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A new concept for blast hardened bulkheads with attached aluminum foam

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Abstract. The use of blast hardened bulkheads (BHBs) is an effective vulnerability hardening technique for improving the survivability of naval warships when internal explosions occur due to being shot by an anti-surface missile. In this paper, a new concept of BHBs reinforced by aluminum (Al) foam is proposed. The new concept can significantly reduce the blast pressures transferred to bulkheads and, unlike conventional BHBs, can be easily installed to operating naval warships. Chamber model blast tests were performed to demonstrate the effectiveness of the Al-foam BHBs and the results are further supported by numerical simulations. Finally, a practical preliminary is proposed for the Al-foam BHBs.

Keywords: survivability; internal blast; blast hardened bulkhead; aluminum foam; chamber model blast test

1. Introduction

Naval warships confront extensive and extreme combat situations in execution of their duty. In order to minimize damage from enemy attack and protect the crew, combat capability, and mobility of the vessel; survivability is considered the most essential part of warship design. Researchers and engineers have focused on developing vulnerability-hardening techniques that can effectively improve the survivability of a warship. Although remarkable concepts have been proposed and adopted, new hardening designs are continuously demanded because newly developed weapons always aim to exploit any remaining vulnerability of warships.

Recently, anti-surface missiles are considered to provide a major intimidation factor. By adopting a Semi Armor Piercing (SAP) warhead with a delay fuse, they are designed to pierce a hull and explode inside it. Generally, the hull structure of warships is compartmentalized by watertight bulkheads, so they can maintain buoyancy after failure of some compartments. However, the internal blast from an anti-surface missile can rupture watertight bulkheads, and if flooding propagates through adjacent compartments, eventually, the warship will sink.

For this reason, recently-built warships are equipped with reinforced bulkhead, called blast hardened bulkheads (BHBs) (ALION S&T 2013, Krauthammer 2008, Agency for Defense Development 2014, Stark and Sajdak 2012, Lee and Zhao 2013, Galle and Erkel 2002, Raymond 2001). As shown in Fig. 1, BHBs can improve survivability of the warship against an internal blast by blocking propagation of physical and functional damage. This also provides secondary advantages such as enhanced survivability of redundant (dual) installations of vital equipment, such as engines, electric generators, and combat system cabinets.

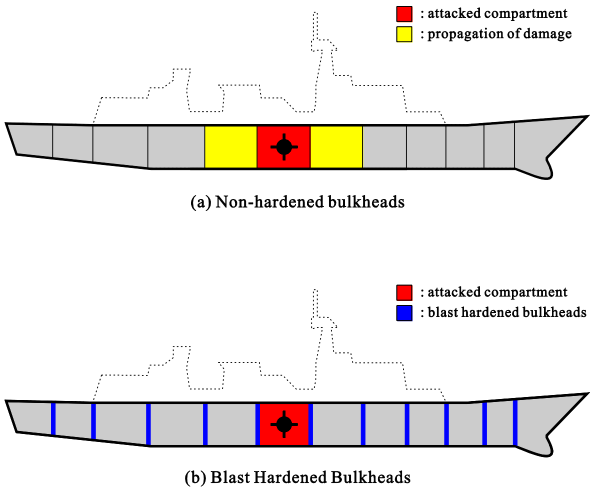

Fig. 1 Background and necessity of BHBs

The most conventional BHBs, called curtain type BHBs, are designed so that the thickness of upper and lower parts is increased in order to resist ruptures at the edges. This transforms the bending stress at the corners into membrane

