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Energy dissipation in thin metallic shells under projectile impact

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ABSTRACT

The ballistic performance of hemispherical aluminium shells was studied and the energy absorption in different modes of deformation has been computed. The experiments were performed wherein blunt and ogive nosed steel projectiles of 19 mm diameter were fired on 0.7–1.5 mm thick 1100-H12 aluminum hemispherical shells of different effective spans. The mechanics of deformation and energy absorption capacity was found to be significantly influenced by the shell thickness and projectile nose shape. The ogive nosed projectile caused failure through perforation by petal formation. Against blunt nosed projectile, however, the shells underwent significant dishing and reverse bending and thus defeated the projectile by dissipating its energy in global plastic deformation. The experimental findings were reproduced numerically on ABAQUS/Explicit finite element code. The numerical results were further employed for the computation of plastic strain energy in stretching in polar, radial, elevation and shear directions of the shell in order to eventually extract the total energy absorbed in plastic deformation. For a given span diameter and thickness of shell, the energy dissipation was found maximum in shear stretching while it was minimum in polar stretching of the material.

1. Introduction

Thin-walled shell structures including automobiles, aircraft, floating vessels and submarines experience low to high intensity of loading during their service life and offer substantial resistance due to their significant reserve strength and predominant membrane action. However, the localised impact loading upon these structures could be highly critical as a matter of their low flexural rigidity and small transverse stiffness.

Thin cylindrical and spherical metallic shells have been studied under different conditions of quasi-static loading (Johnson and Reid, 1978) and the results with respect to their geometry (Updike, 1972; Thomas et al., 1976; Watson et al., 1976a, 1976 b; De Oliveira and Weirzbicki, 1982; Gupta and Gupta, 1993; Gupta et al., 1998, 1999), material characteristics (Watson et al., 1976b) and support conditions (De Oliveira and Weirzbicki, 1982) have been shown to have significant influence on both axisymmetric and transverse modes of deformation and eventually the energy absorption capacity.

When the rate of loading is increased beyond a certain limit ($10\ s^{-1}$), the deformation becomes highly localised, and the material behaviour becomes strain rate and temperature dependent. The dynamic response of the metallic shells, especially under projectile impact, has been rarely exploited in the open literature (Corbett et al., 1996). Moreover, the available studies on this subject are confined to (radial) impact on cylindrical shells. Ma and Stronge (1985) studied the effect of filling medium (air, water and sand) on the ballistic response of thin (1.2, 2.1 and 3.3 mm) mild steel tubes impacted radially by hardened steel spheres and observed that the density of filling medium improves the wall stiffness (for local dishing) and hence the ballistic limit. The thinning of the contact region, in contrast, was found to be insensitive to the density of filling medium. Palomby and Stronge (1988) studied the permanent transverse deformation of thin (1.2 and 2.0 mm) cylindrical shells against projectile impact. The deformation was of elliptical shape with major axis directed along the generators and an increase in the magnitude and extent of deformation with increase in projectile velocity until ballistic limit and subsequent decrease with further increase in velocity was also noticed. The deformation has also been seen to decrease with increase in the nose radius of the impacting projectile.

The response of annealed tube, cold drawn tube and welded seamed tubes was explored by Corbett et al. (1990). The minimum perforation velocity of annealed tubes decreased consistently with

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Table 1
Material parameters for 1100-H12 aluminium target (Gupta et al., 2006).

Modulus of Elasticity, E (N/mm^2)	65,762
Poison's Ratio, ν	0.3
Density, ρ (kg/m^3)	2700
Yield Stress, A (N/mm^2)	148.361
B (N/mm^2)	345.513
n	0.183
Reference Strain Rate, $\dot{\varepsilon}_0$ (s^{-1})	1.0
C	0.001
m	0.859
T_{melt}(K)	893
T_0 (K)	293
Specific Heat, C_p(J/kg-K)	920
Inelastic heat fraction, α	0.9
D_1	0.071
D_2	1.248
D_3	−1.142
D_4	0.147
D_5	0.0

increase in nose radius of projectile from 12.7 mm to ∞ (flat nose) while for as-received tubes it has been found to be dependent upon the wall thickness. The cold drawn tubes deformed in brittle manner under static and dynamic perforation tests with identical perforation energies and oval shaped indentation that was confined to three to four punch diameters against hemispherical tipped indenter. However, the welded seamed tubes experienced more ductile and rate dependent deformation and their critical perforation energies were over three times higher when loaded statically as opposed to dynamically.

