimposed axial loads. The authors of [6] did a Bree type estimate of the ratcheting strain. They found that the analysis by the use of the Bree estimation without work hardening is conservative compared to the measured results. They also found that an increase of the yield strength by 22% or more and the use of the Bree estimation resulted in a fairly close but conservative comparison. The authors did not report on any comparisons with more detailed analytical methods.

In order to obtain clearer answers to the question of the use of 1.35 S_y for austenitic steels for thermal ratcheting tests and detailed analyses at temperatures that do not involve creep. This would permit direct evaluations of the validity of the "hardening assumption". The second would be radial and general multiaxial subsequent yield surface tests with a clearer definition of the onset of yield in a multiaxial sense. As discussed in [5], and by Michno and Findley [7], experimental results are very dependent on the choice of offset strain and the capability of the instrumentation. From uniaxial specimen data, the yield strength is obtained by the use of a 0.2% offset strain. Most multiaxial tests are made such that after plastic flow, the subsequent "yield" surface is probed with only minute strains that are a tiny fraction of the 0.2% offset strain used for uniaxial yield strength. If a value of 0.2% offset effective strain is used to define multiaxial stress yield it would affect subsequent yield behavior. This means that a whole series of identical specimens would have to be used to map a single subsequent yield surface.

6. CLOSURE

Material properties are developed on the basis of uniaxial specimen tests. From these tests certain metallurgical characteristics are surmised and certain numerical values defined. The numerical values that are related by means of analysis to the structure are obtained from the stress strain curves for different material compositions under specified conditions of heat treatment for various product forms, etc.

The relationship of these numerical material properties to fabricated structures is carried out by means of constitutive equations and various types of analysis. In the inelastic portion of this relationship there are many uncertainties especially for analyses which include repeated loading into the plastic region. In order to gain more confidence in this area it is necessary that the structural experimenter become more involved. What is required is a systematic matrix of experimental results based upon clearly established measurement parameters that are consistently applicable to multiaxial as well as uniaxial tests. It is necessary that for a time the metallurgist and analyst take a back seat to the structural experimentalist.

The discussion herein has in the main been restricted to the plasticity portion of inelastic behavior with just one or two references to creep. When one considers creep, the problems are compounded by the complexities of the interactions between creep and plastic behavior as well as by the difficulties in multiaxial analysis of creep behavior.

7. ACKNOWLEDGEMENTS

The author appreciates the many discussions on the subject with Code committee members and with colleagues at Foster Wheeler Corporation. In particular, Dr. T. V. Narayanan was very helpful in his discussion of explicit ideas in the paper. The author would like to thank the Foster Wheeler Development Corporation for the opportunity to carry out this work and for the permission to publish it.