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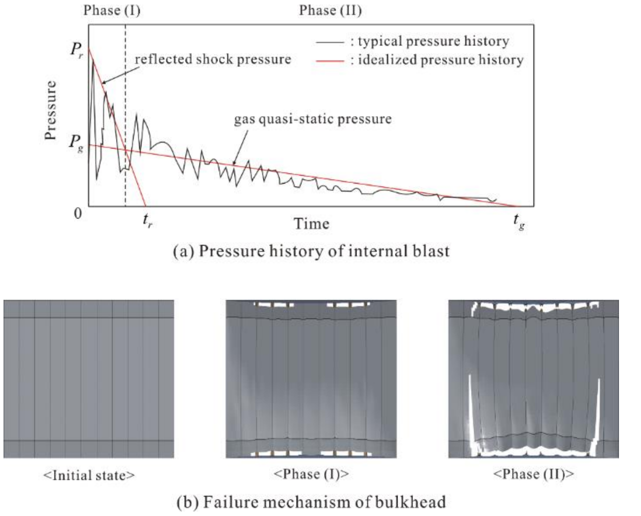


Fig. 2 Pressure history and resultant deformed shape after internal blast

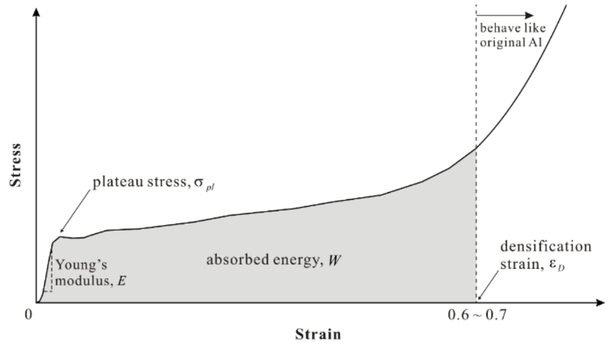


Fig. 3 Compressive stress-strain curve of Al-foam (schematic view)

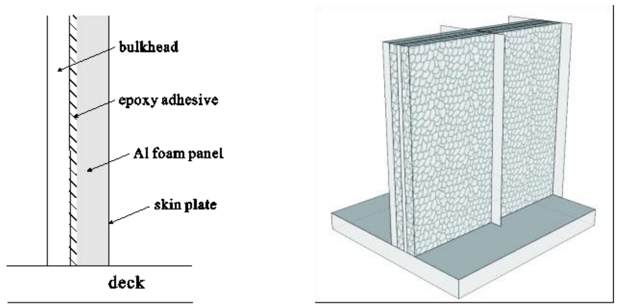


Fig. 4 Simplified illustration of Al-foam attached BHBs

Fig. 5 Conducting the chamber model internal blast test

stress according to a plastic deformation mechanism. However, curtain type BHBs (thickness 10-15 mm) significantly increase the weight of warships (Stark and Sajdak 2012), and require special welding methods to maintain structural strength. Furthermore, to apply curtain BHBs to operating warships involves extreme cost and technical renovation.

In this paper, we present a new BHB concept involving attached aluminum (Al) foam that can effectively improve the survivability of naval warships from internal explosion. The present work is the first proposal of the Al-foam type BHBs. As a sacrificial device, Al-foam panels can absorb and greatly reduce the blast pressure conveyed to bulkheads, and also have a number of secondary advantages-lightness, sound and vibration absorption, heat insulation, and electromagnetic shielding, all of which are necessary properties for bulkheads of naval warships. Moreover, Al-foam BHBs provide excellent absorption even after simple attachment without any special installation technique, so they can quickly and economically be applied to operating warships, unlike conventional types of BHBs.

This paper is organized as follows. A conceptual introduction to the Al-foam BHBs is given in Section 2. In Section 3 we describe a chamber model internal blast test for verifying performance of the new type of BHBs against internal blast. We provide further support for the effectiveness of the new bulkhead with a numerical study utilizing LS-DYNA in Section 4. Then, in Section 5, we propose a practical, preliminary design methodology. We conclude with a summary and directions for future study in Section 6.

