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Crushing and energy absorption characteristics of combined geometry shells at quasi-static and dynamic strain rates: Experimental and numerical study

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ABSTRACT

The quasi-static and dynamic crushing response and the energy absorption characteristics of combined geometry shells composed of a hemispherical cap and a cylindrical segment were investigated both experimentally and numerically. The inelastic deformation of the shells initiated with the inversion of the hemisphere cap and followed by the axisymmetric or diamond folding of the cylindrical segment depending on the loading rate and dimensions. The fracture of the thinner specimens in dynamic tests was ascribed to the rise of the flow stress to the fracture stress with increasing strain rate. The hemisphere cap absorbed more energy at dynamic rates than at quasi-static rates, while it exhibited lower strain rate and inertia sensitivities than the cylinder segment. For both the hemisphere cap and the cylinder segment, the inertial effect was shown to be more pronounced than strain rate effect at increasing impact velocities.

1. Introduction

The combined geometry shells with the combinations of such as cylindrical, spherical and conical shapes are widely employed in engineered structures, the examples of which may include the nose-cone of aircrafts and projectiles and the shape of fuel and gas tanks and pressure hulls. The superior energy absorption characteristics of combined geometry shells lie in the crushing behavior of their constituents. These structures crush progressively, mostly in planar form, under static and dynamic compressive loads, leading to relatively high efficiency of the conversion of kinetic energy into irreversible plastic deformation energy. Determination of the crushing mechanisms and energy absorption characteristics of these structures under various loading conditions and deformation rates are important to assure the required protection level by energy absorption without any damage on the protected structures.

One of the earliest studies on the thin-walled cylindrical tubes was performed by Alexander [1]. Alexander proposed an analytical model for predicting the average axisymmetric crushing loads of thin-walled tubes. The tubes with low D/t ratios (diameter/wall-thickness) and rigidly perfectly plastic materials tend to exhibit axisymmetric mode (concertina) of deformation [2], while the tubes with high D/t ratios and strain hardening materials exhibit asymmetric mode (diamond) of deformation [3]. The effect of foam-filling and end-constraining on the crushing behavior of thin-walled tubes has been investigated widely, the examples of which include Santosa et al. [4], Güden and Kavi [5] and Singace and El-Sobky [3]. A coupled experimental and numerical study on the quasi-static crushing of tubes was performed by Taşdemirci [6]. The crush behavior of segmented thin-walled tubes was investigated in a recent study by Shahi and Marzbanrad [7]. Updike [8] investigated large compression deformation of a rigid-plastic spherical shell and proposed an analytical model relating the crushing force to the deformation. De Oliveira and Wierzbicki [9] derived closed form solutions for conical and spherical shells subjected to point and boss loading. The solutions were reported valid until the crush distance reached the spherical shell radius. Gupta et al. [10] investigated the buckling of thin spherical shells under axial loads. The deformation history of thin spherical shells was divided into three modes distinguished in the load-deformation history as the decreasing slopes; local flattening, axisymmetric inward dimpling, and asymmetric lobe formation. Quasi-static and dynamic crushing and deformation behavior of metallic spherical shells were investigated by Gupta and Venkatesh [11], Gupta and Gupta [12] and Gupta et al. [13] for different loading rates. The collapse behavior of the arrays of ping-pong balls were investigated both experimentally and numerically by Ruan et al. [14], Dong et al. [15], and Bao and Yu [16].

Although, there have been quite many studies on the static and dynamic crushing behavior of tubes, spheres, hemispheres, and cones, few examples of which are broadly outlined above; there have been few experimental and numerical studies in the

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literature on the static and dynamic crushing of the combinations of these geometries. Ghamarian and Abadi [17], Ghamarian et al. [18] and Ghamarian and Zarei [19] investigated the energy absorption characteristics of empty and foam-filled circular and conical end-capped tubes and showed that the absorbed energy increased with increasing impact velocity. Gupta [20] investigated the static deformation behavior of tube-frusta combined geometry experimentally and numerically. The mode of collapse was observed by a development of one concertina fold and followed by a plastic zone. Ghamarian et al. [21] used shallow spheres as end-cap in conical tubes. The crush force efficiency and absorbed energy was reported to increase with increasing shallow spherical cap radius. Shojaeefard et al. [22] studied the quasi-static crushing behavior of combined cylindrical and square section tubes and showed that the absorbed energy of the combined tubes was slightly higher than both square and circular tubes of the same length.

The aim of the current study is to determine both experimentally and numerically the energy absorption characteristics and crushing behavior of the combined geometry shells (hemispherical cap and cylindrical segment) at quasi-static and high strain rates. This study is a part of an experimental and numerical work on the investigation of the use of combined geometry shells in the structures designed specially against blast and impact loading. The consistency between the experimental and numerical results showed that the numerical methodology followed in this study can further be used to predict the deformation modes and energy absorption behavior of sandwich structures.

