Small-sized model for Pressure-tight Ceramic Housings with an Elongated Ceramic Cylinder

Kenichi Asakawa, Yosaku Maeda, and Tadahiro Hyakudome
Marine Technology Center, JAMSEC
2-15, Natsushima-cyo, Yokosuka-shi
Kanagawa, 237-0061 Japan
asakawa@jamstec.go.jp

Masao Yoshida and Naoyuki Okubo
Kyocera Corp/
1-1, Kokubu-yamashita-cho, Kirishima-shi
Kagoshima 899-4396, Japan

***Abstract*— We propose a simple design method of a ceramic pressure-tight housing having an extended length of cylinder and metal caps. Ceramics have higher compressive strength and lower specific gravity than typical metals. Moreover, they are free from erosion by seawater. For that reason, we can produce light pressure-tight ceramic housings that have good durability for deep-water applications. The proposed ceramic housings have greater buoyancy than metal housings. We also propose a simpler design method of metal caps. We confirmed its validity through Finite Element Method (FEM) analysis and hydraulic pressure tests using small-sized ceramic housings with metal caps.**

Keywords*— Ceramic; Pressure-tight housing; metal caps; ceramic cylinder;

I. INTRODUCTION

We proposed a new design method of a ceramic pressure-tight housing having metal caps at the previous OCEANS conference [1]. In this paper, we propose a new simple method to extend the length of cylinder, and confirm its validity by means of hydraulic pressure tests with small-sized models.

Ceramics, as presented in Fig. 1, have higher compressive strength and higher Young's modulus than typical metals. Moreover, they are free from erosion by seawater. For that reason, we can produce light pressure-tight ceramic housings that have good durability for deep-water applications. They can also reduce the amount of additional expensive syntactic foam when being applied to underwater vehicles that require neutral buoyancy. Moreover, because they are nonmagnetic and insulating materials, they are suitable for housings of electromagnetic sensors. However, common design methods of pressure-tight housings cannot be applied to ceramic ones because the pulling and bending strengths of ceramics are only a fraction of the compressive strength, as presented in Fig. 1.

Stachiw [2] conducted a series of vigorous studies of ceramics pressure-tight housings since 1961. His work led to development of 3.6-inch and 10-inch ceramic flotation spheres for use in deep sea applications [3], [4], and a ceramic pressure-tight housing for use on a 11 km water depth hybrid underwater vehicle: NEREUS [5]. We have already developed ceramic spherical housings for ocean-bottom seismometers [6]. Seven ceramic spherical housings which can stand hydraulic

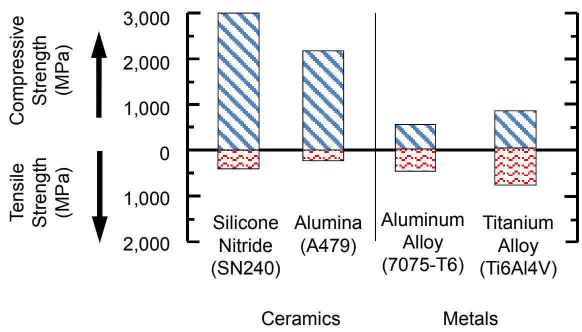

Fig. 1 Strength of ceramics and metals.

pressure of 110 MPa have been developed so far, and six of them were used for the actual seismic exploration [7] of the geological formation beneath the Japan Trench where the Great East Japan Earthquake happened in 2011. The outer diameter of the ceramic spherical pressure-tight housing is 445 mm, that is almost same as that of conventional pressure-tight glass spherical housings. Seismic exploration of seafloor deeper than 6,000 meters where catastrophic earthquakes periodically happened became possible using this ceramic pressure-tight spherical housings.

One of issues to be addressed is that the length of ceramic cylinders are restricted by the size of the production capacity. Usually ceramic cylinders are grinded in order to heighten dimensional accuracies after being sintered. The length of grinding machines restricts the length of ceramic cylinders. Typical maximum lengths are several tens of centimeters. We introduced a simple method to elongate its length and confirmed its validity through hydraulic pressure tests using small-sized ceramic housings.

Another issue is the design of caps. Usually, through-holes are necessary to mount underwater connectors on the pressure housings. However, stress concentrations of about two-fold appearing around through-holes make their design and fabrication complex when ceramics are used as the material. We can avoid this issue by adopting metal caps, but differences in displacements caused by hydraulic pressure at contact faces between metal caps and ceramic cylinders are expected to produce tensile stress on ceramic cylinders. We must reduce this tensile stress because tensile strengths of ceramics are only a fraction of the compressive strength, as described above. In the previous paper, we have addressed this issue by adding ribs to metal caps to equilibrate the displacement of metal caps and the ceramic cylinder at the joint. We also introduced another new simple method to address this issue. We have confirmed its validity through FEM analysis and hydraulic pressure tests using small-sized ceramic housings.

