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Investigation of the effects of perturbation forces to buckling in internally pressurized torispherical pressure vessel heads

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ABSTRACT

The object of this paper is to investigate the effects of perturbation forces to buckling in pressure vessel heads. The pressure vessel heads in concern are confined to torispherical geometry with thin walls. Perturbation forces can alter not only the critical load for buckling but the buckled shape as well. In this paper in addition to previously used perturbation model, three more different perturbation force configurations are applied to the knuckle of the vessel. Internally pressurized three-dimensional torispherical pressure vessel head model that is previously used in literature is constructed and finite element program ANSYS Workbench is used for the solutions. First of all eigenvalue solutions are performed for each model. Then nonlinear instability solutions are conducted to obtain more realistic instability pressure values. For the nonlinear analyses not only large deformation static analyses but also large deformation transient analyses are conducted. For nonlinear analyses, perfectly plastic material model is used. It is concluded that instability pressures obtained by transient analyses are closer to plastic pressure values by PWC and ASME TES criteria and perturbation models increase instability pressure and equivalent plastic strain values.

1. Introduction

Thin-walled torispherical pressure vessel heads are widely used in industry. Buckling is one of the major problems that a designer has to deal with during the design process of these thin-walled structures in which structural members collapse under compressive loads greater than the material can withstand. Due to the existence of unstable post-buckling behavior, torispherical pressure vessel heads are sensitive to small geometric or load imperfections. Finite element analysis is widely used in the design of these structures [1,2].

Extensive studies are presented on the buckling of pressure vessels. Khan et al. presented an experimental technique for the buckling test of shells under external pressure to determine buckling load [3]. Miller worked on buckling criteria for torispherical heads under internal pressure which are especially outside the limits of ASME codes [4].

Some of the previous works deal with elastic analysis of pressure vessel components. According to limit analysis theorems, the elastic compensation method (ECM) can obtain both upper bound and lower bound limit loads. Though the upper bound limit load given by the ECM is more accurate than the lower bound limit load [5], the lower bound limit load is safer. Yang et al., proposed modified elastic compensation method (MECM) to improve the precision of the elastic compensation method (ECM) [6]. MECM can provide a good estimation of plastic limit loads for complex structures.

Athiannan and Palaninathan's study concerns experimental studies on buckling of thin-walled circular cylindrical shells under transverse shear. The buckling loads are also obtained from finite element models and empirical formulas and codes are compared [7]. Li et al. made an investigation of structures to identify and characterize the condition of gross plastic deformation in pressure vessel design by analysis. Limit analysis and bilinear hardening plastic analysis is performed. A criterion of plastic collapse based on the curvature of the load–plastic work history is proposed [8].

Muscat et al. proposed a criterion for evaluating the critical limit values and determining the plastic loads in pressure vessel design. The proposed criterion is based on the plastic work dissipated in the structure as loading progresses and can be used for structures subject to a single load or a combination of multiple loads. The limit and plastic loads are determined purely by the inelastic response of the structure and are not influenced by the initial elastic response [9]. Blachut's study provides results of a numerical and experimental investigation into static stability of externally pressurized layered hemispherical and torispherical domes. Buckling/collapse tests are also conducted on domes from various materials [10].

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In pressure vessel design, it is required to satisfy certain criteria related to failure modes. In general, the fundamental failure mechanism related to static loading is denoted as gross plastic deformation (GPD). PD5500 Unfired fusion welded pressure vessels [11], ASME Boiler and pressure vessel code Sections III and VIII [12] and EN13445-3:2002 Unfired pressure vessels [13] codes specify two different approaches to the designer. The most commonly used method is based on linear elastic stress analysis of the vessel. GPD failure is related to the primary stress category, which is yield-limited to preclude failure due to this mechanism. The second method requires an inelastic analysis concerning post yield behavior to simulate the GPD mechanism. The GPD load is calculated directly from the inelastic analysis. In EN13445 regulations, this method is called as "the direct route". Mackenzie et al. made an extensive review on the descriptions of the code contents [14]. The ASME Twice Elastic Slope (TES), criterion uses an empirical procedure for calculating collapse loads in experimental stress analysis of pressure vessels [12].