2. Concept of Al-foam BHBs

Before discussing the new concept, we report our results from investigation of the mechanism by which bulkheads fail after an internal blast. Fig. 2(a) shows the typical pressure history of an internal blast (UFC 2008, Baker 1973), and Fig. 2(b) demonstrates the failure of a non-hardened bulkhead of which the size, material, and scantlings are similar to those of actual warships. The demonstration was performed using LS-DYNA, and the numerical modeling employed is described in Section 4. An internal blast can be theoretically represented as two kinds of pressure loads: the reflect shock pressure (Phase I) and the gas quasi-static pressure (Phase II). The reflect shock pressure initially imparted to the bulkhead causes highly concentrated impact loading and crack failure (Lee *et al.* 2014). The gas quasi-static pressure from hot, high-pressure gases causes the cracks to propagate, eventually causing the structure to break down. Considering the failure mechanism, the most critical point in BHB design is how to resist the extremely high loading from the reflect shock pressure.

To endure the reflect shock pressure, conventional BHB design is focused on methods to directly reinforce

Table 1 Material properties of Al-foam (Shim 2013)

Basic	Composition	Al over 97%
	Porous structure	Closed-cell
	Density	0.2 - 0.5 g/cm^3
Acoustic	Sound absorption	NRC 0.70 - 0.75
Mechanical	Tensile strength	1.3 - 2.0 MPa
	Compressive strength	1.5 - 2.0 MPa
Heat	conduction	0.268 W/m・K
Others	Melting point	Over 780°C
	Electromagnetic shield	Over 90 dB
	Salt spray test	OK

bulkheads by increasing plate thicknesses, or by changing shapes or materials. The existing concepts can successfully resist the reflect shock pressure, but they greatly increase the weight of ships, and are hard to apply in operating warships. To overcome the above drawbacks, here we give a new concept attaching sacrificial devices to bulkheads. The new concept can reduce the peak pressure of the reflect shock pressure conveyed to bulkheads as well as abate total impact damage by increasing the duration of the reflect shock pressure. Furthermore, it can be installed handily in operating warships (ALION S&T 2013).

We now focus on Al-foam as a sacrificial material for BHBs. Al-foam is an ultralight metal material, structurally similar to sponge, with density of 0.2-0.5 g/cm^3. This material is manufactured in accordance with the following procedure:

(i) Melt Al ingots,

(ii) Add foaming agents such as TiH2,

(iii) Pour into a mold and allow to cool.

The internal porous structure enables this material to absorb shock energy by compressive plastic behavior as shown in Fig. 3. In contrast with conventional shock-absorption structures such as honeycomb-core or corrugated-core panels, the foam shows relatively more isotropic behavior than others. That is, its behavior is quite independent with respect to the direction of shock loading. Moreover, this material has additional benefits such as sound and vibration absorption, heat insulation, electromagnetic shielding, and recyclability (see Table 1). For these reasons, demands for this novel material are increasing in commercial as well as military fields, for protection of the facilities in military and commercial buildings, protection of armored vehicles, and as filler for crushable bumpers for general vehicles (Ashby *et al.* 2000, Shim 2013, Hou *et al.* 2010, Yun *et al.* 2014, Shim and Yun 2010).

This new type of BHB can be simply installed by attaching Al-foam panels to existing bulkheads using an epoxy adhesive, as shown in Fig. 4. The Al-foam panels consist of core material (Al-foams with thickness of 50 or 70 mm) and skin plate (mild steel with a thickness of 0.6 mm). This combined structure shows excellent shock energy absorption and mechanical stiffness with overall low

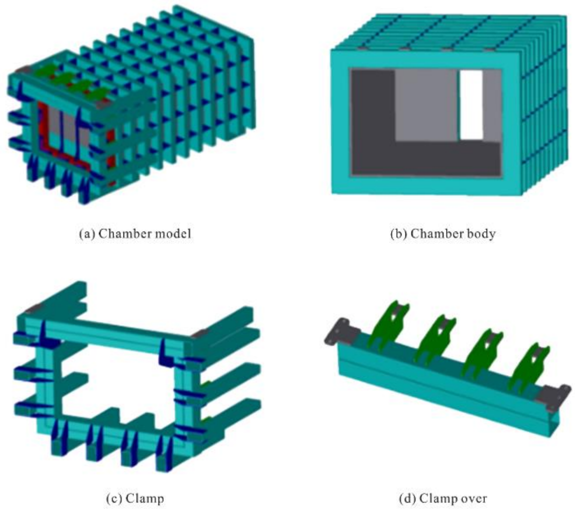


Fig. 6 Parts of the chamber model

weight. Above all, the major advantage of the Al-foam BHBs is that they can easily be applied to operating warships that are currently without BHBs. In addition, the use of Al-foam BHBs in new warships is expected to reduce their weight considerably.