II. Design Concept and FEM Analysis

Fig. 2 illustrates the basic configuration to elongate the length of the cylinder. It is just simply connect two adjacent ceramic cylinders having the same inner and outer diameters. In the previous paper [1], we have sealed the coupling portion between metal caps and ceramic cylinder with self bonding rubber tape. We used the same methods to connect and seal ceramic cylinders. In order to avoid misalignment, ring-shaped guides made of synthetic resin are arranged at the coupling portion. Clearances between guides and cylinders are made small to avoid misalignment. By heating the guides made of synthetic resin, we can easily couple cylinders and guides because of the difference between thermal expansion coefficients of ceramics and synthetic resins. Self bonding rubber tapes are wounded over the guide to secure the sealing. Another tapes of synthetic resin are wound over the self bonding rubber tapes in order to protect them. Alignments and sealing between metal caps and ceramic cylinders are also carried out in a similar manner.

In order to simplify the structure of caps, we took slippage between ceramic cylinders and metal caps into consideration. Taking these slippage into consideration, we would be able to understand the stress distribution around the coupling portion more correctly.

We have measured friction coefficients between ceramics and metals. Table 1 shows the experimentally obtained static friction coefficients. In the experiment, we put a circular metal plate on a ceramics plate, and pull the metal plate with a spring balance to measure the pulling force when it starts to move. On the metal plate, weights are added. We used aluminum alloys of 7075-T6, 6061-T6 and titanium alloy of 6Al4Va. Tufram coatings are applied to the aluminum alloys. You can see from Table 1 that (1) static friction coefficients for aluminum alloys are lower than those for titanium alloys, and (2) static friction coefficients for SN240 are lower than those for A479. The reason of (1), we think, is due to the Tufram coating.

The shape of the cap is basically a hemisphere. In order to secure the alignment, a portion of the cap is inserted in the cylinder. The thickness of the joint portion of the cap is increased to make the inserted portion and to widen the contacting area between the metal cap and the cylinder.

Fig.3 shows an example of the result of FEM analyses of stress distributions. For these analyses, alumina ceramic (A479; Kyocera Corp.) was used for the ceramic cylinder and aluminum alloy (A7075-T6) was used for the metal cap. The hydraulic pressure was set to 60 MPa. The inner and the outer diameter of the cylinder are 100 mm and 109 mm respectively. Its thickness was determined using the buckling pressure shown in the following formula [8] assuming an infinitely long cylinder.

$$P_k = \frac{E}{4(1-\nu^2)}\left(\frac{t}{r_c}\right)^3 \tag{1}$$

where

- P_k: Buckling pressure (Pa)
- E: Young's modulus (Pa)
- ν: Poisson's ratio
- t: Thickness of the cylinder (m)
- r_c: Radius of the cylinder (m)

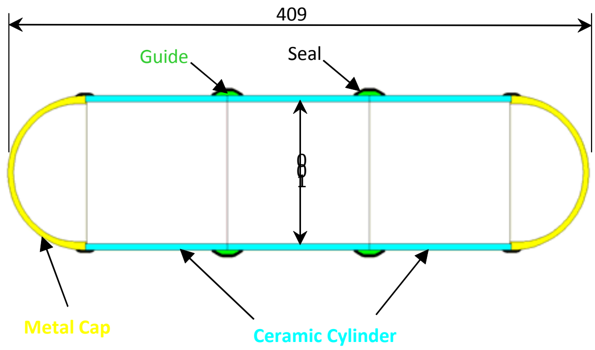

Fig. 2 Cross section view of the housing with elongated ceramic cylinder
(unit: mm)

Table 1 Measured static friction coefficients between metals and ceramics

	Al 7075-T6	Al 6061-T6	Ti 6Al4Va
SN240	0.12	0.11	0.23
A479	0.16	0.19	0.31

SN240 and A479 are silicone nitride ceramics and alumina ceramics respectively produced by Kyocera Corporation.