2. Experiments and modeling

2.1. Materials and testing

The investigated non-standard size combined geometry shells were prepared by deep-drawing 0.5 and 1 mm thick AISI 304L stainless steel sheet blanks between punch and die. The tooling for the deep-drawing process was machined locally for the present study. The edge of the deep drawn cylindrical segment on the bottom side formed during the forming process was trimmed by a cutting tool on a CNC lathe. The prepared specimens of various configurations commonly consisted of a hemispherical cap and a cylindrical segment. Four different combined geometry shell configurations were tested and modeled. The coding of the configurations is as follows: S1X, S2X, B1X and B2X. The first letters, S and B, refer to the sample's radius. The samples 15 mm in diameter are coded as S (small) and the samples in 25 mm diameter as B (big). The pictures of prepared small and big radius combined shells are shown in Fig. 1. The numbers after the first letters, 1 and 2, refer to the sample thickness of 0.5 and 1 mm, respectively. The last number in the coding, X, represents the type of the test applied. The quasi-static test is coded as 1 and drop-weight test as 2. The code of B12, for example, refers to a sample with 12.5 mm diameter and 0.5 mm thickness, tested in drop-weight.

The tested drawn combined geometry shells are noted to show variations in wall thickness due to the nature of applied deep drawing process, which stretches the blanks over the die surface at the edges inhomogeneously. To assess the wall thickness variations in the section walls, the applied deep drawing process was simulated in LS-DYNA 971 and the resultant thickness variations were assessed numerically. The numerically determined thicknesses were then compared with the experimentally measured thicknesses on the shell wall segments.

For the numerical model of the applied deep-drawing process, the elastic and plastic deformation behaviors of as-received AISI 304L stainless steel sheets were determined at quasi-static and high strain rates. The quasi-static tension tests were performed in accord with ASTM E8M-04 standard at the strain rates of 10^{-3}, 10^{-2} and $10^{-1}\,s^{-1}$ using a Shimadzu universal test machine and high strain rate tension tests were conducted in a tensile Split Hopkinson Pressure Bar (SHPB) at the average strain rates of 1100 and 1400 s^{-1}. The details of the used 316L stainless steel bar tensile SHPB and the methodology of extracting material constitutive equation are given elsewhere [23]. The axial displacements of quasi-static test specimens were recorded using a video extensometer, while a high speed camera was used to monitor the deformation during the SHPB tension tests. Typical quasi-static and high strain rate true stress-true plastic strain curves of AISI 304L stainless steel are shown in Fig. 2. The tested stainless steel shows a strong strain rate dependent flow stress as seen in Fig. 2. The yield stress increases from about 230 MPa at quasi-static strain rate to about 475 MPa at high strain rate. The fracture strain is also found strain rate dependent; the fracture strain decreases from about 0.6 at quasi-static strain rate to about 0.3 at high strain rate. As elaborated in detail in the modeling section, a constitutive model incorporating the effect of strain rate on both strength and failure strain was used in the simulations.

In the quasi-static compression testing ($1 \times 10^{-3}\,s^{-1}$) of the combined geometry shells two different cross-head speeds were implemented: 13 mm-high combined geometry shell specimens were compressed at a cross-head speed of 0.78 mm min^{-1}, while 23 mm-high specimens were compressed at a cross-head speed of 1.38 mm min^{-1}. Low velocity impact tests were conducted in a Fractovis drop-weight tower (Fig. 3). The main constituents of the drop-weight tester include striker holder, striker weights and striker tip. The striker was attached to a 90 kN strain-gaged sensor. The tests were conducted using a flat end striker tip and the striker velocity

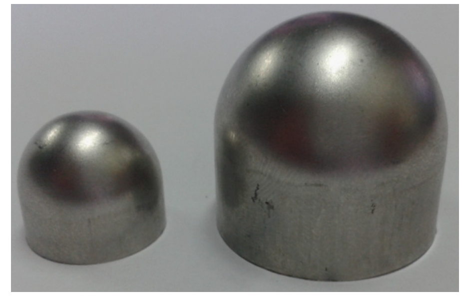

Fig. 1. Small and big radius combined geometry shells.

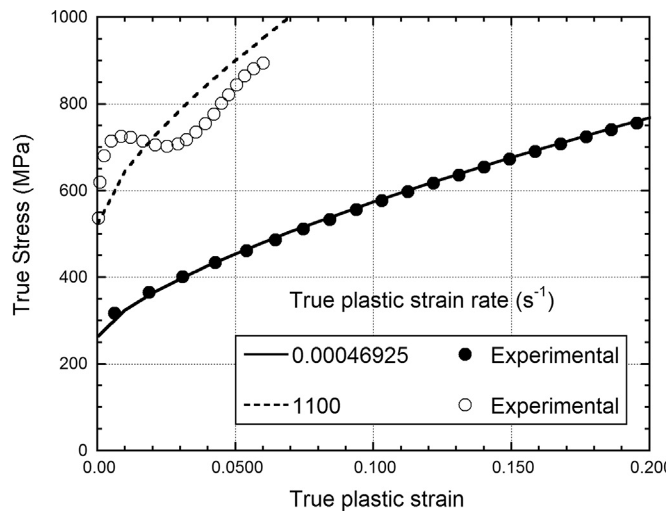

Fig. 2. Experimental tensile stress–strain curves of AISI 304L steel at quasi-static and high strain rates and corresponding Johnson–Cook model fits.