On Design of Discontinuities in Structures for Elevated Temperature Service

G. Baylac
Electricité de France, Département BP, 22 av. Wagram, F-75382 Paris Cedex 08, France
B. Kasraie, J.S. Porowski, W.J. O'Donnell, M.L. Badlani
O'Donnell & Associates, Inc., 241 Curry Hollow Road, Pittsburgh, Pennsylvania 15236, U.S.A.

ABSTRACT

A typical structural discontinuity represented by a stepped cylindrical shell, subjected to internal pressure and down temperature transient is analyzed.

Solutions based on elastic core concept are applied in order to obtain bounds on accumulated strains. It is shown how the obtained bounds can be used with results of elastic analysis to provide evaluation of the maximum strain component in the discontinuity region.

INTRODUCTION

ASME Boiler and Pressure Vessels Code Case N-47 includes the methods for bounding the inelastic strains accumulated due to creep ratcheting in components subjected to cyclic loads at elevated temperature. These bounds, however, are applicable only for locations away from structural discontinuities. The critical locations in a component often occur at places where the materials, geometry and mechanical or thermal loading changes abruptly to cause complex combinations of cyclic stresses. Such discontinuities, indeed, can be analyzed by full inelastic analyses of local regions in the structure. However, the analyses are expensive, the formulation of boundary conditions difficult and the results of certain numerical methods used in computer programs for performing inelastic analyses are not always reliable. An extension of the existing bounding methods to include structural discontinuities would therefore provide valuable assistance in design. Such methods are useful not only during the preliminary design stage but for the evaluation of structural integrity in final design analyses as well. The initial phase of their development is described herein.

Existing bounds in the Code are based on uniaxial solutions developed in References [1, 2]. These solutions consider only the cyclic character of bending stress whereas the membrane component is considered primary and is maintained constant throughout the loading history. At structural discontinuities it is important to include the cyclic character of membrane discontinuity stresses.

A cylindrical shell with step change of wall thickness subjected to pressure and thermal transients is considered. Elastic results illustrating typical interrelation between thermal shock and thermally induced discontinuity stresses are obtained and a modification of the simplified method given in Code Case N-47 for bounding creep ratcheting is proposed. This modification considers effects of cyclic membrane component of discontinuity stress. Results of elastic plastic analysis are given to illustrate the effect of redistribution of stress during the transient conditions on stress distribution during operation.

ANALYZED MODELS

The model used to obtain elastic stress resultants is shown in Figure 1. A cylindrical shell of two thicknesses, a and b, is subjected to pressure and thermal transients of the fluid inside the vessel. Discontinuity stresses arise due to pressure and nonuniform temperature distributions during the transient. The nonuniform radial deformation of the thinner and thicker parts causes membrane and bending stresses in two principal directions. Additional bending stresses are generated due to temperature gradients through-the-wall.

The models with wall thickness of thin section a = 3 inches and a = 0.5 inches were analyzed.

FINITE ELEMENT ANALYSES

The stepped cylinder of Figure 1 was modeled with ANSYS using two-dimensional quadrilateral isoparametric elements. In order to attenuate the discontinuity effects sufficiently long cylindrical lengths were included in the model on either side of the discontinuity. The finite element models are shown in Figure 2a and 2b for the thin wall thickness a_1 and a_2, respectively.

Internal pressure was applied at the inner surface of the shell. Appropriate force and displacement boundary conditions consistent with the structural response of the axisymmetric shell subjected to this pressure were applied. Referring to Figure 2, these were as follows:

(1) On the thick section boundary PQ, the axial displacement in the Y direction is constrained.

(2) On the thin section boundary RS, the nodes are coupled in the Y direction and the blow-off pressure is specified.

For the thermal transient analysis, the down transient used is illustrated in Figure 3. The transient was applied as surface temperatures to the inside surface, all other surfaces being treated as adiabatic. The resulting temperature distribution in time was subsequently used for obtaining the thermal stress history.