In Mackenzie et al.' study, plastic collapse or gross plastic deformation loads are evaluated for two sample torispherical heads by 2D and 3D FEA based on an elastic-perfectly plastic material model [14]. They considered small and large deformation effects and the geometry and load perturbations. Their study contains the formation of the gross plastic deformation mechanism in the models in relation to the elastic–plastic buckling response of the vessels. In their study both ASME TES and plastic work criteria (PWC) are considered. The PWC criterion requires a plot of load against normalized load–plastic work curvature.

The object of this paper is to investigate the effects of perturbation forces to buckling in pressure vessel heads. Internally pressurized three-dimensional torispherical pressure vessel head model that is previously used in literature is constructed and finite element program ANSYS Workbench is used for the solutions. Four different perturbation models are set up to investigate the effects of perturbation forces to buckling. As a first step, linear buckling analyses are conducted prior to solving the nonlinear buckling shapes to understand the effect of perturbation models to the deformation modes of the geometry in concern. Consequently, nonlinear instability analyses are performed for each perturbation model. Two types of nonlinear analyses are conducted. These are large deformation static analysis and transient analyses. Elastic perfectly plastic material model is used for all nonlinear analyses. The pressure vessel head model is assumed to have no initial shape imperfections.

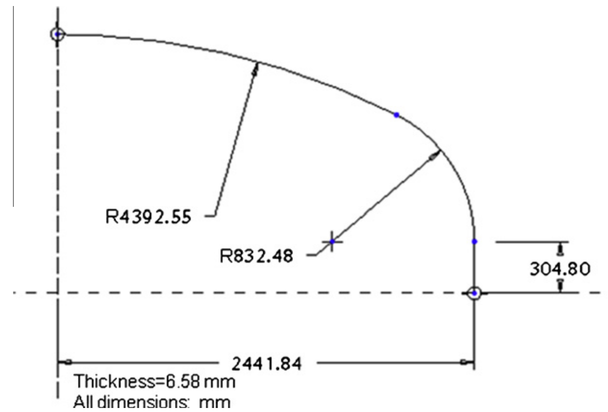

Fig. 1. Torisperical head geometry.

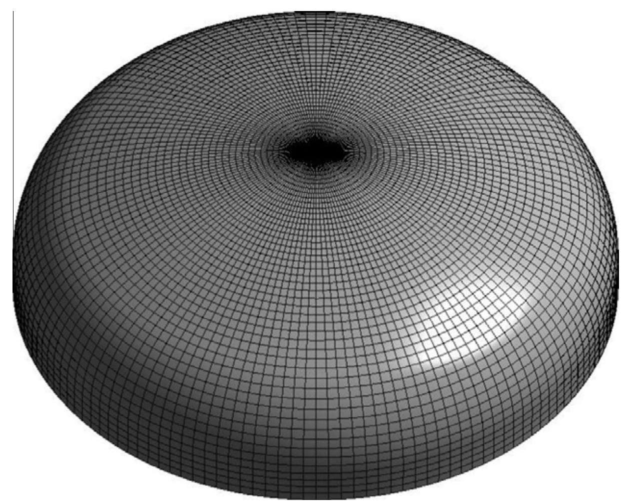

Fig. 2. Finite element model.

Table 1
Material properties of torispherical pressure vessel head.

Young's modulus (GPa)	Yield strength (MPa)
200	353

2. Finite element model

2.1. Geometry

For the analyses of a thin wall torispherical head, the same geometry investigated previously by Miller et al. [15] and Galletly and Blachut [16] and Mackenzie et al. [14] is considered. The geometry of torispherical head is given in Fig. 1.

2.2. Finite element mesh

Ansys Workbench version 12 is used for the finite element analyses [17]. In the finite element mesh 4-noded SOLSH190 solid shell element with shell option is used for simulating torispherical head. SOLSH190 element can be used for a wide range of thickness from thin to moderately thick geometry (supports Mindlin-Reissner shell theory).

The element has plasticity, hyperelasticity, stress stiffening, creep, large deflection, and large strain capabilities. The element formulation is based on logarithmic strain and true stress measures. Each complete model is 3D and consists of 8672 elements as shown in Fig. 2.

2.3. Material properties

Material properties used in static analyses are given in Table 1. For large deformation static and transient analyses elastic perfectly plastic material model is used.

2.4. The loading and boundary conditions

The bottom free face of torispherical head is subjected to frictionless support boundary condition. As loading condition different values of pressures are applied to crown, knuckle and cylinder regions. The graph of these pressures is presented in Fig. 6.