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BOUNDS ON CREEP RATCHETING IN ASME CODE

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ABSTRACT

For more than a decade simplified methods for bounding creep ratcheting strains have been used in the ASME Code to design components for elevated temperature service. The background and a brief history of the development of the rules is given. Current simplified methods in Code Case N-47 are applicable for complex cycling load histories including severe cycles which may result in plastic strain increments.

NOMENCLATURE

P_L	local primary membrane stress intensity
P_b	local primary bending stress intensity
σ_c	effective creep stress (elastic core stress)
S_y	yield strength
K_t	Code Case N-47 factor related to relaxation of bending stress
z, σ	coordinate system in Figure 3
a,b,c	interface coordinates in Figure 3
$\sigma_p, \sigma_t, \sigma_c$	membrane, thermal and elastic core stresses shown in Figure 3
σ_ℓ	relaxation level of σ_c stress in equation (4)
$\epsilon_{(n)}$	total inelastic strain increment in cycle (n) in equation (5)
$\nu_{(n)}, \delta_{(n)}, \eta_{(n)}$	creep, relaxation and plastic strain increments in equation (5)
E	elastic modulus
(σ_c)	calculated nominal value of σ_c in plastic ratcheting regime
$S_{y(H)}, S_{y(L)}$	yield strength at hot and cold end of the thermal cycle
X,Y,Z	dimensionless values of membrane, bending and core stress in CC N-47
$'$	primes define dimensionless values
T,C	subscripts in equations (11)(12) defining tension and compression respectively
$\Delta\epsilon$	strain range
$\Delta\epsilon_{el}$	elastic strain range
$\Delta\epsilon_{cr}$	creep strain range
Σp_i	membrane stress components in equation (26)
Σt_i	thermal stress components in equation (27)
Σc_i	core stress in equations (28)(29)
	subscripts M and B define primary membrane and bending components in equation (26)
	subscripts m and b define secondary membrane and bending stress in equations (26)(27)
	subscript r defines thermal stress due to discontinuity
	subscript t defines thermal stress due to through the wall temperature gradient
p	pressure (psi)
T	temperature (°F)
$\dot{T}$	temperature rate (°F/sec)

INTRODUCTION

For more than fifteen years, the pressure vessel and piping components for elevated temperature service in the United States and elsewhere in the world have been designed using rules given in the ASME Boiler and Pressure Vessel Code Case N-47 [1] and its predecessor CC-1592. The technique and the resulting rules for bounding accumulated strains therein are based on the Elastic Core Concept first developed for the Pressure Vessel Research Committee. Extensive experimental work performed by the National Laboratories in the United States has confirmed conservatism of the method for the typical cases encountered in design. Further analyses have been performed to apply the method for a broad variety of structural problems and to provide background for new code rules. The applicability of the method has been extended to consider strain hardening effects and bounds for load histories including severe cycles in the plastic ratcheting regime. Basic work needed to treat more complex stress fields and geometries was completed under the Oak Ridge National Laboratory sponsorship. Alternative use of the rules for discontinuities have also been derived.

The theoretical background of the Code rules and practical application of the Elastic Core Concept in design of components subjected to cyclic load histories in the creep regime is described herein. The extended formulation of the rules including bounds for inelastic strains accumulated in the plastic ratcheting regime has been incorporated into the 1986 edition of the ASME Code Case N-47. Practical use of the method is illustrated by sample problems included at the end of the paper. The first sample problem demonstrates the use of rules in the CC N-47 for the simple case of a pressurized tube subjected to thermal transients in elastic shakedown regimes. Application of the extended rules is explained by the second example where the load histogram includes deep excursions into the plastic ratcheting regime.

THERMAL STRESS CYCLES

Thermal gradients through the wall of the vessel may occur during both steady operation and transient conditions. For example, the heat generated in a fuel can or heat exchanger tube must be transferred through the wall to the coolant. The resulting thermal gradient introduces stresses when the unit is brought to power. However, these thermal stresses tend to relax due to creep during elevated temperature operation. Thus, after a sufficiently long period of initial operation, the vessel or tube walls support only pressure-induced stresses in spite of the thermal gradient. Each subsequent shutdown, however, causes residual stresses that are of equal magnitude but opposite in sign to the initially generated thermal stresses. Such changes in structural response are analogous to the effect of self-springing in piping system for elevated temperature service [2].