The numerical values of the material properties used to obtain the generalized results herein were the following:

Elastic Modulus	E	$= 30 \times 10^6$ psi
Poisson's Ratio	ν	$= 0.3$
Yield Stress	S_y	= 60,000 psi
Thermal Conductivity	k	= 20 Btu/hr-ft °F
Density	ρ	$= 0.289$ lbm/m^{-3}
Specific heat	c	= 0.1 Btu/lbm °F

RESULTS

The elastic results of the finite element analysis for internal pressure loading are shown for model of Figure 2b in Figure 4.

The schematic illustrating the notation for the stresses generated by the pressure and the thermal transient is shown in Figure 5. Bending stress generated by the thermal transient can be decomposed into a through-the-wall thermal shock component which remains positive during downshock, and the thermal expansion component which may have the opposite sign.

The results of the thermal analysis are shown in Figures 6 and 7 for the models of Figure 2a and 2b respectively. The stresses are shown for cross-section B-B. The thermal shock stress quickly reaches its peak at the end of the transient ramp. Peaks of thermal expansion stress may or may not show significant delay as illustrated in Figures 6 and 7 respectively.

EVALUATION OF CORE STRESS AT DISCONTINUITY

An effective evaluation of the core stresses at two principal directions can be obtained by simultaneous biaxial solution including membrane and bending stress components [3]. The biaxial solution in [3] was obtained for sustained membrane stresses. This solution can be extended to include the interactive effect of thermally-induced hoop bending $\sigma_{\tau m}$. The maximum core stress in the hoop direction, Σ_c, is governed by the maximum membrane Σ_m and maximum bending Σ_t stresses at the critical location and instant. Since the hoop stress $\sigma_{\tau m}$ vanishes after reheating of the component to the uniform operation temperature, the resulting core stress Σ_c should be reduced by subtracting $\sigma_{\tau m}$ before entering the isochronous curve.

When the resulting membrane and bending stresses in two planes are of the same sign, simpler bounds based on applying uniaxial solutions individually for stresses in two principal directions can conservatively be used.

The maximum range of bending stress should be used to obtain the core stress. The algebraic sum of thermally induced hoop membrane stress and the pressure-induced hoop stress should be used. The sum of the pressure-induced membrane and bending should be taken as the load controlled, sustained component. The resulting relations are as follows:

$$\Sigma_{p_i} = \sum \left\{ \sigma_{pM_i} + \sigma_{pB_i} + \sigma_{\tau m_i} \right\}_{max} \quad (1)$$

$$\Sigma_{t_i} = \sum \left\{ \sigma_{tb_i} + \sigma_{\tau b_i} \right\}_{range\ max} \quad (2)$$

The elastic core stress in regimes S_1 and S_2 is given by:

$$\Sigma_{c_i} = S_y + \Sigma_i - 2\sqrt{\Sigma_{t_i}(S_y - \Sigma_{p_i})} \quad \text{in } S_1 \quad (3)$$

$$\Sigma_{c_i} = \frac{\Sigma_{p_i}\Sigma_{t_i}}{S_y} \quad \text{in } S_2 \quad (4)$$

The maximum core stress Σ_c is reduced by $\sigma_{\tau m}$ before elevated temperature operation begins:

$$\sigma_c = \Sigma_c - \sigma_{\tau m} \quad (5)$$

The controlling stresses occur when the core stress σ_{c_i} on either plane reaches a maximum. The maximum σ_c value is multiplied by 1.25 as required by Code Case N-47 and then used to enter the isochronous curves. This is done because these isochronous curves are based on averaged properties and the design criteria are based on minimum properties. The evaluation should include all possible combinations of stress in time for all locations in the discontinuity region.

In time two instants occur which usually result in the worst combination of stresses. The first instant, indicated by Arrow A in Figure 5, occurs at the end of the temperature ramp during the transient when the thermal shock reaches its peak. The second instant, shown by arrow B, may occur in the region adjacent to that where the thermally induced hoop membrane stress reaches its maximum. The elastic core solutions discussed herein can only be applied where σ_c stress remain below the yield stress S_y.

