Evaluation of Small Models of Ceramic Housings for 11,000 m Ocean Bottom Seismometers

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***Abstract*-We have designed and produced small models of ceramic pressure housings for use in a free-fall floating ocean-bottom seismometer that is useful at up to 11,000 m water depth. We also present a new design method of plural through-holes for underwater connectors on ceramic hemispheres. Its design concept and the results of finite element analysis (FEA) are presented along with results of hydraulic pressure tests using 1/4-scale models. Actual-size ceramic pressure housing will be completed soon.**

I. Introduction

Because ceramics have higher compressive strength than that of titanium alloys, ceramic pressure housings can provide positive buoyancy even for deep ocean applications at 11,000 m depth, which corresponds to the deepest abyssal water on Earth. When applied to underwater vehicles, they can reduce the need for additional buoyant materials, and consequently reduce the weight, size, and cost of deep ocean vehicles. However, because the pulling and bending strengths of ceramic are only a fraction of the compressive strength, as shown in Fig. 1, and because of its brittleness, common pressure-housing design methods are not directly applicable to ceramic pressure housings.

Stachiw [1] initiated the study of ceramic pressure housings earlier than 1961, and conducted vigorous studies since then. In 2005, Weston [2] and Stachiw [3] developed 3.6-inch and 10-inch ceramic hemispheres for deep submergence ROV/AUV systems. Bowen [4] used these ceramic pressure housings and ceramic spheres for a 11,000 m depth hybrid underwater vehicle ‘NEREUS.’ At JAMSTEC in Japan, Yano [5] started the study of ceramic housings in 2004. Following studies by Yano, Asakawa [6] presented a new design method for ceramic pressure housings for use in underwater vehicles. He produced a small model of a pressure housing shown in Fig. 2 and confirmed that it can withstand 120 MPa external hydraulic pressure, which corresponds to 12,000 m water depth.

Another important application of ceramic pressure housings is for free-fall floating ocean-bottom seismometers (OBS). The OBSs are thrown from vessels. Thereafter, they settle on the seafloor. They remain on the seafloor for several months and record tremors using built-in recorders. After completion of monitoring, they receive an acoustic command to detach the anchors and ascend to the sea surface by themselves. They have buoyancy of a few kilograms when detaching anchors. After popping up to the sea-surface, they are recovered by vessels.

Commonly, glass spheres have been used as pressure housings for free-fall floating ocean-bottom seismometers. However, their maximum applicable depth is limited to 6,000

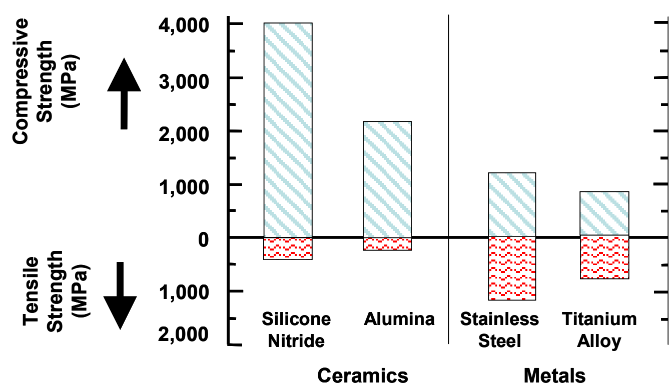

Figure 1 Comparison of strength of ceramic and metals.

Figure 2 Photo of the small model for ceramic pressure housing which can withstand 120 MPa hydraulic pressure.

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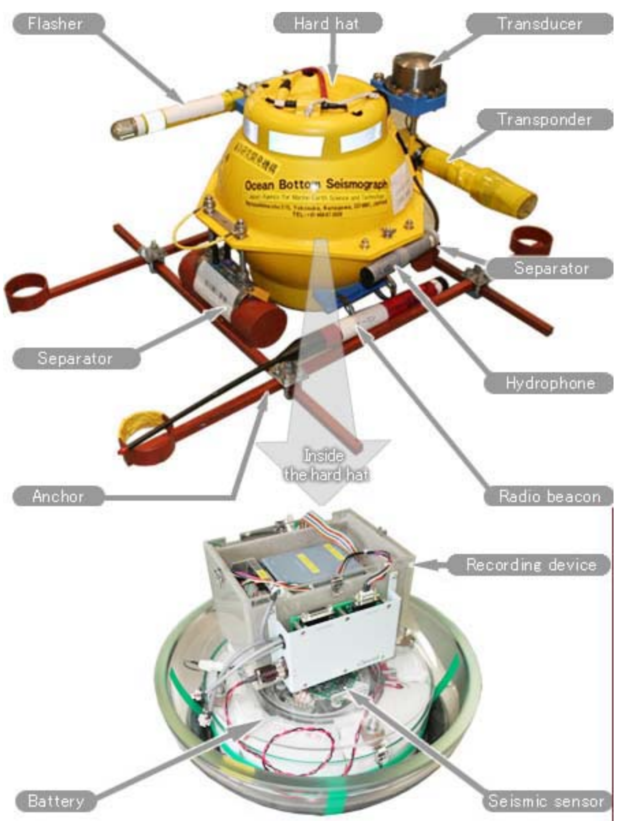