3. Experimental study

To determine the feasibility of the concept, chamber model internal blast tests were conducted. In this section, the experimental setup is described in detail and its results are presented. Specific numerical values regarding the explosion were withheld at the request of the Agency for Defense Development of the Republic of Korea.

3.1 Experimental setup

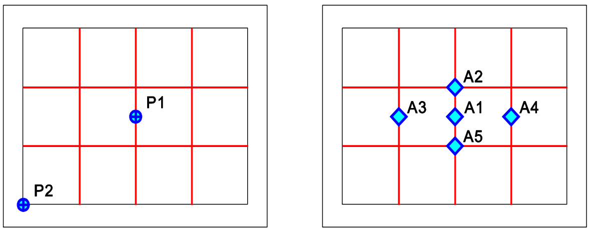
The overall description of the chamber model internal blast tests is well illustrated in Fig. 5. Fig. 5(a) displays the installation of the bulkhead specimen in the chamber body, and Fig. 5(b) shows the internal blasts introduced by detonating a spherical body of TNT in the center of the chamber body. The detailed specifications of the chamber model, specimen type, conditions of the explosion, and measurement methods are presented here.

Chamber model

In order to replicate a part of an actual warship, a chamber model was built using mild steel (SS400). For conducting a series of tests with a single chamber model, it was designed as a specimen-replaceable instrument. The chamber model consisted of a chamber body, a clamp, and a clamp cover, as illustrated in Fig. 6. The chamber body had an open front for installation of bulkhead specimens, and its back side had a vent area for emitting blast gases, see Fig. 6(b). The clamp and clamp cover, in Fig. 6(c) and (d), were used to confine the bulkhead specimens. In addition, all parts were greatly reinforced with stiffeners because they had to remain unchanged during successive blast tests.

Specimen type

The specimens consisted of a bulkhead of high tensile



(a) Pressure gauges (b) Acceleration sensors

Fig. 7 Position of the measurement sensors

Table 2 Test cases for Al-foam attached BHBs

No.	Thickness		
	Bulkhead	Al-foam	Skin Plate
Test 1	6 mm	None	None
Test 2	6 mm	50 mm	0.6 mm
Test 3	6 mm	70 mm	0.6 mm
Test 4	6 mm	50+50 mm	0.6 mm

shipbuilding steel (AH36), Al-foam with density 0.20 g/cm^3, and skin plate of mild steel (SS400). To demonstrate their performance depending on the thickness of Al-foam, four bulkhead specimens were prepared as shown in Table 2.

Explosion condition

In order to describe the same magnitude of internal peak pressure as would occur during an internal blast by anti-surface missile, the amount of TNT was carefully chosen by following the UFC Manual (UFD 2008). We used a spherical mass of TNT with an electrical signal detonator and with a booster (DXT-65) at its center. The TNT was placed at the center of the chamber.

