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Experimental and numerical buckling failure analysis of acrylic hemispheres for application in neutrino detector

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ABSTRACT

The experimental and numerical methods were proposed to investigate the buckling failure behaviors of acrylic hemispheres under external pressure in this paper. The history of transient failure in the experiment was captured and recorded by a high-speed camera, which revealed the failure mode of acrylic hemispheres. Results showed that the critical buckling loads predicted by numerical buckling analysis were good agreement with experimental data. Lastly, the research results were applied into the stability design of an acrylic spherical vessel with the diameter of 35.5 m for China's Jiangmen Underground Neutrino Observatory (JUNO) neutrino detector. A feasible scheme of the acrylic sphere was proposed to avoid buckling failure.

1. Introduction

Acrylic has been widely applied in many areas for its excellent transparency and mechanical properties. Acrylic structures can provide visibility and safely sustain external or internal pressure of almost any magnitude. Acrylic spheres have been used for oceanographic research vehicles. Naval Experimental Manned Observatory (NEMO), the first submersible incorporating a spherical acrylic pressure hull, was developed at the Naval Civil Engineering Laboratory in 1970 [1]. Since then several other submersibles have been built with spherical acrylic pressure shells [2–3].

Now a new industry has been born as a spin-off from acrylic ocean engineering technology, which has found acrylic spheres useful in different application areas. With the advantages of transparent, the largest volume-to-surface ratio, optimum stress distribution and low radioactivity, acrylic spherical vessel has been used in physical experiments. In 1999, a transparent acrylic sphere, which was 12 m in diameter, was built to contain heavy water for the Sudbury Neutrinos Observatory (SNO) [4–5]. The detector has made a huge contribution to the discovery of neutrino oscillation, which won the 2015 Nobel Prize in physics. Research on neutrinos mysteries has continued. The Jiangmen Underground Neutrino Observatory (JUNO) will be launched to investigate more fundamental problems of neutrino physics [6]. It has been supported by the Strategic Priority Research Program of the Chinese Academy of Sciences. The project needs to construct a hyper-scale acrylic sphere with the inside diameter of 35.5 m as the containment vessel. The stable running of the acrylic spherical vessel is of great significance for JUNO project.

As we all know, the thin-walled vessels under external pressure trend to fail because of buckling before material failure. The buckling of spherical shells under external pressure has been researched for decades and many theoretical, experimental and numerical investigations have been carried out [7–11]. There are complete and mature design criteria for spherical heads or pressure

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vessels made of steel [12–14]. However, few investigations or experimental data can be found in the published literature to study the buckling failure behavior of acrylic spherical vessels. And there are no design standards to guide the safety design of acrylic vessels.

With the rapid development of computer science and finite element methods (FEM), many practical numerical analysis programs have been developed to investigate the buckling behavior of structures [15–17]. It was found out that the predicted results agreed well with that by experiments in existing literatures. So the finite element method can be applied to analyze the buckling failure behavior of the acrylic spherical vessels.

In this paper, experimental and numerical buckling failure analyses of twelve acrylic hemispheres under uniform external pressure are carried out. The objective of this paper is to obtain the buckling failure modes of acrylic hemispheres. Also, the accuracy of the numerical buckling analysis of acrylic hemispheres will be verified by the experimental data. Besides, the research results will be applied into the stability design of an acrylic spherical vessel for JUNO neutrino detector.

2. Experimental analysis

2.1. Specimen preparation

All the acrylic hemisphere specimens were free-blown formed from 8 mm acrylic flat sheets [18], and the radius was 600 mm. The flange along the equator resulting from the free-formed process was reserved. The finished hemispheres have smooth inside and outside surfaces and no further polishing was needed to achieve the potential transparency of acrylic plastic. The wall thickness decreased from the equator to the pole, while the deviation in the sphericity may be large or small which depended on the technical capability of the fabricator, the ratio of thickness to diameter of the sphere, temperature, and many other factors.

In order to control the hemisphere sphericity and local thickness deviations in a specified tolerance, all the specimens were checked by an inspection tool after fabrication. The inspection tool was composed by two vertical semi-toroidal plates with internal radius of 610 mm (Fig. 1). The test points were located along sixteen equally spaced meridians of the hemisphere, as shown in Fig. 2(a). Along each meridian, seven test points were located every 15°, as shown in Fig. 2(b). Thicknesses of the hemisphere at these test points were measured using an ultrasonic probe. In all instances, the maximum thickness (t_{max}) was at the equator, and the minimum thickness (t_{min}) was at the top. The radial deviations (l) from inspection tool to the hemisphere at these test points were also measured. The radial deviations of the test points at the same latitude were required to be within 0.01 time the radius. The thickness deviations of the test points at the same latitude were required to be within 0.1 time the average measured thickness. Eventually, twelve specimens were selected. Samples of the measured local wall thickness and the radial deviations are shown in Tables 1 and 2 separately.

2.2. Material properties

Uniaxial tensile tests were conducted on dumbbell-shaped acrylic samples to obtain the mechanical properties. These samples were cut from the flat sheet, which was used to fabricate the hemispheres. Tests were carried out according to the standard of ASTM D638 [19]. Five specimens, with gauge length = 50 mm, gauge width = 19 mm, thickness = 14 mm, were prepared for uniaxial tension. The tests were conducted at room temperature, which was the same as the operating temperature of hemispherical experiments.

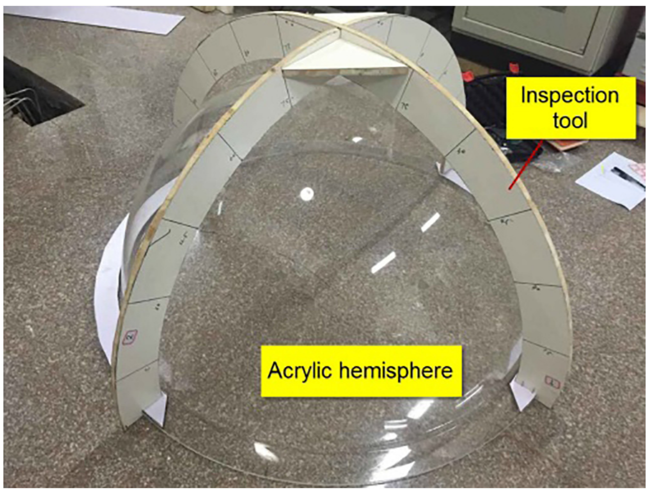

Fig. 1. Inspection tool with nominal 610 mm external radius.