Table 2 Mechanical properties of materials used in the FEM analyses

	A479	AL 7075-T6
Young's Modulus	360 GPa	71 GPa
Poisson Ratio	0.23	0.33
Density	3.8	2.8

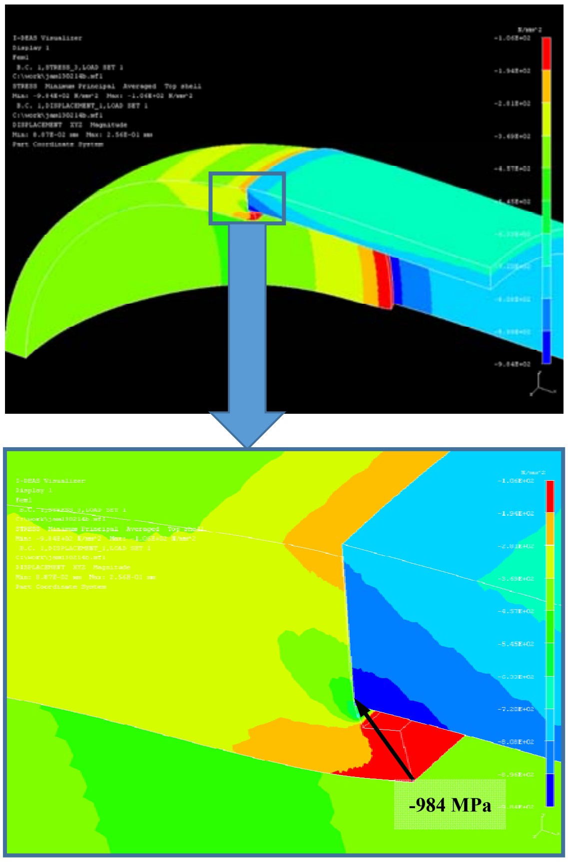

Fig. 3(a) Contour of the minor principal stress

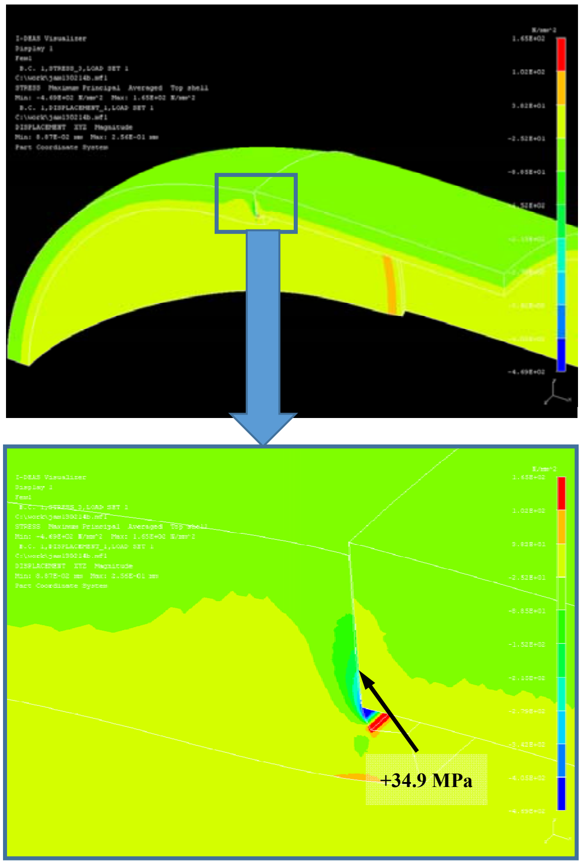

Fig. 3(b) Contour of the major principal stress

The safety factor for the ceramic cylinder was set to 1.0 against the buckling pressure. The outer diameter of the metal cap was made to equal to that of the ceramic cylinder to ensure the smooth coupling. The thickness of the metal cap is 3.9 mm. The theoretical hoop stress at the inner surface is about 451 MPa, that is about 89 % of the 0.2 % yield strength of the material. The friction coefficient between the ceramic cylinder and the metal cap is assumed to be 0.16.

The result of the FEM analysis (Fig.3a) shows that the maximum of minor principal stresses on the ceramic cylinder at the jointing portion are about -984 MPa, that is well below the uniaxial compressive strength of the material (about 2GPa). The major principal stresses displayed in Fig.3b are also well below the tensile strength of the material (about 170 MPa). These results show that the analysed pressure-tight housing has enough strength against hydraulic pressure of 60 MPa.

III. Hydraulic Pressure Tests

In order to verify the validity of the proposed structure, we have made five ceramic cylinders and a couple of metal caps, and conducted a series of hydraulic pressure tests. The cylinders and caps are made of alumina ceramic A479 and aluminum alloy AL 7075-T6 respectively. The sizes are listed in Table 2.

