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Linear and nonlinear elastic buckling of stereolithography resin egg-shaped shells subjected to external pressure

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ABSTRACT

This study explored the elastic buckling of egg-shaped shells made of stereolithography resin. The shells had identical nominal geometry parameters with the thickness of 2 mm, the major axis of 232 mm, and the minor axis of 160 mm, respectively. Five near-perfect laboratory-scale models were fabricated using stereolithography appearance (SLA), a rapid prototyping technique. Each model was scanned by a three-dimensional optical scanner, measured using a micrometer, and tested in a pressure chamber. The buckling behaviours of egg-shaped shells with deterministic geometric imperfections were experimentally, analytically, and numerically analysed. The perfect egg-shaped shell was also compared with the fabricated egg-shaped models. A good agreement among them was obtained. The remarkable experimental results of egg-shaped shells were presented in this paper by using 3D printing technologies, which shows the high machining accuracy of 3D printing technologies and provides a new solution for the limitation of experimental study into non-typical shells of revolution. Also, the study could provide a new non-typical shell structure and its stability evaluation approach for space vehicles, pressure tanks, and pressure hulls.

1. Introduction

Thin-walled shells of revolution have received considerable attention for their application in engineering fields, such as space vehicles, pressure tanks, and deep-water pressure hulls. Conventional shells, such as those with a spherical, cylindrical, or conical shape, and unconventional shells, such as those with an ellipsoidal, parabolical, or hyperboloidal shape, have been explored for decades [1–6]. The buckling behaviours of these shells have been a focus of research and are of considerable significance for the stability of structures. However, such shells under external pressure can easily lose stability [7]; thinner shells tend to fail because of elastic buckling, whereas thicker shells fail largely because of plastic buckling [8]. The buckling regimes of shells can vary, mostly depending on the thickness-to-radius ratio.

Shells with a positive Gaussian curvature are generally accepted as a desired structure with a high load-carrying capacity. Substantial theoretical, experimental and numerical studies have been done to explore the buckling behaviours of these shells [9–14]. In particular, a spherical shell is an ideal solution because of the extremely efficient stress and strain distribution in its material [15–17]. Recently, Zhang et al. [18] carried out numerous hydrostatic pressure tests on a series of laboratory-scale spherical shell models made of 304 stainless steel sheets. These shells, with the same nominal diameter of 150 mm but different thicknesses, were numerically and experimentally investigated regarding elastic–plastic buckling. A good agreement could be obtained in this study, and similar results can be found in two other studies [19,20]. Notably, spherical shells have difficulties in hydrodynamics and inner space utilisation and are highly sensitive to geometric imperfections [21,22]. As an alternative to spherical shells, barrelled shells are frequently proposed. Elastic–plastic buckling of externally pressurised barrelled shells with meridians in the form of circular arcs was reported by Blachut [23]. A comparison between theoretical prediction and experimental data was performed. Moreover, Jasion and Magnucki have investigated a set of barrelled shells with Cassini oval [24], clothoidal-spherical [25], and circular arc meridians [26]. The buckling behaviour of these shells was analysed analytically and numerically. However, Jasion and Magnucki's works lacked experiments to further verify the validity of the results because of the difficulty associated with the manufacturing process and are still in the 'paperwork' stage. The real buckling behaviours of shells would be determined by deterministic geometric imperfections and material properties during the manufacturing process.

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An eggshell is a slightly elongated closed shell of revolution of positive Gaussian curvature and smoothly varying profile throughout, with the ends of the shell having smaller radii of curvature than the middle portions, where one end is more pointed than the other. Egg-shaped structure has many advantages such as an excellent load-carrying capacity, weight-to-strength ratio, span-to-thickness ratio, and aesthetic appeal [27]. These shells have attracted many interests in recent articles due to its promising application in various engineering fields. Zingoni [28–31] investigated the stress and deformation of egg-shaped sludge digesters, numerically and theoretically, as well as the shell-of-revolution sludge digesters of parabolic ogival form and the cone-cone axisymmetric shell junctions. Additionally, our previous studies have proposed a set of egg-shaped shells and prolate egg-shaped domes based on the geometric function of goose eggshells [18,22,32,33]. It can be found that an egg-shaped shell has an overall superior performance to a spherical one. However, these studies focused on the elastic–plastic buckling of egg-shaped shells, analytically and numerically. Experimental study into resin egg-shaped shells has not yet been performed. Also, the elastic buckling of egg-shaped laboratory-scale models has yet to be studied. These limitations have prevented shells from being used in further applications.

To overcome these limitations, this paper therefore proposed a class of egg-shaped shells with the same nominal geometric parameters. Five stereolithography resin models were fabricated through rapid prototyping technology. The geometric shape and wall thickness of each model were measured accurately. All models were externally pressurised in a pressure chamber uniformly and successively. The linear and nonlinear elastic buckling behaviours of each egg-shaped laboratory-scale model were experimentally, analytically, and numerically analysed. Additionally, to further study the difference between imperfect and perfect resin egg-shaped shells, the linear elastic buckling of the perfect resin egg-shaped shell was numerically explored. This work deeply investigated egg-shaped shells and provides a solid foundation for further applications in engineering.