Figure 3 Configuration of typical ocean bottom seismometer (from http://www.nmeweb.jp/e/duties_tectonic_obs2.html#obs_hh).

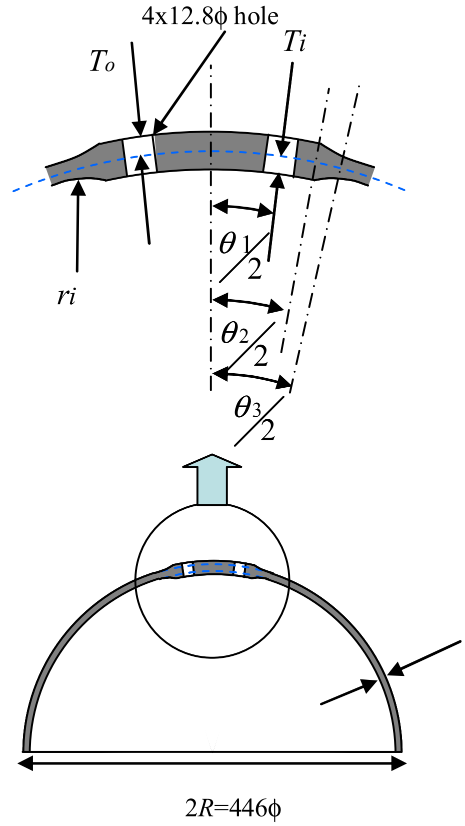

Figure 4 Cross-section view of the designed ceramic pressure housing.

m. To extend the maximum depth, a new light and robust material for pressure housings is necessary. We have started to develop ceramic housings for OBS which can submerge to 11,000 m water depth.

One issue to be addressed is that plural through-holes for underwater connectors are needed on pressure housings to connect devices outside of housings to electronics inside the housings. Asakawa [7] presented a design method for single through-holes on a ceramic hemisphere. As described herein, we propose a new design method for plural through-holes and reinforcement around them on ceramic hemispheres. We have conducted Finite Element Analysis (FEA) to evaluate the stress concentration. Then, we made two 1/4-scale models of about 110 mm in outer diameter to evaluate their strength against hydraulic pressure. As described in this paper, we report the outline of these studies.

II. Ocean Bottom Seismometer

Fig. 3 shows the typical OBS configuration. The pressure housing is a glass sphere. Its inner and outer diameter, rated depth and buoyancy are, respectively, 40.4 cm, 43.2 cm, 6,700 m and 25.4 kg. In the glass sphere, a triaxial seismometer, a recorder and batteries are installed. A flasher, a radio beacon, and an acoustic transponder, a hydrophone and anchors are arranged outside of the glass sphere. The glass sphere consists of two glass hemispheres. The seal between the two hemispheres is secured by sealing tape.

Two underwater connectors are mounted on the glass sphere. One is used to connect electronics in the glass sphere to a hydrophone. Another is to connect the OBS to a computer.

III. FEA Analysis

Fig. 4 portrays a cross-section of the proposed ceramic pressure housing. The maximum applicable water depth is 11,000 m. Silicon nitride (SN240; Kyocera Corp.) is assumed as the material because of its excellent mechanical properties. The compressive strength, the Young's modulus and three-point flexure strength are, respectively, about 3 GPa, 300 GPa, and 1.02 GPa. We selected a safety factor of 2 as the design criterion. The weight in air and the available buoyancy are, respectively, about 20 kg and 29 kg. They provide sufficient buoyancy that the same electric devices and sensors as those used for the common OBS are applicable.

