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Estimation of static burst pressure in unflawed high pressure cylinders using nonlinear FEA☆

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ABSTRACT

A study has been carried out to predict the static burst pressure in closed thick-walled unflawed cylinders using finite element analysis (FEA). The failure of the cylinder purely by ductile fracture mode is considered in the analysis. Thick-walled cylinders of different diameter ratios (K = outer diameter/inner diameter, ranging from 1.5 to 6) have been investigated. The commercially available ANSYS FEA code has been used, for carrying out an implicit elasto-plastic analysis of the cylinders considering the geometric and material nonlinearities. The Arc-length algorithm available in ANSYS code has been employed to overcome the solution convergence problem, due to tangent singularity at limit state. The FEA predicted static burst pressure for thick-walled cylinders over the considered range of diameters ratios i.e., K = 1.5 to 6, showed good agreement with Svensson burst model. The implication of using elastic-perfectly plastic model for the prediction of static burst pressure has also been investigated.

1. Introduction

Thick-walled cylinders find wide application in the areas of chemical, petro-chemical, nuclear, power plant, military equipment etc. The recent developments in high pressure applications like food sterilisation, Isostatic pressing and the hydrostatic extrusion of metals have increased the magnitude of pressures that needs to be contained within the pressure boundary. The ASME [1] Boiler and Pressure Vessel code, section VIII division (3), provides comprehensive codes for designing and constructing high pressure cylinders. The code recommends the use of elastic plastic stress analysis for determining the plastic collapse loads, as it closely approximates the actual structural behavior considering the geometric and material nonlinearities. Numerous research papers have been found in the literature, for the prediction of burst pressure in cylindrical shells. Liping Xue et al. [2], demonstrated the prediction of burst pressure in cylindrical shells using FEA by both static and dynamic approaches. Christopher et al. [3], compared the experimental burst results of cylindrical shells with various empirical, semi-empirical and analytical models. Peng-fei LIU et al. [4], showed the application of Arc-length algorithm and restart analysis for estimating plastic collapse load in a thin-walled pressure vessel and compared it with experimental results.

Svensson [5] derived a solution for estimating burst pressure in cylindrical and spherical pressure vessels. The formula (Eq. (10)) takes in to account the effect of strain hardening exponent of the material on the burst pressure prediction. Several researchers have reported good agreement of Svensson model with experimental burst tests. Turner [8] derived an expression to estimate the burst pressure of the cylinder in terms of the diameter ratio and the ultimate stress. The model is based on the assumption that on reaching the burst pressure, the shearing stresses are uniform over the entire thickness of the cylinder wall and equal to the ultimate shearing strength of the material. As the ultimate shearing strength of the material is difficult to ascertain directly from specimen tests, the final form is derived in terms of ultimate tensile strength of the material as shown in Eq. (8). Faupel [7] has proposed a model which takes into account the effect of yield and ultimate stress on the cylinder burst pressure. From the literature survey, it can be seen, a considerable amount of work has been carried out for predicting the static burst pressure in cylindrical shells. Hence, this work is mainly focused on investigating the burst pressure in thick-walled cylinder of different thicknesses (K = 1.5 to 6), employing finite element analysis. The results from the analysis are compared with the popular mathematical and empirical models available in literature [5–7,9].

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Nomenclature

e	2.718281828 (base of natural log)
σ_r	radial stress (MPa)
σ_θ	hoop stress (MPa)
σ_z	longitudinal stress (MPa)
σ_y	yield stress (MPa)
σ_{ult}	ultimate stress (MPa)
D_o	outer diameter of the cylinder (mm)
D_i	inner diameter of the cylinder (mm)
D	mean diameter of the cylinder (mm)
K	D_o/D_i
r	radius of the cylinder (mm)
r_o	outer radius of the cylinder (mm)
r_i	inner radius of the cylinder (mm)
r_p	plastic zone radius of the cylinder (mm)
p_a	applied pressure (MPa)
P_{burst}	bursting pressure (MPa)
A_1	constant equal to yield strength of the material
B_1	strain-hardening coefficient
n	strain-hardening exponent = 0.032
v	displacement in y-direction

2. Theoretical models

Huang [8] has developed an analytical solution based on Von Mises criterion for determining the stresses in an elastic-plastic cylinder (Fig. 1). The relations are derived based on plane strain condition and incompressible volume assumption. The simplified bi-linear kinematic hardening model as well as the nonlinear material models (true stress-strain curve from experiments) can be used to represent the material behavior. The principal stresses determined from FEA in elastic and elasto- plastic regions of the cylinder are validated using the Huang's model relations given below.