2. Materials and methods

With the development of computer-aided design (CAD) and rapid prototyping technology, designers can rapidly generate an initial prototype from a concept. One rapid prototyping technology, stereolithography appearance (SLA), has played an increasingly vital role in fabricating models with complex geometries and surfaces [33–36]. Using stereolithography appearance (SLA), five laboratory-scale models was fabricated, measured, and tested in this section.

2.1. Manufacturing

The contour of an egg-shaped shell is illustrated in Fig. 1(a), with the sharp and blunt ends together with the middle area. The radius, $R(x)$, of the circumference of the egg-shaped shell can be determined by Eq. (1), which was established by Narushin [37,38] and frequently adopted in our previous studies [18,22,32]. The validity of the Eq. (1) also has been proved by our previous work through doing the actual measurements of geometry of biological goose egg shells [39].

$$R(x) = \pm\sqrt{L^{\frac{2}{n+1}}x^{\frac{2n}{n+1}} - x^2},\ \ n = 1.057(L/B)^{2.372} \tag{1}$$

As shown in Fig. 1(a), the geometry of an egg-shaped shell consists of a major axis (axis of revolution), L; minor axis, B; thickness, t; meridional radius, R_1; and circumferential radius, R_2. To be convenient for manufacturing and testing, the sizes of the major axis, minor axis, and thickness were designed to 232 mm, 160 mm, and 2 mm, respectively, in this study. The shape index, *SI*, can then be obtained from Eq. (2), and the value was calculated to be 0.69. According to the aforementioned designed values, the variations in the meridional (R_1) and circumferential (R_2) radii along the major axis (from the sharp end to the blunt end) are graphed in Fig. 1(b).

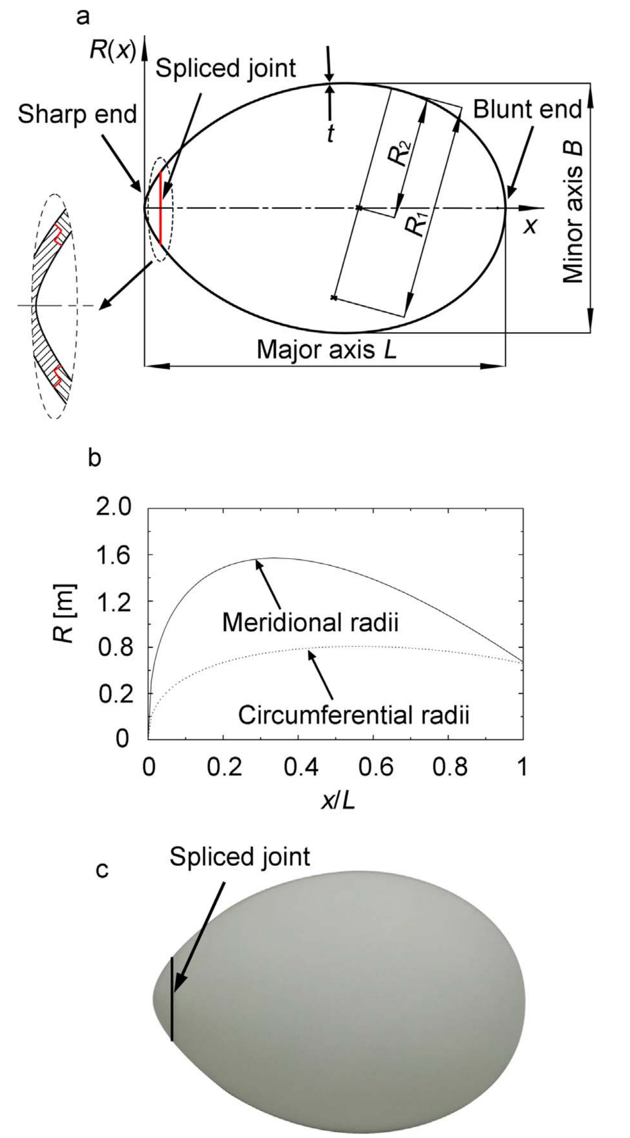

Fig. 1. Geometry of an egg-shaped shell (a) and its meridional and circumferential radius (b) together with its manufacturing model (c).

$$SI = B/L \tag{2}$$

All egg-shaped shells were built using stereolithography appearance (SLA), which has been widely used for structures with a complex shape. This technology was provided by the three-dimensional (3D) rapid prototyping company WeNext (Shenzheng, China). A commercially available stereolithography resin called 'Future 8000', produced by Royal DSM, was used to perform the investigation on egg-shaped shells. This type of resin has the advantages of high accuracy, low cost, and good mechanical performance. The resin material was assumed to be elastic with the following properties: Young's modulus $E = 2510$ MPa and Poisson's ratio $\mu = 0.41$, which were directly provided by the three-dimensional (3D) rapid prototyping company WeNext. This resin was used for solid-state laser systems (approximately 300 nm laser wavelength) with a recommended critical exposure, EC, of 8.8 mJ/cm^2 and a penetration depth, Dp, of 0.124 mm. Through the use of the aforementioned settings, a ProJet 3500 cpx max system was selected to fabricate the egg-shaped shells with a beam diameter of 0.25 mm and layer thickness of 0.1 mm.

During the rapid prototyping process, a fine point support was employed to ensure greater surface accomplish. To easily remove