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A study of development mode of collapse with variation of strains and stresses during compression of metallic shells having dome-cone shape

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ABSTRACT

The present paper deals with the experimental and computational analysis of the deformation behaviour of the metallic thin walled aluminium shells having dome-cone combined geometry. The specimens were tested on a universal testing machine INSTRON under axial compression to identify their modes of collapse and to study the associated energy absorption capacity. In experiments all the shell specimens were found to collapse with the formation of an axisymmetric mode of collapse due to development of the associated plastic Zones in dome and cones.

A Finite Element computational model of development of the axisymmetric mode of collapse is presented and analysed, using a non-linear finite element code FORGE2. The proposed finite element model for this purpose idealizes the deformation as axisymmetric. Six noded triangular elements were used to discretize the domain. The material of the shell specimens was idealized as rigid visco-plastic. Experimental and computed results of the deformed shapes and their corresponding load-compression and energy-compression curves were presented and compared to validate the computational model. Typical variations of equivalent strain, equivalent strain rate and nodal velocity distribution are presented to help in predicting the mode of collapse. On the basis of the obtained results development of the axisymmetric mode of collapse has been presented, analysed and discussed.

1. Introduction

Metallic shells are often employed as energy absorbing elements to safeguard the passengers inside the road vehicle, railway coach, aircraft and ship. These shells include single geometry shells and sometimes combined geometry shells. The main aim is to protect these structures from serious damages while subjected to impact load in event of an accident. These metallic shells may have different shapes which include; cylindrical, spherical and conical. The combined geometry metallic shells may have combinations of spherical, cylindrical and conical shapes. Such combined geometry shells are also widely employed in different structures which include the nose-cone of aircrafts and projectiles and the shape of fuel and gas tanks and pressure hulls. The energy absorption characteristics of combined geometry shells can be customized by choosing a suitable combination of geometrical shape and lie in the crushing behaviour of their constituents. During the impact these shells are deformed with plastic regions and different modes of collapse. Each mode of deformation develops with an independent mechanics and has its own associated energy absorption capability. These modes of deformation depend on many process parameters. In general these parameters are history of loading, geometrical parameters and material properties. In the past few decades, special effort has been spent, on experimental [1,11,12,3,4], analytical [9,13] and numerical [1,10,7,8] research to establish understanding on mechanics of deformation of shells and their associated energy absorbing capacity. Mamalis et al. [10] and Gupta [5] presented experimental and numerical studies on collapse of metallic cones having different geometrical properties. The true modes of deformation obtained during experiments were compared with the computed ones and found in good agreements. Both true and computed load-compression and energy-compression curves were also comparable. For numerical investigations Mamalis et al. [10] employed LS-DYNA finite element code while Gupta [5] used FORGE2. Gupta et al. [3,4] studied the collapse of metallic conical shells and domes by conducting experiments and numerical investigations. The shells and domes were axially compressed with a quasistatic and impact loading. The mechanics of collapse of metallic hemispherical domes was also experimentally and numerically studied by compressing them with a cylindrical mandrel [8] and a flat plate [8] in the past. They found that the thick domes were collapsed by development of axisymmetric while thin domes by non-axisymmetric mode

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of deformation. For numerical investigations they employed FORGE2 finite element code. They also found that the true collapse modes were comparable with the computed ones. Numerically obtained load-compression variations also matched well with the experimental load-compression curves.

From the previous research it is clear that a good number of research articles are available which covers the investigation of collapse of cones and domes. But, hardly any study is available which covers the collapse behaviour of shells having combined geometry of dome and cone subjected to axial compression.

It is also clear from the literature that the finite element method has been reached to the state maturity and capable to simulate the large deformation problems. In this paper an attempt has been made to numerically simulate the collapse behaviour of metallic shells having cone-dome geometry using the finite element method. The computational model has been validated to compare its findings by performing an experimental study also. The mechanics of development of mode of collapse of the shells is also addressed with the help of experimental and numerical findings.

2. Experiments

Specimens having dome and cone combined geometry were made from commercially available aluminium sheets of thicknesses 3 mm, 3.5 mm and 4 mm. After procuring the specimens their wall thickness and the other dimensions at different locations were measured. Fig. 1 shows the geometrical details at key points of the representative specimens DC1 (see Table 1). These specimens were tested after annealing. The annealing of the specimens was done by soaking them at 300 °C for 60 min, and allowing them to cool in the furnace gradually for 24 h. An INSTRON universal testing machine of 250 t capacity was employed for experimentation. Specimens were centrally positioned on the bottom platen of the machine with crown of the dome touching the top platen of the machine. The upper platen was moved at a constant downward velocity of 10 mm/min. The load-compression curves were recorded with the automatic recorder of the machine. The deformed shapes of the specimens at different stages of the compression process were photographed. It was observed that during the whole collapse process the mode of deformation was axisymmetric for all specimens. Fig. 2 depicts the photographs of the development of the mode of collapse at few key stages. It is very clear that the mode of collapse remains axisymmetric throughout its development process. The corresponding experimental load-compression and calculated energy-compression curves for these specimens are presented in Figs. 3(a) and (b) respectively. Energy-compression variations are obtained by integrating the load-compression curves.