Table 3 and Fig. 4 show the list of the hydraulic pressure

Table 2 Size of the small-sized pressure-tight housings for hydraulic pressure tests (in mm)

part	portion	size
cylinder	inner diameter	100
	outer diameter	109
	length	100
cap	inner diameter	101.2
	outer diameter	109

tests and photos of small-sized pressure-tight housings. In order to make it slippery, we applied a lubricant on the coupling surfaces. We have conducted a series of cyclic hydraulic pressure tests up to 118 cycles and 60 MPa. The results of all tests were pretty well, and we could find no failure, no chipping of ceramics nor water leak. We think the endurable hydraulic pressure would be restricted by the strength of the metal cap.

Table 3 List of Hydraulic Pressure Tests

Number of jointed cylinders	Test ID	Test conditions
2	1	5 min @60 MPa held speed: 2 MPa/min, one cycle
	2	60 MPa max speed : 20 MPa/min, 52 cycles
3	3	10 min@60 MPa held speed: 4 MPa/min, one cycle
	4	60 MPa max Speed: 20 MPa/min 117 cycles

IV. Concluding Remarks

Ceramics have some distinguished features for use of underwater pressure housings such as higher compressive strength, higher Young's modulus and corrosion resistance against seawater. However, common design methods cannot be applied for ceramic pressure-tight housings because the pulling and bending strengths of ceramics are only a fraction of the compressive strength.

In this paper, we propose a new simple design method for elongated cylindrical ceramic housings with metal caps. Plural ceramic cylinders can easily connected to make a long cylinder. Only rings of synthetic resin and self bonding rubber tape are used to joint ceramic cylinders. We also showed that taking slippage between metal caps and ceramic cylinder into consideration, we can use metal caps without ribs. This simple structure of metal caps lower the manufacturing cost.

We have evaluated the proposed design method by FEM analyses and a series of hydraulic pressure tests using small-sized pressure-tight housings.

We can expect that the ceramic housings will be used in many deeper water applications because they can provide lighter pressure-tight housings which can reduce the amount of expensive buoyancy material.

Fig. 4(a) Photo of a small-sized pressure-tight housing for hydraulic pressure tests with two jointed ceramic cylinders

Fig. 4(b) Photo of a small-sized pressure-tight housing for hydraulic pressure tests with three jointed ceramic cylinders

References

[1] Kenichi Asakawa, Tadahiro Hyakudome, Masao Yoshida and Naoyuki Ookubo, "FEM Analysis of Pressure-tight Ceramic Housings with Metal Caps," in Proc. of OCEANS'12 MTS/IEEE YEOSU, 2012.

[2] J. D. Stachiw, D. Peters and G. McDonald, "Ceramic External Pressure Housings for Deep Sea Vehicle J. Clerk Maxwell," in Proc. OCEANS'06 MTS/IEEE Boston, 2006.

[3] S. Weston, J. Stachiw, R. Merewether, M. Olsson and G. Jemmott, "Alumina Ceramic 3.6-in Floatation Spheres for 11 km ROV/AUV Systems," in Proc. OCEANS'05 MTS/IEEE Washington, 2005.

[4] J. D. Stachiw and D. Peters, "Alumina Ceramic 10-in Floatation Spheres for Deep Submergence ROV/AUV Systems," in Proc. OCEANS'05 MTS/IEEE Washington, 2005.

[5] A. D. Bowen, D. R. Yoerger, C. Taylor, R. McCabe, J. Howland, D. Gomez-Ibanez, J. C. Kinsey, M. Heintz, G. McDonald, D. B. Peters, B. Fletcher, C. Young, J. Buescher, L. L. Whitcomb, S. C. Martin, S. E. Webster and M. V. Jakuba, "The Nereus Hybrid Underwater Robotic Vehicle for Global Ocean Science Operations to 11,000 m Depth," in Proc. OCEANS'08 MTS/IEEE Quebec, 2008.

[6] Kenichi Asakawa, Tadahiro Hyakudome, Masao Yoshida, Naoyuki Okubo, Makoto Ito, and Ikumasa Terada, "Ceramic Pressure-Tight Housings for Ocean-Bottom Seismometers Applicable to 11-km Water Depth," IEEE J. of Oceanic Eng. Vol. 37, No. 4, pp.756-763, 2012.

[7] Yosaku Maeda, Kenichi Asakawa, Koichiro Obana and Ikumasa Terada, "Super-deep-sea Ocean Bottom Seismometers Using Ceramic Spheres," in Proc. International Symp. on Underwater Technology 2013, in CD-ROM, 2013.

[8] Shinichi Takagawa, "Preliminary Design Method for Deep Sea Ceramic Pressure Vessel," in Conference proceedings, the Japan Society of Naval Architects and Ocean Engineers, 7W, pp.43-46, 2008-G2-6, 2008.