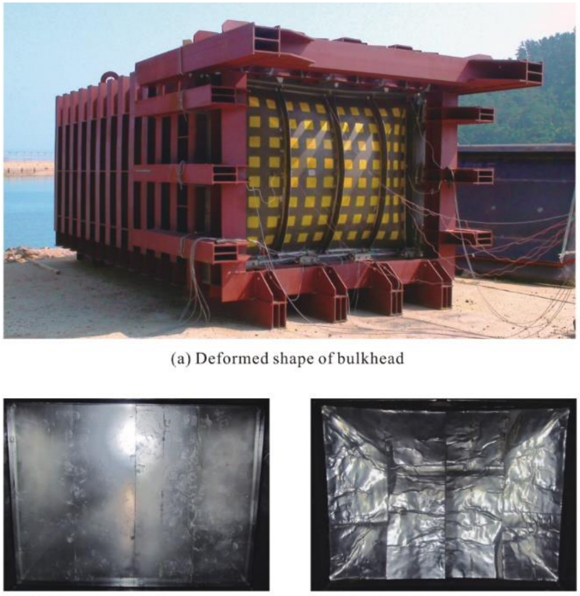
Measurement method

To measure the behavior of the bulkhead specimens, a high-speed camera, pressure gauges, acceleration sensors, and Vernier calipers were used. The overall blast condition for a very short moment was recorded and investigated using a high-speed camera. Two pressure gauges were mounted on each specimen, as shown in Fig. 7(a). Five acceleration sensors were arranged to observe dynamic response, and their positions are marked in Fig. 7(b). The maximum deflection of each specimen was also measured using Vernier calipers.

3.2 Experimental results

During the chamber blast tests, plastic deformations were observed in the shape of an arc, but ruptures were not shown in every test case, as shown in Fig. 8. Generally, it is known that aluminum materials are prone to melting when exposed to fire. However, no indications of burning or melting appeared during the experiments, as shown in Fig. 8(b). This is due to closed air-cell structure of the Al-foam. Actually, metallic foams have remarkably low values of thermal conductivity, in the range 0.3-35 W/m·K (Ashby *et al.* 2000).

In order to observe the reduction of shock pressure



(a) Deformed shape of bulkhead

(b) Initial shape of Al-foam panel (c) Deformed shape of Al-foam panel

Fig. 8 Configurations of experimental results

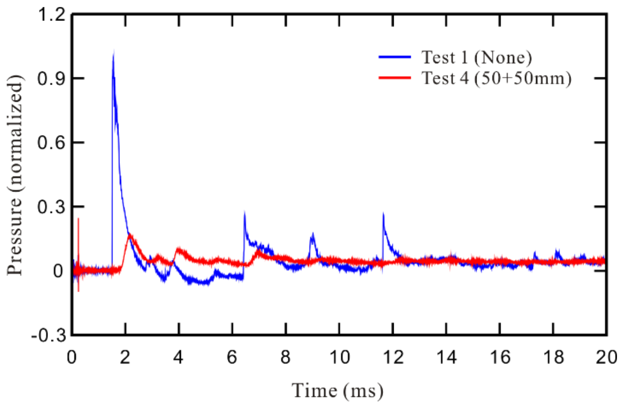


Fig. 9 Comparison of pressure history (original vs Al-foam through)

provided by the Al-foam, we compared the pressure history data of Test 1 (the shock imparted to the gauges directly) and Test 4 (the shock passed through the Al-foam and imparted to the gauges) at pressure gauge P1 (see Fig. 7(a)). The peak pressure of Test 4 was reduced to 15% of that in Test 1, as shown in Fig. 9. Also notable is the fact that overall pressure history was flattened. This means that Al-foams can mitigate the blast impact and convert impulsive loads into nearly static loads.

The deformation histories of the specimens were observed by analyzing videos from a high-speed camera (see Table 3). In the cases of the Al-foam BHBs (Test 2-4), deformations started later and showed longer duration than did the non-hardened bulkhead (Test 1). Actually, the peak acceleration of the deformations decreased with increasing thickness of the Al-foam panels (see Fig. 10). The remaining deflections decreased as the thickness of Al-foam panel increased, see Table 4. Test 4 (50+50 mm double-layered panel), however, indicated a larger remaining deflection than did Test 3 (70 mm single panel). Although the overall panel thickness in Test 4 was larger than in Test

Table 3 Deformation time history of Al-foam BHB

No.	Deformation		
	Start	Finish	Duration
Test 1 (None)	1.9 ms	7.7 ms	5.8 ms
Test 2 (50 mm)	2.2 ms	9.1 ms	6.9 ms