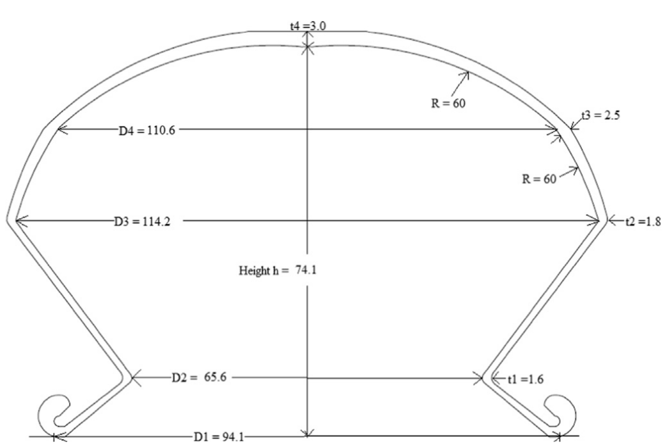

Fig. 1. Typical dimensions of a specimen DC1.

3. Computational study

3.1. Governing equations

Finite element formulations for non-linear problems of plasticity are classified into solid formulations and flow formulations. In the flow formulation which is employed here, the elastic components of strain are neglected as small compared to their plastic counterparts. An updated Lagrangian reference system is employed wherein the velocities are considered as the basic unknowns and the incompressibility condition is incorporated using a penalty function. The overall deformation is analysed in terms of a large number of deformation steps. Linearised relationship between the stress and strain rate is assumed to exist during each step and a quasi-steady state is assumed for each incremental solution. The computational procedure is linked to a re-zoning procedure.

Each deformation step is treated as a boundary value problem. At the beginning of a given step, the problem domain Ω (i. e. the volume occupied by the deforming specimen), the state of inhomogeneity and the values of material parameters are supposed to be given or determined already. The velocity vector $\tilde{\nu}$ is prescribed on a part of surface S_V together with traction on the remainder of surface S_f. Solution to the incremental problem at any given time provides the velocity and stress distributions that satisfy the governing equations in the body as well as boundary conditions on the surface. The material is assumed as homogeneous, isotropic, incompressible and rigid visco-plastic. The details of formulations and solution technique can be found elsewhere [6]. The constitutive relation for such a material is given by the Norton-Hoff law as follows

$$\tilde{S}_{ij} = 2K\,(\sqrt{3}\dot{\bar{\varepsilon}})^{m-1}\tilde{\dot{\varepsilon}}_{ij} \tag{1}$$

where $\dot{\bar{\varepsilon}} = \left(\frac{2}{3}\tilde{\dot{\varepsilon}}_{ij}\cdot\tilde{\dot{\varepsilon}}_{ij}\right)^{1/2}$, $\tilde{\dot{\varepsilon}}_{ij} = 1/2(v_{i,j} + v_{j,i})$

where $\tilde{S}_{ij}$, $\tilde{\dot{\varepsilon}}_{ij}$, K and m represents the components of the deviatoric stress tensor, strain rate tensor, material consistency and strain rate sensitivity index respectively. The v_i is the component of velocity in the direction "i" at any point of the problem domain. The incompressibility condition is written as below

$$\text{div}\,\tilde{\nu} = 0 \quad \text{over the problem domain } \Omega \tag{2}$$

where $\tilde{\nu}$ is the velocity vector at any point of the domain.

The material consistency K depends upon the thermo-mechanical condition of the material. For most metals, the behaviour of K can be approximated by means of the following multiplicative law:

$$K = K_o\,(1 + a\bar{\varepsilon})\,e^{\beta/T} \tag{3}$$

where K_0 is a constant, a is the strain hardening parameter, β is the temperature sensitivity term and T is the absolute temperature. The values of the parameters K_0, a, β and m can be found by conducting uniaxial tensile tests at different strain rates and temperatures. By suitable choice of these parameters, Eqs. (1) and (3) can approximate the mechanical behaviour of most of the metals at different temperatures and strain rate ranges. Since the compression was carried out at room temperature, the constitutive equation for uniaxial case gets the form as follows

$$\bar{\sigma} = K_{ot}(1 + a\bar{\varepsilon})\dot{\bar{\varepsilon}}^{m} \tag{4}$$

where $\bar{\sigma}$ is the equivalent stress for uniaxial case and $K_{ot} = K_o\,(\sqrt{3})^{m+1}\,e^{\beta/T}$

The friction between the workpiece and the tool is modelled with a viscoplastic law

$$\tau_f = -\alpha\,K_o(1 + a\bar{\varepsilon})\,\dot{\bar{\varepsilon}}^{m}\,\tilde{\nu}_f\,\|\tilde{\nu}_f\|^{p-1} \tag{5}$$

where ||.|| indicates the norm of a vector, $\tilde{\nu}_f$ is the sliding velocity between tube and platen, α is the friction factor and p is a material parameter whose value is often taken equal to m. During the