Thermal gradients during transient conditions occur in the vessel wall subjected to temperature drops during shutdown or severe fluctuations of temperature inside the vessel. Thermal shock stresses rise to their maximum and then vanish after the temperature becomes uniform again. Reheat of the vessel is usually slow and causes only insignificant thermal gradients. There is no time for creep to interact during the transient. Thus, creep effects need to be considered only during the long steady state periods of operation when the stress fields redistributed by the transients relax in time. The basic solution for maintained pressure stresses which interact with cyclically applied thermal stresses is therefore applicable both when there is a thermal gradient during steady operation and when the thermal gradient occurs only instantaneously during the transient conditions.

The simple cases of a cylindrical shell or a plane wall conducting heat subjected to thermal transient through-the-wall temperature gradients result in a cyclic bending component of stress. In the more complex cases of structural discontinuity, thermal stress includes both cyclic membrane and bending components. The bounding technique in Code Case N-47 considers cyclic character of stress only for thermally induced bending component classified as secondary stress, whereas membrane component due to pressure is categorized as sustained primary stress. The cyclic character of the thermal membrane stress at a discontinuity can be adequately evaluated as explained later in the text.

STRAIN LIMITS IN CODE CASE N-47

Accumulated strains and deflections in a vessel subjected to pressure and cyclic thermal loading in the creep regime may lead to excessive distortion or fracture unless the accumulated strains are limited. Not only are the accumulated strains and distortions typically much higher in vessels operated in the creep regime than in lower temperature vessels, but also most pressure vessel steels have significantly reduced ductility when subjected to long-term creep at elevated temperatures. These are the basic reasons for using strain limits for pressure vessels to be operated in the creep regime, but strain limits are also used to limit the allowable amount of creep ratcheting and to place more restrictive limits on weldments.

Code Case N-47 limits maximum positive, inelastic principle strains as follows:

Strains averaged through the thickness	1%
Strains at the surface due to the equivalent linear distribution of strain through the thickness	2%
Maximum local strains	5%

For weldments, the above limits are reduced by one-half to 0.5%, 1.0% and 2.5%, respectively.

Code Case N-47 provides methods for evaluation of the accumulated strains for shell structures subjected to sustained primary stresses and cyclic displacement controlled stresses. The bounds based on the Elastic Core Concept for enhanced creep are used in the Code for this purpose. The bounded elastic core stress, σ_c for the loading regimes which do not include plastic ratchet as originally introduced in Code Case N-47 is shown in Figure 1. P_L and P_b denote the local primary membrane and primary bending stress intensity, respectively.

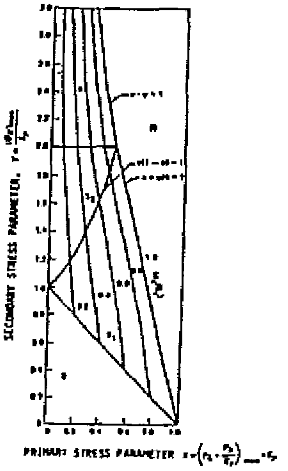

FIGURE 1 ELASTIC CORE STRESS, σ_C BOUNDED IN CODE CASE N-47

$Q_{R,max}$ is defined by CC N-47 as the maximum range of the linearized secondary bending stress during the service loadings. Use of the K_t factor allows credit for creep redistribution of bending stress.

The accumulated strain is obtained using the σ_c effective creep stress in the isochronous stress-strain curves, as shown, for example, in Figure 2. Since the isochronous curves in the Code are based on average properties, a factor of 1.25 is used with σ_c to relate the resulting strains to minimum properties. The next sections describe the development of the bounds.

BOUNDING TECHNIQUE IN SIMPLIFIED INELASTIC EVALUATIONS

The interactive effect of thermal cycles on the stress distribution in the wall of a pressurized vessel was evaluated using the model originally proposed by Miller [3] for elastic-plastic behavior, and redefined by Bree [4] for cyclic load histories including creep. Miller analyzed plastic ratcheting. His criteria limiting pressure and thermal stresses to eliminate component incremental growth are included in Section III of the Code for low-temperature design. In the presence of creep, the structure after some cycling develops a so-called steady-state stress cycle. The appropriate theorem was proved by Fredrick and Armstrong [5]. Bree noted in his model that although creep caused the resulting stress field to relax, each thermal cycle, subsequent to the relaxation period, reinstituted the original elastic-plastic stress distribution.