We assume four through-holes of 12.8 mm in diameter arranged symmetrically. It is well known that stress concentration appears around holes. In the case of an infinite plate with a single hole, to which two orthogonal compressive stresses or tensile stress are applied, the stress at the edge of the hole is double that far from the hole. To lower this stress

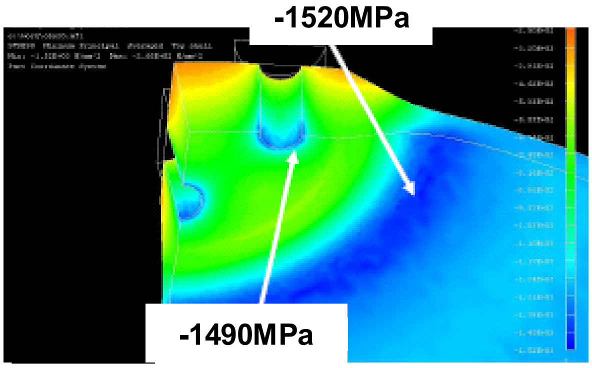

Figure 5a The contour of the minor principal stress.

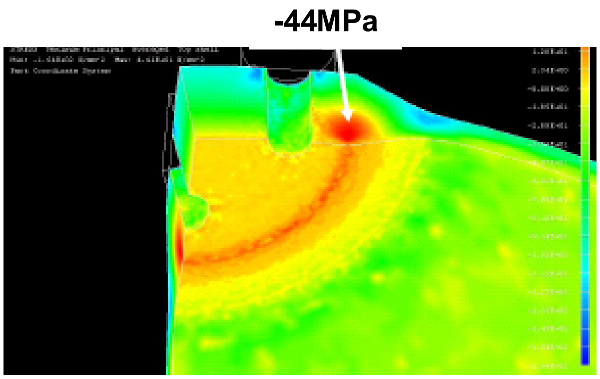

Figure 5b Contour of the major principal stress.

concentration, the wall thickness around holes is increased, as shown in Fig. 4.

In the figure, *Ti* and *To* respectively denote the thickness of the reinforcement at the inner and outer surface of the hemisphere. *T* denotes the wall thickness out of the reinforced area. The wall thickness around the through hole is increased to *Ti*+*To* from *T*. The reinforced thickness *Ti*+*To* reduces to *T* between the apex angle of $\theta_2/2$ and $\theta_3/2$. Furthermore, r_1 denotes the fillet radius. The outer surface, where O-rings are placed, is flattened.

Figs. 5a and 5b present examples of the results of the FEA: Fig. 5a shows the contour of the minor principal stress; Fig. 5b shows the contour of the major principal stress. Using the symmetry, only a 1/4 portion of the hemisphere was analyzed. The outer radius 2*R* and the wall thickness *T* are set, respectively, to 446 mm and 9.8 mm. The theoretically calculated hoop stress at the inner surface of the ideal sphere is 1.31 GPa, which coincides with the FEA result of 1.32 GPa. The maximum of the minor principal stresses appear at the outer edge of the reinforcement on the inner surface (at the fillet) and the inner edge of through holes. Their values are, respectively, -1.52 GPa and -1.49 GPa. These values depend mainly on *Ti*, *To* and radius of fillet *r*1. We selected *Ti* and *To* so that these maximum values are about half of the

Figure 6 Photo of a 1/4-scale ceramic sphere.

compressive strength of SN240 (ca. 3 GPa). The ratio of the stress concentration in this case is about 1.15. The maximum of the major principal stress appears on the inner surface. Its value is about -44 MPa, which is much lower than the tensile strength of SN240.

IV. Small-sized Model and Hydraulic Pressure Tests

We produced two 1/4-sized models of the designed ceramic pressure housing portrayed in Fig. 6 and confirmed their strength against hydraulic pressure. The two hemispheres were mutually coupled and the seal between them was secured with sealing tape. Hydraulic pressure of 110 MPa was added for 60 min, causing no leak or damage. We will conduct cyclic pressure tests and higher-pressure and longer hydraulic tests.

V. Concluding Remarks

Ceramic has excellent features for use as a material of pressure housings for use in the deep sea: high compressive strength, low density, and high resistance against corrosion. However, it is a brittle material; its tensile strength is only a fraction of the compressive strength. For that reason, common design criteria for metal pressure housings can not be applied directly to ceramic housings.

We have proposed a new design method of through holes on ceramic hemispheres and applied it to ceramic pressure housings for floating OBSs for 1,100 m water depth. Because OBSs should ascend to the sea surface by themselves after completing observation and detaching the anchors, the housing should have sufficient buoyancy. Ceramic housings can provide buoyancy even at the depth of 11,000 m. At the top of the hemisphere, four through-holes of 12.8 mm diameter are arranged symmetrically.

We conducted FEA analysis to design reinforcement around the through holes. Although only one example of the results is presented in this paper, we have been conducting a series of analyses. We will report all results in the near future.

We have also produced two 1/4-scale housings and conducted hydraulic pressure tests of 110 MPa. We are now planning to perform more vigorous pressure tests to evaluate the performance.

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