For Elastic Zone: $(r_p \le r \le r_0)$

$$\sigma_r = \frac{\sigma_y}{\sqrt{3}} r_p^2 \left[\frac{1}{r_0^2} - \frac{1}{r^2}\right] \tag{1}$$

$$\sigma_\theta = \frac{\sigma_y}{\sqrt{3}} r_p^2 \left[\frac{1}{r_0^2} + \frac{1}{r^2}\right] \tag{2}$$

$$\sigma_z = \frac{\sigma_y}{\sqrt{3}} r_p^2 \left[\frac{1}{r_0^2}\right] \tag{3}$$

For Plastic Zone: $(r_i \le r \le r_p)$

$$\sigma_r = \frac{2}{\sqrt{3}} A_1 \ln\frac{r}{r_i} + \frac{\sigma_y - A_1}{\sqrt{3}B_1} r_p^{2B_1}\left[\frac{1}{r_i^{2B_1}} - \frac{1}{r^{2B_1}}\right] - p_a \tag{4}$$

$$\sigma_\theta = \frac{2}{\sqrt{3}} A_1 \left[\ln\frac{r}{r_i} + 1\right] + \frac{\sigma_y - A_1}{\sqrt{3}B_1} r_p^{2B_1}\left[\frac{1}{r_i^{2B_1}} + (2B_1 - 1)\frac{1}{r^{2B_1}}\right] - p_a \tag{5}$$

$$\sigma_z = \frac{1}{\sqrt{3}} A_1 \left[2\ln\frac{r}{r_i} + 1\right] + \frac{\sigma_y - A_1}{\sqrt{3}B_1} r_p^{2B_1}\left[\frac{1}{r_i^{2B_1}} + (B_1 - 1)\frac{1}{r^{2B_1}}\right] - p_a \tag{6}$$

Relation between applied pressure and plastic radius,

$$p_a = \frac{2}{\sqrt{3}} A_1 \ln\frac{r_p}{r_i} + \frac{\sigma_y - A_1}{\sqrt{3}B_1}\left(\frac{r_p}{r_i}\right)^{2B_1} - \frac{\sigma_y}{\sqrt{3}}\left(\frac{r_p}{r_o}\right)^2 - \frac{(1 - B_1)\sigma_y - A_1}{\sqrt{3}B_1} \tag{7}$$

The static burst pressures of cylinders, determined from the FEA (implicit analysis) have been compared with the following models found in the literature.

Turner [6] :

$$P_{burst} = \sigma_{ult} \ln K \tag{8}$$

Faupel [7] :

$$P_{burst} = \frac{2\sigma_y}{\sqrt{3}} \ln K \left(2 - \frac{\sigma_y}{\sigma_{ult}}\right) \tag{9}$$

Svensson [5] :

$$P_{burst} = \left(\frac{0.25}{n + 0.227}\right)\left(\frac{e}{n}\right)^n \sigma_{ult} \ln K \tag{10}$$

Maximum Shear stress criterion [9] :

$$P_{burst} = 2\sigma_{ult}\frac{K - 1}{K + 1} \tag{11}$$

3. Model geometry

The cylinder has an overall length of 800 mm and an effective length of 500 mm (Fig. 2.(b)), with a constant internal diameter of 50 mm. The cylinder is closed at both ends by means of end covers. The internal diameter is maintained constant and the outer diameter of the cylinder is varied to obtain cylinders of different diameter ratios, K = 1.5–6. The meshed axisymmetric segment of different cylinders, used in the analysis are shown in Fig. 3.

4. Material properties and models

The precipitation hardened stainless steel 17-4 PH (UNS no. S17400/H1075), one of the alloy steel recommended by ASME code [1] for constructing high pressure cylinders, has been used in this analysis. The 17-4 PH steel offers high strength and hardness along with excellent corrosion resistance compared with other class of steels. It has good manufacturability and can be age hardened by low temperature heat treatment process. The true stress-strain curve (Fig. 4) for the steel has been obtained from the ASME code KD-231.4 [1], using the properties from Table 1. The elastic perfectly plastic model, a simplification of non-linear model is also shown in Fig. 4.

5. Finite element model

An implicit, nonlinear, static, FEA of the cylinder was carried out using ANSYS program. The higher order 2-D element, Plane 183 was used to build an axisymmetric model, taking advantage of the rotational symmetry of the cylinder. The model was constrained in y-direction at the mid-transverse section, to prevent rigid body motion of the cylinder (Fig. 2(c)). The pressure loading was applied at the inner wall of the cylinder. The true stress-strain curve of the material (Fig. 4) was defined in ANSYS, by using the Multilinear kinematic hardening material model [10]. The elastic-perfectly plastic model, which neglects the strain hardening effect was also defined, in a similar manner. The geometric nonlinearity option was included in the model, to account for the large deformations that can occur during the full plastic yielding of the cylinder wall. The material nonlinearity option was also included, to account for plasticity in the post-yield regime. The von-Mises yield

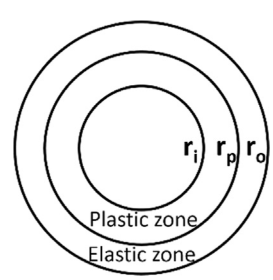

Fig. 1. Cylinder with elastic and plastic zones.