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A new pressure vessel design by analysis method avoiding stress categorization

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ABSTRACT

Stress categorization in the design by analysis (DBA) procedure for protection against plastic collapse in pressure vessel has been problematic during application. For example, it is difficult to determine the proportion of primary and secondary stress at the gross structural discontinuities. This paper proposes a new method to avoid the stress categorization by extending the current elastic stress analysis method in ASME Code based on lower bound limit load theory. The proposed method assumes a stress distribution along the stress classification line (SCL) in the form of limit stress state for a beam under membrane and bending load, rather than a linear stress distribution. The effectiveness of proposed method is verified by comparing with the elastic stress analysis, Limit-Load Analysis, Elastic-Plastic stress Analysis of the ASME Code for axisymmetric pressure vessels. The results concluded that the new method is effective easy to use.

1. Introduction

The ASME Boiler & Pressure Vessel Code (2015) [1,2] and EN 13335–3:2009 [3] provide Design by Analysis (DBA) methods based on elastic stress analysis for design against plastic collapse failure mode. In the assessment procedure for gross plastic deformation check, the calculated stress along SCL under defined loading condition is processed into linearized stresses including membrane stress and bending stress. These linearized stresses need to be categorized into general primary membrane stress, local primary membrane stress, primary membrane plus bending stress and primary membrane plus secondary bending stress. These categorized stresses and combinations are then limited to corresponding allowable values according to Hopper diagram in Code.

The approach of stress categorization dates back to the related concept put forward by Kroenke (1973) [4] who established the procedure to calculate the required quantities from FE analytical results. The significant contributions in providing specific guidelines for categorization of the resultant stresses from finite element analysis are made by Hechmer and Hollinger [5–10]. Eslami and Sharyat [11] developed a technique distinguishing the primary and secondary stresses by considering a viscoelastic model subjected to the mechanical as well as thermal load. They concluded that the thermal stresses contribute partly to the primary stress in the case of thermal plastically loaded vessels. Lu, Chen and Li [12] proposed a two-step approach (TSA) of stress classification and a primary structure method (PSM) to identify primary stress. Fanous and Seshadri [13] proposed the R-node method used to investigate the primary stresses and their locations in both simple and complex geometries. Gao [14] proposed a simple method to derive primary bending stress by identification of the loads that cause primary bending stress. Godbole and Pore [15] proposed a new method for stress categorization based on fitting a least squares plane to two dimensional variation of a stress quantity. Labbe [16] studied categorization of seismically-induced stresses for civil and mechanical engineering and drew a conclusion that a seismic input cannot be a priori regarded as primary or secondary.

From the previous works mentioned above stress categorization is an essential but problematic in the DBA procedure. It is desirable to make an improvement to the method avoiding the stress categorization on DBA procedure. The current authors [17] proposed an initial concept based on the lower bound limit load. But the validity of the method was not validated by applying to typical pressure vessel models. Furthermore, a problem about the value of stress distribution parameters was not addressed. In this paper, a complete description of the new method is proposed and applied to four pressure vessel models.

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Nomenclature

SCL	Stress classification line
LAL	Limit Analysis Line
M	Membrane stress
B	Bending stress
M_m	Moment derived from true stress distribution along SCL
N_f	Force derived from true stress distribution along SCL
M + B	Membrane plus bending stress
FEM	Finite Element Model
LIMIT	Limit-load analysis method
EP	Elastic-plastic stress analysis method
Gao	The method proposed in Ref.[14].
DBA-L	The method proposed in this paper
σy	Yield stress
Sm	2/3 of yield stress
E	Young's modulus
σ_a	Stress amplitude used in DBA-L method
d	Position parameter used in DBA-L method
σ_e^p	The minimum value of Mises stress on LAL for load set P
P_m	General primary membrane stress
P_L	Local primary membrane stress
Q	Secondary stress
$P_{allowable}$	Allowable load

2. DBA-L method

The stress categorization procedure for primary stress may therefore be considered to be a form of lower bound limit load analysis. The lower bound limit load theorem (Lubliner 1990) [18] states: *If, for a given load, there exists a statically admissible stress field in which the stress nowhere exceeds yield then that load is a lower bound on the limit load of the structure*. As the primary stress categorization is an equilibrium stress distribution and the limits on primary stress yield-limit the maximum allowable primary stress, the primary stress field satisfies the lower bound limit load theorem and the associated load can be viewed as a lower bound on the limit load of the vessel. This interpretation is valid only if the stress categorization procedure is applied correctly and all primary stresses are identified in the procedure. If a primary stress is incorrectly specified as secondary stress it may exceed the yield-limited (as the primary plus secondary stress limit is $3Sm$ or $2\sigma y$).

