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Experimental and numerical investigations into collapse behavior of hemispherical shells under drop hammer impact

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ABSTRACT

Dynamic response for a series of cylindrical shells filled with water were discussed previously, which indicated that the limit buckling load of the cylindrical shells was greatly improved by the presence of water. To obtain a good protective structure, a double layered liquid-filled hemispherical shell structure is designed. Three kinds of structures (single layered empty hemispherical shell, double layered empty hemispherical shells, and single layered liquid-filled hemispherical shell) are compared with the double layered liquid-filled hemispherical shells. The collapse behavior of four kinds of hemispherical shell structures and their deformation modes under drop hammer impact are presented to investigate the effects of inner water on the response of the liquid-filled hemispherical shells. Test results show that the effects of inner water mainly include "distributing loadings" and "ironing effect". Double layered liquid-filled hemispherical shells have the highest bearing capacity among all four kinds of structures. Three-dimensional numerical simulations of all the tested specimens were carried out using ANSYS and LS-DYNA. Under same impact condition, the effective protection space of empty hemispherical shells is very small due to its larger vertex displacement. In terms of generalized specific energy absorption (η) of structures with same vertex displacement, liquid-filled hemispherical shells are better than empty shells. For liquid-filled shells, η of double layered shells is smaller than single layered shell, but single layered shell has no inner space. Parameter analysis indicates that only the outer thickness has a significant effect on the impact force. Increasing the outer thickness and ensuring a reasonable distance between the inner and outer shell can improve the crashworthiness of double layered liquid-filled shells and protect the internal objects.

1. Introduction

Thin-walled hemispherical shells have been widely used in various engineering fields, e.g., aviation, navigation, machinery, chemical industry, and construction, because of intrinsic properties and excellent energy-absorbing capacity of such structures. Hemispherical shell has high bearing capacity, but the thin wall makes it easy to lose stability. Therefore, the deformation modes of hemispherical shells have gotten much attention from many researchers and engineers.

A majority of both theoretical and experimental studies of thin-walled hemispherical shells were focused on quasi-static deformation initially. Updike [1] first studied the problems of large deformation of a rigid plastic hemispherical shell compressed between two rigid plates. Three deformation stages were considered: the elastic deformation, the formation of axis-symmetric inward dimple, and the development of non-symmetric multiple lobes. An analytical model of the relationship between the axial crushing force and the max deformation of shell was also proposed, which is restricted to overall compression of deformation about one tenth of the shell radius. Pogorelov [2] proposed an approximate analytic model for the first axis-symmetric buckling transition by numerical integration of the complete set of shape equations. Gupta et al. [3,4] studied hemispherical shells with R/t ratios that range from 15 to 240, and developed an analytical model based on the energy dissipation. Nasto et al. [5] performed a hybrid experimental study of the localization of deformation in thin spherical elastic shells under indentation. They quantified how the formation and evolution of the localization in shells is affected by the indenter's curvature. Knoche and Kierfeld [6] offered an explanation of the secondary buckling transition, where the dimple loses its axis-symmetry, within continuum elasticity theory. Yang et al. [7] designed two loading mechanisms of

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Nomenclature

E	Young's modulus
E_t	shear modulus
H	striking height
M	striking mass
m	mass of outer shell
P	impact force
P_{max}	maximum impact force
P_m	mean impact force
R	radius of outer shell
R'	radius of inner shell
R/t	radius to thickness ratio of outer shell
t	thickness of outer shell
t'	thickness of inner shell
U	energy absorption
δ	compression displacement
δ_t	max compression displacement
Δ	depth of inward dimpling of outer shell
ν	Poisson's ratio
ρ	density
σ_0	yield limit
η	generalized specific energy absorption

hemispherical shells and proposed the fourth deformation stage: peripheral buckling and deformation.

In recent years, the behavior of spherical shells under dynamic loadings has been related to possible strain rate and inertia effects. Dong et al. [8] selected Ping pong balls as thin-walled spheres and presented experimental studies on the dynamic behavior of thin-walled spheres and sphere arrays in response to different impact velocity. The experiments were performed using a modified Split Hopkinson Pressure Bar (SHPB) test system. It illuminates that the deformation and buckling modes are sensitive to the loading rate. Karagiozova et al. [9] studied the deformation and snap-through behavior of a thin-walled elastic spherical shell impacted against a flat surface. They found the increase of the impact force is caused by both the inertia forces and deformation energy. Bao and Yu [10] studied collision and rebound behavior of ping pong balls on a rigid target. The effects of thickness-to-radius ratio, initial velocity, yield strain and coefficient of friction on the dynamic deformation features were discussed.