Typical stress profiles for characteristic combinations of sustained pressure stress σ_p and cyclic thermal stress σ_t are shown in Figure 3 for loading combinations resulting in purely elastic cycling, E; shakedown S_1 and S_2; and captive plastic cycling, P. The loading combinations resulting in these regimes are shown in Figure 1 for X and Y coordinates corresponding to σ_p and σ_t values normalized to yield strength S_y. For regimes S and P there exists a portion of the wall thickness, $a < z < b$ shaded in Figure 3 which remains elastic (except for creep) throughout the life of the vessel. This portion of the wall is defined as the Elastic Core.

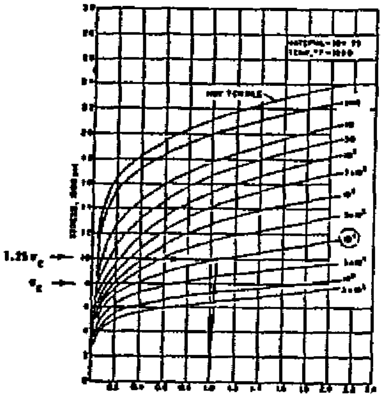

FIGURE 2 USE OF ISOCHRONOUS CURVES BASED ON AVERAGED PROPERTIES TO DETERMINE MAXIMUM INELASTIC STRAINS

The history of stress in the Elastic Core can conveniently be used to bound inelastic strains accumulated through the wall of the vessel. The use of the Elastic Core stress for creep rupture damage evaluation, instead of primary stresses for design conditions averaged through the wall as required by the CC N-47, has also been postulated [6]. Note that short-term redistribution of stress in the Elastic Core during the transient does not affect the accumulation of inelastic strain or creep damage and, therefore, in such evaluations can simply be disregarded. Creep strains and damage occur only during long-term operation at elevated temperature.

The mid-wall stress in the elastic region E is not affected by the cyclic thermal bending. Elastic Core extends through the thickness of the wall. However, in the S and P regimes only part of the wall remains elastic and the Elastic Core stresses are increased above the pressure stresses due to the interaction of the cyclic thermal bending. This causes enhanced creep and accelerated damage of the material.

Figure 3 also shows the stress profiles for regimes R_1 and R_2, where plastic ratcheting occurs. Notice that the surface layers, which flow plastically within the thermal cycle, overlap. Vanishing of the Elastic Core, in fact, defines the interface between the shakedown and captive plastic cycling regimes and the plastic ratcheting regimes.

Bounds on Stresses in Elastic Core and Inelastic Strain Accumulation

In the considered model the core stress decreases during creep relaxation. It is also assumed that the creep deformation during the transient and subsequent low temperature part of the thermal cycle is negligible. The maximum value of stress in the Elastic Core during operation at elevated temperature occurs directly after the thermal transient. Its value is given by the simple relations derived from equilibrium considerations in plastic solutions for stress profiles in Figure 3 as follows:

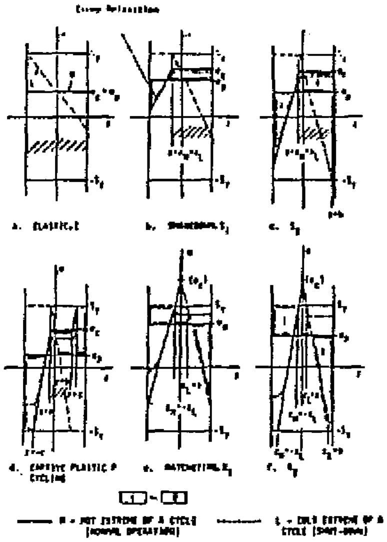

FIGURE 3 CHARACTERISTIC STRESS PROFILES AT EXTREMES OF LOADING CYCLE FOR STRESS REGIMES IN FIGURE 1