Table 4 Remaining deflection of experimental results and analytic estimations

No.	Deflection	
	Experiments	Estimations
Test 1 (None)	322 mm	340 mm (+18 mm)
Test 2 (50 mm)	312 mm	311 mm (-1 mm)
Test 3 (70 mm)	276 mm	297 mm (+21 mm)
Test 4 (50+50 mm)	284 mm	286 mm (+2 mm)

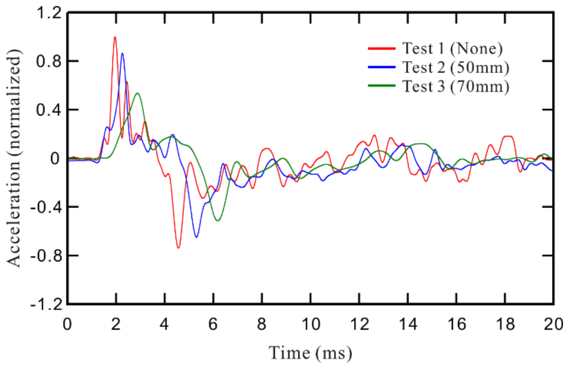


Fig. 10 Acceleration history of Al-foam BHBs at plate center

Table 5 Input parameters for materials

Parameters	Normal Al-Foam	High Density Foam	High Strength Foam
RO (g/mm^3)	2.0×10^{-4}	3.0×10^{-4}	2.8×10^{-4}
E (MPa)	190	418	277
PR	0.0	0.0	0.0
TSC (MPa)	0.76	1.51	1.27
DAMP	0.5	0.5	0.5

3, the results showed a different tendency. Further studies are needed to determine the differences in the deforming mechanism of single and double layer panels.

In summary, the experimental results prove that Al-foam can absorb reflect shocks and reduce impulsive effects. From these results, we present a practical idea for design of Al-foam BHBs in Section 5.

4. Numerical study

For this section, we performed numerical simulations of the chamber model internal blast tests to support the

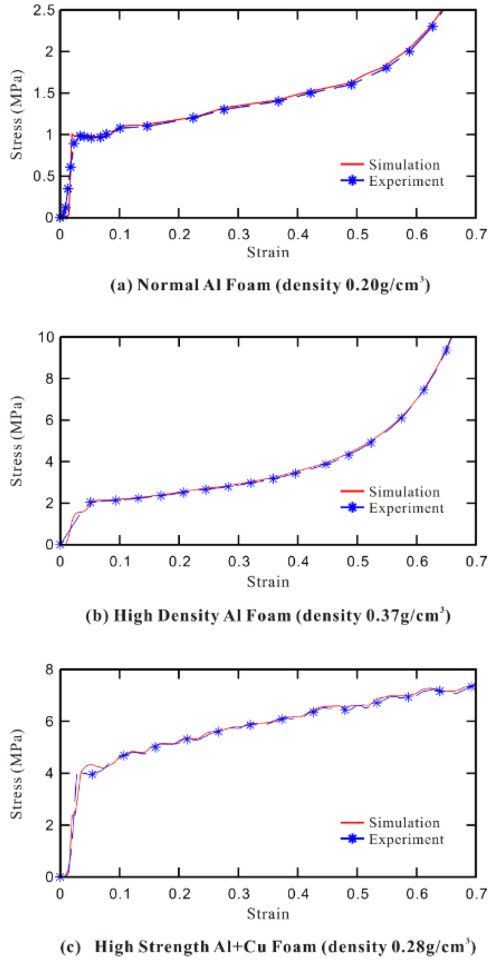


Fig. 11 Compressive stress-strain curves of Al-foam (simulation vs experiment)