The deformation of plate backed tube and simply supported tube was explored by Zhang and Stronge (1996). The plate backed tubes exhibited two stages of deformation (crumpling and bending) while the simply supported tubes experienced three stages deformation (crumpling, bending and perforation). An analogy between transverse deflection of beam on foundation and radial deflection of tube was proposed by Zhang and Stronge (1996) to predict plugging phenomenon and ballistic limit of rigid plastic tubes assuming that the perforation occurs when shear deformation in contact region reaches a critical value. The proposed model estimated the ballistic limit of mild steel tubes of various thicknesses within 3–28% of experimental results (Palomby and Stronge, 1988; Corbett et al., 1990). The model was further employed (Zhang, 1998) for predicting minimum speed for rupture in 3.46 mm thick mild steel tubes against 41 g flat nosed projectile at varying angles of obliquity. It reproduced the same with an error of 13% for 0°, 26% for 60° and almost exactly for 45° obliquity in comparison to the actual results (Zhang and Stronge, 1998). It was observed that the minimum speed for rupture decreased with increasing angle of incidence until 45° and then it increased with further increase in the angle; in confirmation to experimental results.

The mechanics of deformation in spherical shells is more complex due to their doubly curved structure and these are relatively unstable and prone to buckling under concentrated loading. The complex doubly curved geometry of spherical shells however enhances their utility for structural and mechanical applications. A theoretical relationship between permanent central deflection and initial impact energy on non-axisymmetric deformation of spherical shell under rigid plastic assumption was established based by Zhong and Ruiz (1990). The missile was assumed to have flat nose and its diameter was small enough not to give rise to either perforation or buckling of the shell. The model broadly estimated the deformation in thin shells between 65 and 80% accuracy for a range of incidence velocity (20–300 m/s) and mass of projectile (10–300 kg). The deformation of spherical shell against blunt nosed cylinder was studied by Ning et al. (2006) by introducing an isometric transformation of the surface bending and employing Perzyna-Symonds constitutive equations for deriving rigid viscoplastic hardening, rigid viscoplastic and rigid plastic solutions. The theoretical variation of dimple radius with incidence velocities using rigid plastic solution was found to have best agreement with the experiments. The dimple radius as well as central deflection of the shell was found to increase with increase in the initial projectile velocity and curvature of shell and decreased with increase in the shell thickness. Surprisingly, the behaviour of spherical shells has been very less studied under high rate of deformation in spite of their significant practical utility in structural systems such as protective helmets, pressure vessels and aircrafts and their susceptibility to such events.

The present study explores the impact response of thin hemispherical shells of 1100-H12 aluminium alloy by studying the effect of its span diameter, thickness and shape of indenter on the ballistic resistance and energy dissipation in different modes of plastic deformation. The ballistic experiments have been carried out wherein hemispherical shells of span diameter 68, 100, 150 and 200 mm and thickness 0.7, 1 and 1.5 mm were impacted by 19 mm diameter ogive and blunt nosed steel projectiles at normal incidence. Against ogive nosed projectile the shell experienced perforation by petal formation and hence its perforation resistance was estimated by obtaining ballistic limit, V_{50}. Against blunt nosed

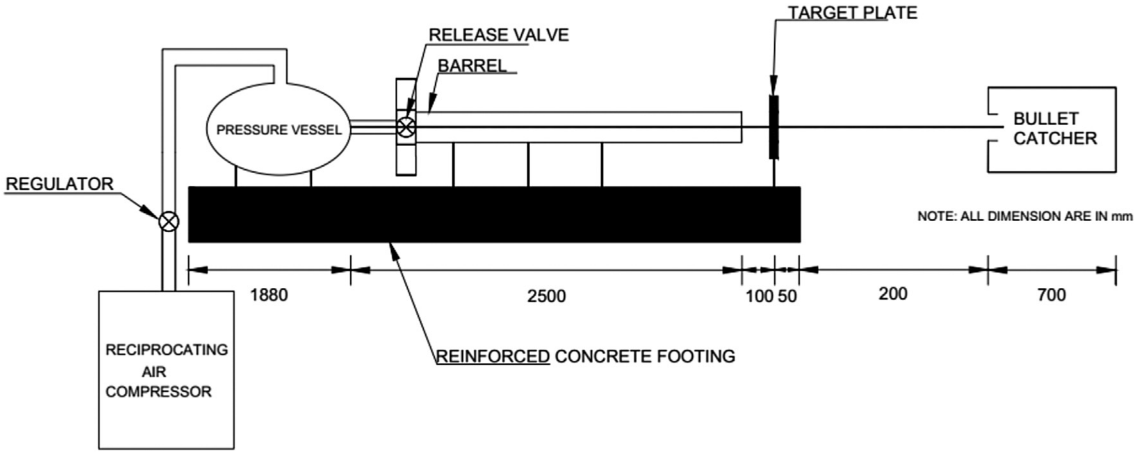

Fig. 1. Schematic of experimental set up.