In the stress categorization procedure for secondary or incremental plastic collapse assessment, all operating loads are applied (mechanical and thermal) and the membrane and bending stress distributions evaluated. A 3Sm stress limit is then applied to the membrane plus bending stress and the allowable operating load calculated. This analysis can be interpreted as satisfying Melan's lower bound (elastic) shakedown theorem, which states: *for a given cyclic load set the structure will exhibit shakedown if a constant residual stress field can be found such that the yield condition is not violated for any combination of cyclic elastic and residual stresses*.

In principle, the linearized stress distribution could be used directly in a limit analysis or direct route design of the vessel. This would not yield good designs in practice as the solution is generally a poor lower bound due to the assumed form of stress distribution. The stress classification procedure identifies this implicitly through the different values of allowable stress specified for membrane and bending stress. However, it is possible to obtain an improved limit load solution by assuming an alternative form of through thickness stress distribution.

As stated in Ref. [17], instead of the linearized stress distribution, an alternative form of stress distribution along the SCL is assumed, which can produce a more accurate prediction for limit stress state. The assumed through thickness distribution is the general limit state stress distribution in a beam under combined membrane and bending load. Here the stress distribution shown in Fig. 1, defined in terms of parameters σ_a and d, is considered. The parameters can be determined by considering the force and moment equilibrium conditions.

A limit analysis line (LAL) is defined through the vessel in the same manner as the SCL. This is just a matter of changing the name of the line since the analysis procedure is different. Applying force and moment equilibrium:

$$\frac{N_f}{b} = \int_{-\frac{h}{2}}^{\frac{h}{2}} \sigma dz = -\int_{-\frac{h}{2}}^{d} \sigma_a dz + \int_{d}^{\frac{h}{2}} \sigma_a dz = -2\sigma_a d$$

$$\frac{M_m}{b} = \int_{-\frac{h}{2}}^{\frac{h}{2}} \sigma dz = -\int_{-\frac{h}{2}}^{d} \sigma_a zdz + \int_{d}^{\frac{h}{2}} \sigma_a zdz = \sigma_a\left(\frac{h^2}{4} - d^2\right)$$

$$\frac{N_f}{b} = \int_{-\frac{h}{2}}^{\frac{h}{2}} \sigma dz = -\int_{-\frac{h}{2}}^{d} \sigma_a dz + \int_{d}^{\frac{h}{2}} \sigma_a dz = -2\sigma_a d \quad (1)$$

$$\frac{M_m}{b} = \int_{-\frac{h}{2}}^{\frac{h}{2}} \sigma dz = -\int_{-\frac{h}{2}}^{d} \sigma_a zdz + \int_{d}^{\frac{h}{2}} \sigma_a zdz = \sigma_a\left(\frac{h^2}{4} - d^2\right) \quad (2)$$

Substituting σ_a from (1) into (2) and rearranging gives:

$$\frac{N_f d^2}{2} - M_m d - \frac{N_f h^2}{8} = 0 \quad (3)$$

The roots of the quadratic equation (3) are:

$$d = \frac{M_m \pm \sqrt{M_m^2 + N_f^2 h^2}}{N_f} \quad (4)$$

For given values of N_f and M_m, the values of the stress distribution parameters d and σ_a can be evaluated from equations (4) and (1) or (2) respectively. However, two roots in opposite signs for d are calculated from equation (4). The unique value of d can be determined by considering the direction of moment and total force acting on LAL from true stress distribution, as shown in Fig. 2.

The complete procedure of the DBA-L method is as follows.

a) The through wall elastic stress distribution is evaluated in terms of component stresses in the line's xyz co-ordinate system.
b) The cut section forces and moments are evaluated by numerically integrating equations (1) and (2).
c) Equations (1), (2) and (4) are applied to six component stress separately.