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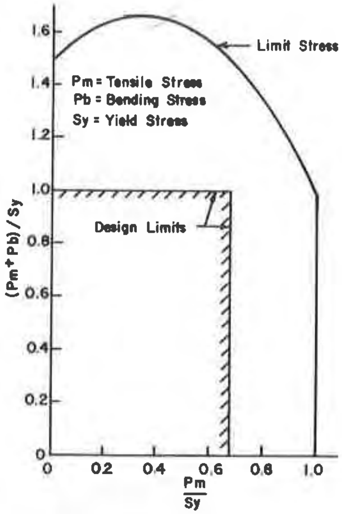
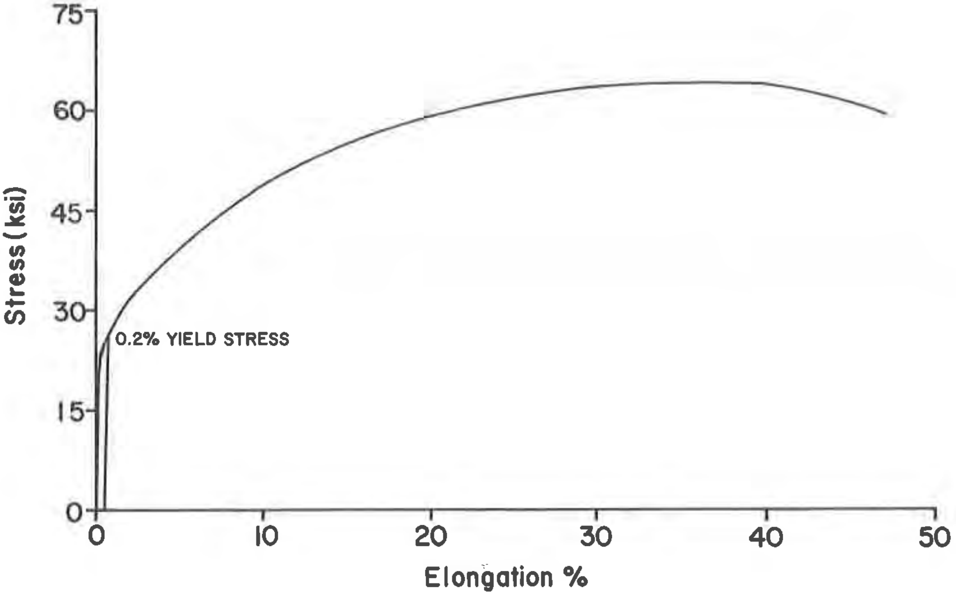
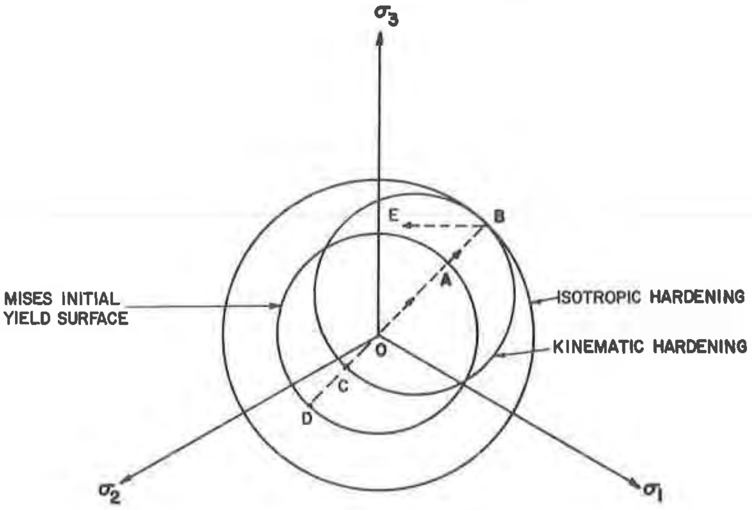
The material presented herein represents the author's interpretation and opinions alone and does not necessarily represent the position of the ASME Boiler and Pressure Vessel Committee.



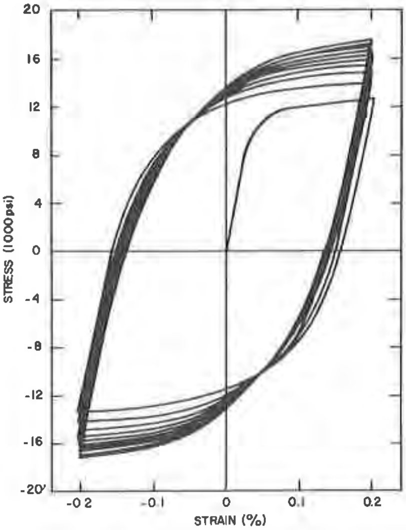
1. Limit Stress for Combined Tension and Bending (Rectangular Section) Taken from [2]



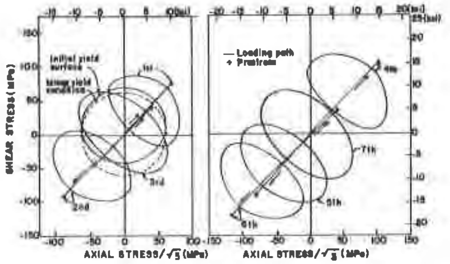
2. Uniaxial Stress-Strain Curve of 304 Austenitic Steel at 300°F (150°C)



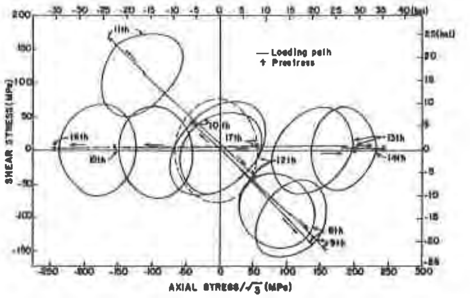
3. Principal Stress Representation of Yield Surface



4. Cyclic Stress-Strain Curve for Annealed Type 304 Austenitic Steel at 800°F (430°C) - Taken from [4]



5. Initial and Subsequent Yield Loci For Segmental Prestress Loading - 304 Stainless Steel at Room Temperature - Taken from [5]



6. Segmental Prestress Loadings and Associated Subsequent Yield Surfaces - 304 Stainless Steel at Room Temperature - Taken from [5]