An inelastic analysis of the discontinuity in Figure 2a was also performed to evaluate the effectiveness of the proposed bounds. Figure 8 indicates development of stress profiles in hoop direction throughout the transient. It is also shown that the core stress evaluated as proposed herein correlates well with the stress obtained by inelastic analysis.

Application of the bounds, of course, required that an elastic analysis be performed to obtain the linearized components of pressure and membrane stress.

CONCLUSIONS

For the simple type of structural discontinuity considered herein, uniaxial solutions can be independently applied to obtain the core stress. The solution is extended to include cyclic thermally induced membrane stress. The resulting maximum core stress value can be used to bound the accumulated strains.

The bounds for strain range and maximum stress based on uniaxial model are available. Future attempts will be made to extend the bounds to more general geometric discontinuities and loading conditions.

ACKNOWLEDGEMENT

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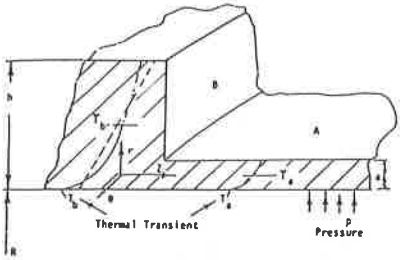

FIGURE 1 SHELL DISCONTINUITY SUBJECTED TO PRESSURE AND THERMAL DOWNSHOCK

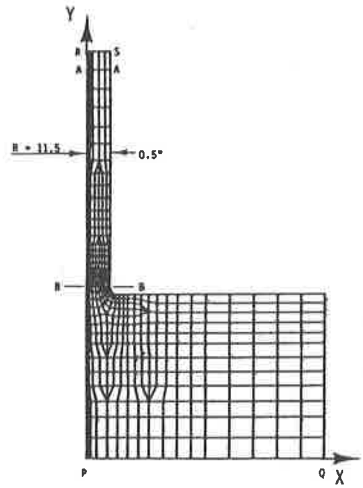

FIGURE 2A FINITE ELEMENT MESH OF STEPPED CYLINDRICAL SHELL

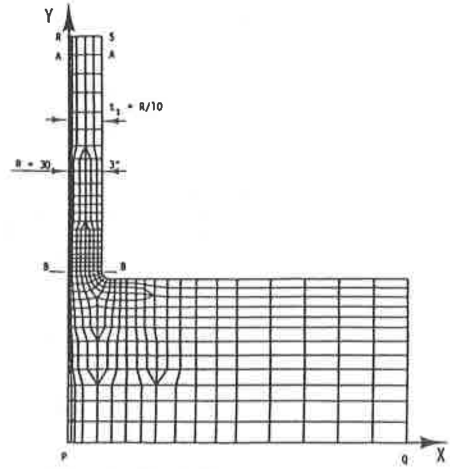

FIGURE 2B FINITE ELEMENT MESH OF STEPPED CYLINDRICAL SHELL

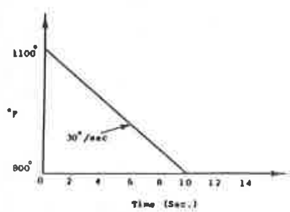

FIGURE 3 THERMAL TRANSIENT FOR STEPPED CYLINDRICAL MODEL

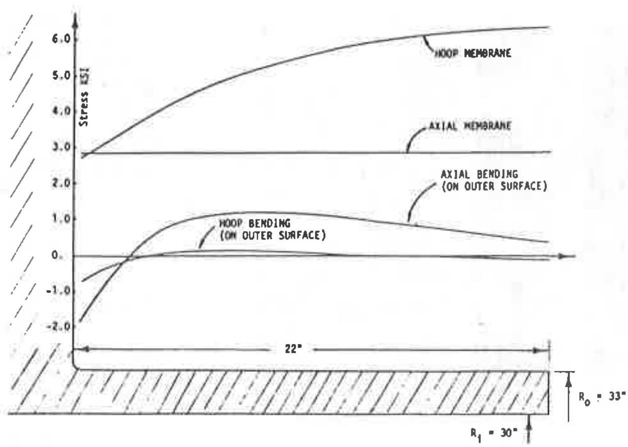

FIGURE 4 STRESS DISTRIBUTION IN PRESSURIZED SHELL OF FIGURE 2B

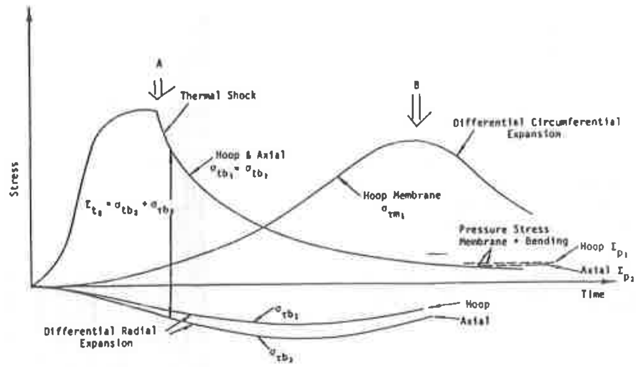

FIGURE 5 SCHEMATIC OF ELASTIC STRESSES AT DISCONTINUITY

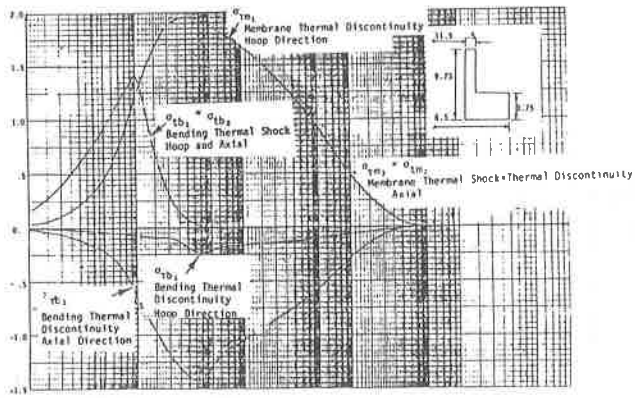

FIGURE 6 THERMALLY INDUCED (DOWNSHOCK) ELASTIC STRESSES AT CROSS SECTION B-B MODEL 2A

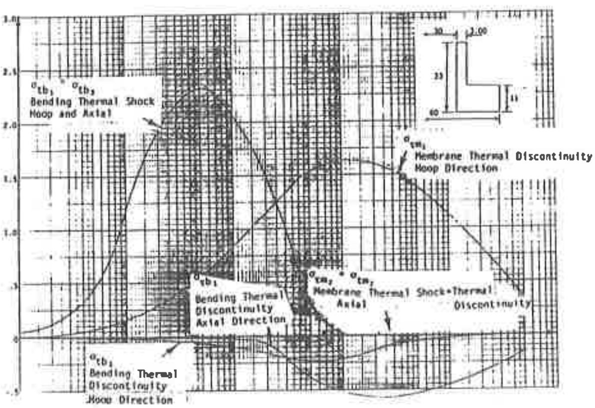

FIGURE 7 THERMALLY INDUCED (DOWNSHOCK) ELASTIC STRESSES AT CROSS SECTION B-B MODEL 2B

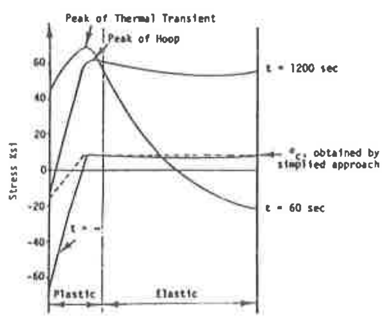

FIGURE 8 ELASTIC-PLASTIC, HOOP STRESS DISTRIBUTION FOR PRESSURE PLUS THERMAL TRANSIENT IN CROSS SECTION B-B