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Buckling behavior of sandwich hemispherical structure considering deformation modes under axial compression

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ABSTRACT

Sandwich structures are often used in space and aviation industry as energy absorption elements due to their load carrying capacity and light weight features. In experiments, it has been found that sandwich hemispherical structures have two different deformation modes referred as dimpling and flat mode under axial compression load. Deformation modes exercise a great influence on load carrying capacity of sandwich hemispherical structure. In this paper, theoretical models for two deformation modes of sandwich hemispherical structures under axial compression have been proposed. The reason for two different deformation modes observed in the compression tests has been explained. A finite element model has been set up and validated by the experimental results. Based on the numerical simulation results, buckling behaviors, load carrying capacities and displacements of top points of two different deformation modes have been compared. It is found that the load carrying capacity of the sandwich hemispherical structure under dimpling mode is about half of that under flat mode with very similar configurations. The deformation mode can be changed from dimpling to flat by adjusting the thicknesses of the out and inner metal sheets. This is a feasible and efficient way to improve the load carrying performance of the sandwich hemispherical structure. The optimal thickness ratio range of out and inner metal sheets are proposed. The methods can help improve the design of sandwich hemispherical structures to obtain better load carrying capacity with reasonable configuration.

1. Introduction

A sandwich structure is a composite structure composed of two face sheets and a core which is bonded to the face sheets. Since the core material is usually much less dense than the face sheets, the sandwich structure offers a much higher stiffness to weight ratio than any comparable hell [1]. So sandwich structures are often used in space and aviation industry as energy absorption elements due to their good load carrying capacity. It is important to investigate the load carrying capacity for different deformation modes of these structures for structure design and performance improvement.

For single metal hemispherical shell, Updike and Kalnins [2] studied the deformation behavior of spherical shells compressed between two rigid plates. An approximate expression was proposed to predict the compressive force and displacement in 1972. Oliveira and Wierzbicki [3] studied the crushing behavior of a few kinds of rotationally symmetric plastic shells under single point load, uniform pressure and compression between two rigid plates. Hemispherical shell structures of mild and stainless steel with the radius-to-thickness-ratio ranging from 8 to 32 were tested and further analyzed by Kinkead et al. [4]. The expression of the rolling-plastic-hinge-radius was calculated based on the assumption that it was asymmetric about the vertical plane. Shariati and Allahbakhsh [5] investigated the buckling and post-buckling characteristics of steel hemispherical shells both experimentally and numerically. Besides the load and energy curves, rolling-plastic-hinge-radii of specimens with different sizes were also listed at various compressive displacements. Yu et al. [6] tested metal hollow balls compressed by two rigid plates to investigate the mechanical property of porous metal material. In their study, the compressive force was predicted by the expression based on the assumption of triangular load. Gupta et al. [7–10] tested aluminum hemispherical shell structures axially compressed by two flat plates through experiments, simulation and theoretical analysis. In their study, an analytical model was developed for the prediction of load-compression and energy-compression curves by using the concepts of stationary and rolling plastic hinges. Effects of different process parameters were pre-

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Nomenclature

E	Young's modulus of material, GPa	t	thickness of shell structure, mm
h	compressive displacement, mm	t_1	thickness of out metal sheet, mm
R	medium radius of metal sheet, mm	t_2	thickness of foam core, mm
R_1	medium radius of out metal sheet, mm	t_3	thickness of inner metal sheet, mm
R_2	medium radius of foam core, mm	x	distance from the hemispherical shell center to a certain position on the flat plain
R_3	medium radius of inner metal sheet, mm	ε_D	ultimate strain of foam
r	radial distance in the spherical coordinate system	ϕ_h	angle between the rotation axis and the horizontal circle related to compressive displacement
r_1	radial distance of out metal sheet in the spherical coordinate system	ϕ_x	angle between the rotation axis and the x-section
r_2	radial distance of foam core in the spherical coordinate system	θ	azimuthal angle in the spherical coordinate system of hemispherical shell structure
r_3	radial distance of inner metal sheet in the spherical coordinate system	σ_0	yield strength of material, MPa
r_h	radius of horizontal circle related to compressive displacement, mm		

sented and discussed through numerical simulation in the literature [9]. It was concluded that the height of the hemispherical shell structure and friction between the shell and flat plate influenced the collapse mode and energy absorbing capacity. Wang et al. [11] proposed a new description based on experimental observation for the evolution of rolling-plastic-hinge-radius to obtain the post-buckling behavior of hemispherical shell under axial compression between two rigid plates. The theoretical model can be used in prediction of post-buckling behavior for different deformation patterns in the asymmetric deformation stage.