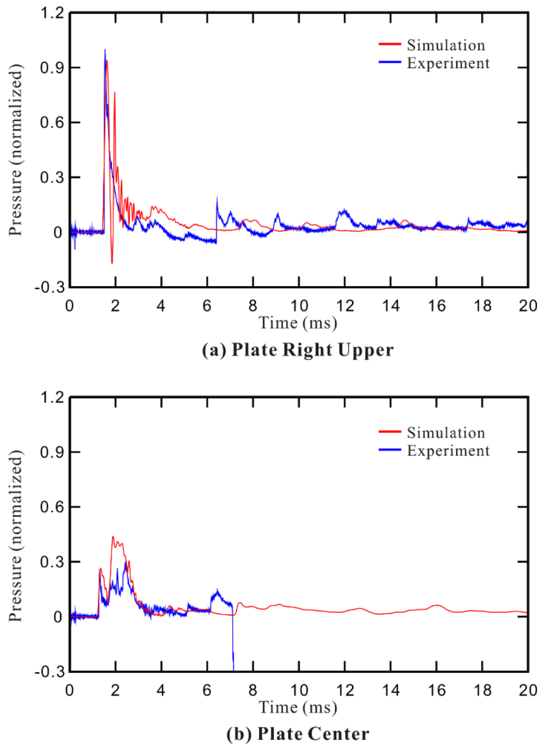


Fig. 12 Pressure history of Test 1 (simulation vs experiment)

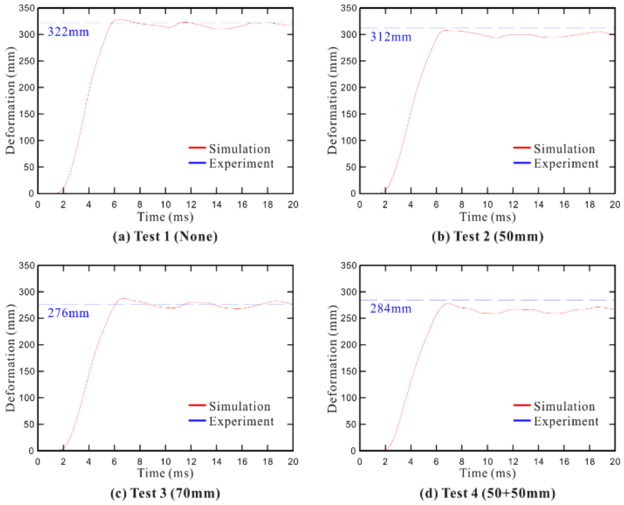


Fig. 13 Deformation history at plate center

Table 6 Design factors of structural parts for Al-foam BHBs

TYPE		Dynamic loading factor, γ_d	Safety margin factor, γ_s
Curtain (conventional)		1.5	2.9
Normal Al-Foam	25 mm	1.44	1.28
	50 mm	1.40	1.23
	75 mm	1.35	1.21
	100 mm	1.31	1.23
High Density Al Foam	25 mm	1.41	1.26
	50 mm	1.38	1.22
	75 mm	1.31	1.21
	100 mm	1.26	1.21
High Strength Foam	25 mm	1.41	1.26
	50 mm	1.38	1.25
	75 mm	1.35	1.19
	100 mm	1.31	1.18

experimental results. A brief introduction to the numerical model and comparison of the simulated results to the experimental results are presented below.

The numerical simulations were carried out using fluid-structure interaction (FSI) in the commercial software (LS-DYNA version 971 R6.1). Structural parts of Al-foam and wedges were modeled using solid elements, and the other structural parts were modeled using shell elements. The average sizes of the structural elements were 4-6 cm, and the overall number of elements was approximately 1,450,000. Air and explosion parts were modeled using Multi-Material Arbitrary Lagrangian and Eulerian (MMALE) formulation, which allows Euler-Lagrangian coupling analysis. In order to model the explosive pressure without instabilities, extremely fine meshes were employed for air modeling. The interaction between the structural parts and air parts was achieved using the Euler-Lagrangian coupling algorithm.

There is an early theoretical study of a constitutive model for metallic foam that introduced a concept of yield surfaces (Deshpande and Fleck 2000), and LS-DYNA was used to develop various material models according to this study. Several researchers have verified the material models by conducting experiments and comparing the experimental and simulated results (Perillo *et al.* 2010, Su *et al.* 2008, Rajan and Uday 2004, Hanssen *et al.* 2000, Reyes *et al* 2004, Bathe 1996, LSTC 2012). Referring to the above studies, we chose the material model MAT_CRUSHABLE_FOAM as the constitutive model of Al-foam. According to the ASTM Standard test data from the manufacturer (Foamtech Co., Ltd.), parameters for three types of Al-foams were obtained (see Table 5). A simulation was conducted using the same conditions as in the manufacturer test, and the numerical (simulated) results showed good agreement with the experimental results (see Fig. 11).