Numerical simulation, as an important method of scientific research, has been used to assist experimental and theoretical research decades ago. In 2004, Gupta et al. [11] presented an axis-symmetric model using Forge2 for axis-symmetric deformation mode of hemispherical shells only. And later in 2007 [12], he constructed a three-dimensional finite element model using shell elements in LS-DYNA, and simulated the non-symmetric deformation of hemispherical shells. Shariati and Allahbakhsh [13] carried out a series of numerical simulations to investigate the buckling of steel hemispherical shells under various loadings, such as a rigid flat plate, some rigid bars with circular, square and spherical cross sections, a rigid tube, a plate with a hole, and an indented tube. Dadrasi [14] studied the dynamic response and energy absorption of aluminum hemispherical shells under axial loading using non-linear finite element techniques. He proposed that energy absorption response was quantified with respect to variations in the parameter of wall thickness, shell diameter, impact mass and impact velocity.

Liquid-filled thin-walled structures, mainly cylindrical shells, were also be simulated by many researchers. Some researchers, such as Timm [15], used the classical Lagrangian formulation of Finite Element Method (FEM) to simulate the thin-walled liquid-filled structures. Jasion and Magnucki [16] studied elastic buckling of horizontal barreled shells filled with liquid. In their studies, the effect of liquid filled in structures is simplified as hydrostatic load applied to shell structures. Matura [17] investigated hypervelocity impact (approx. 3000 m/s) of spherical aluminum projectiles onto hollow aluminum cylinders with either water or sand filling, in which the Euler-Lagrange FV/FE simulations were performed with the commercial hydrocode ANSYS AUTODYN. Caleyron et al. [18] proposed a model based entirely on the Smooth Particle Hydrodynamics (SPH) method for the analysis of tanks under impact.

Although lots of researchers conducted detailed studies on the behavior of empty hemispherical shells or liquid-filled cylinders, but few of them studied on the liquid-filled hemispherical shells. In fact when the liquid is present, the bulk compression of liquid and its inertia will produce a high back-pressure on the wall of shell and change the resistance character of whole shell structures. Lu et al. [19–21] performed experiments and numerical simulations on the dynamic response for metallic cylindrical shells filled with water and discussed the effects of water filled in shells. Results indicated that the limit buckling load of a cylindrical shell was greatly improved with the presence of water.

To obtain a good protective structure, a double layered liquid-filled hemispherical shell structure is designed. Three kinds of structures (single layered empty hemispherical shell, double layered empty hemispherical shells, and single layered liquid-filled hemispherical

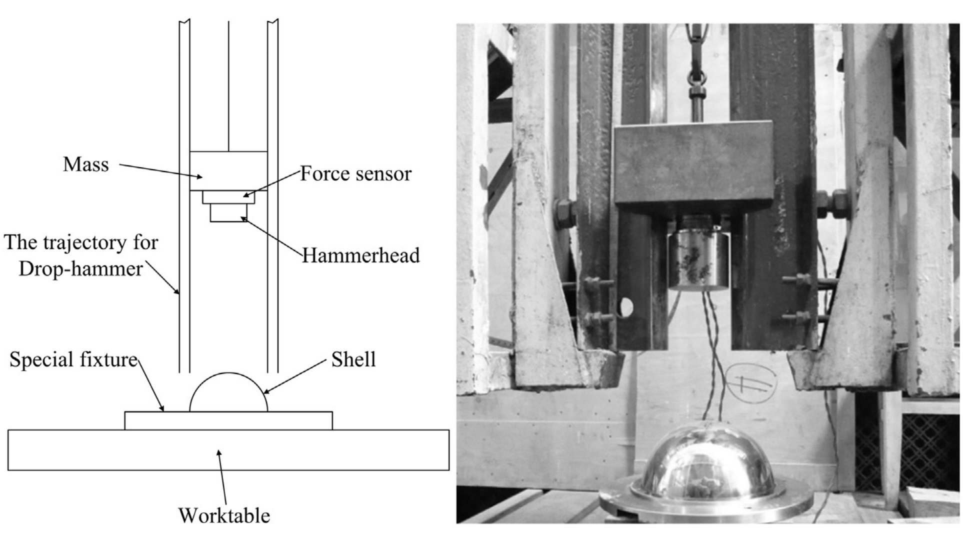

Fig. 1. Drop hammer setup.