For sandwich hemispherical structures, theoretical analysis accompanied by some simple experiments was the main way to investigate the deformation and buckling behavior of this kind of structures in early time. Lin and Popov [12] studied buckling pressures on sandwich structures made of thin aluminum face sheets with aluminum-alloy honey-comb cores. They found that all of the tested specimens buckled in the plastic range. The specimens withstood comparable buckling loads after the first buckling. Sharifi and Popov [13] used an incremental finite element (FE) approach to solve the nonlinear bending and buckling problems of axisymmetric sandwich structures. The elastic-plastic buckling behavior of sandwich cap was worked out to illustrate the application of their method. Mirmiran and Wolde-Tinsae [14,15] developed a nonlinear finite element model to investigate the stability behavior of a pre-stressed sandwich arch. The effects of various geometric, mechanical parameters and local modes of failure were excluded. Using the augmentation technique, post-buckling analysis was performed. Liu and Cheng [16] studied the non-linear buckling of spherical sandwich structures under the uniform edge moments. They solved the non-linear boundary value problem by using modified Newton-spline function method and obtained a more accurate analytical solution.

In recent years, numerical analysis on mechanical stability and dynamic response of curved sandwich structure were realized by some simulation software to obtain the deformation and buckling behavior so as to understand the phenomena more intuitively. Shen et al. [17] investigated curved sandwich panels under air blast loads experimentally. The effects of impulse, panel radius, face sheet thickness and core thickness on the blast resistance of structures were studied. The experimental results showed that the blast intensity, core thickness and face sheet thickness were the principal parameters responsible for the final deflection of the curved sandwich panels. Liu et al. [18] investigated the dynamic responses and blast resistance of all-metallic sandwich-walled hollow cylinders with graded aluminum foam cores, using finite element simulations. They found that the radial deflection of graded cylinders was smaller and the blast resistance superior to that of ungraded ones when subjected to identical air blast load. The influence of face-sheet arrangements was also investigated and the results indicated that the structure with thinner inner face-sheet was superior to that with thicker inner face-sheet. Ling et al. [19–22] investigated deformation/failure modes, blast resistance and energy absorption of metallic cylindrical sandwich structures with closed-cell aluminum foam cores. Results indicated that the deformation/failure, deflection response and energy absorption of sandwich structures were sensitive to the load intensity and geometric configuration. The shock resistance of sandwich structures could be enhanced significantly by optimizing their geometrical configurations; the thickness of back face-sheet has a greater contribution than that of front face-sheet. Wang et al. [23] evaluated the stability of the sandwich hemispherical shell via the sequential thermal-mechanical coupling finite element model. They found that the thermal stress generated from the low temperature load reduced the critical buckling load and changed the buckling modes of sandwich hemispherical shell. Qi et al. [24] used LS-DYNA to examine the dynamic response and protective performance of curved metallic sandwich panel subjected to air blast load. Based on artificial neural network (ANN) meta-models, multi-objective optimization designs of the panel were carried out. Li et al. [25] investigated the dynamic responses of metallic sandwich spherical shells with graded aluminum foam cores under inner blast load. They found the arrangement of the core layers with different relative densities had significant effects on the dynamic plastic responses of the spherical shells. Li et al. [26] found that the spherical sandwich structures had a better performance than that of the cylindrical sandwich hells in resisting the blast loads. Li et al. [27] analyzed the dynamic responses of a sandwich cylindrical shell system under internal blast load, which had graded aluminum tubular cores with different wall thicknesses. They found that the core layers, which had thickness-tapered arrangement from the inner to the out layer, were favorable for the energy dissipation and the out face-sheet deflection. Jin et al. [28] used a fluid model in combination with Abaqus/Explicit to investigate the effects of graded foam cores on the load of a sandwich spherical shell subject to underwater explosion from the inner side. Effects on energy absorption efficiency of core arrangements were discussed and an optimum solution was found out.

Sandwich hemispherical structures are often used as load carrying and energy absorbing components in aviation and space industry. Different from other studies focusing on the dynamic response