The MMALE and FSI methods estimated similar peak pressures and durations as the experimental results (see Fig. 12). According to the results of the actual experiments, the shock pressure was concentrated at corners (2-3 times greater than at the center). The FSI simulation also displayed this condition. The MAT_CRUSHABLE_FOAM material model projected responses similar to those observed in the Al-foam BHB blast tests. We observed that displacements at the plate center exhibited a similar range of error in the simulation and blast tests (see Fig. 13).

5. Preliminary design of Al-foam BHBs

In this section, a preliminary method for design of the Al-foam BHBs is proposed for their practical use. The design of Al-foam BHBs is processed according to three steps. First, Al-foam panels are chosen that are capable of absorbing the anticipated reflect shock pressure. Then, the design target pressure conveyed to the bulkhead is determined by considering the selected Al-foam panels. Finally, the design formula of the bulkheads is applied using the conventional design method for bulkheads.

5.1 Selection of Al-foam panel

The Al-foam panels chosen should be able to accept the peak pressure (=max[$P(t)$]) and the shock impulse ($=\int P(t)dt$) for the anticipated pressure-time history ($P(t)$). The peak pressure and the shock impulse are generally estimated according to the UFC manual (UFC 2008). The manual, based on experimental data, provides references for estimating pressure loads and impulses with respect to explosions. In addition, correction factors can be applied by comparing experimental results and numerical analyses. Then, the design peak pressure P_{rD} and the shock impulse I_{rD} are written as

$$P_{rD} = \alpha_p \times P_{rUFC} \quad \text{and} \quad I_{rD} = \alpha_I I_{UFC} \qquad (1)$$

where P_{rUFC} and I_{UFC} are the peak pressure and the shock impulse from UFC manual respectively, α_p and α_I are the

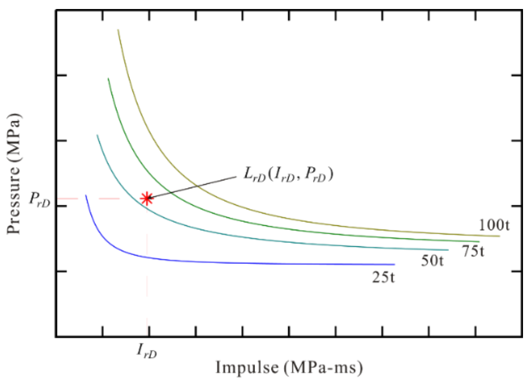


Fig. 14 P-I curves of Al-foam panels and design-load point $L_{rD}(P_{rD}, I_{rD})$ on the P-I diagram

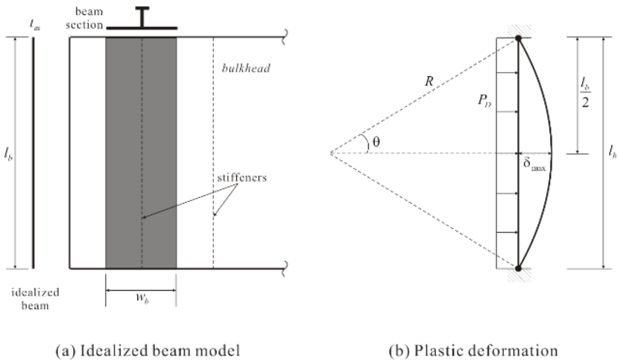


Fig. 15 Assumptions of bulkhead design formulae

experimental correction factors. We recommend α_p=3.2 and α_I=1. Then, suitable panels can be selected according to the P-I curves that are offered by the panel maker. We marked the reflect shock as a design point $L_{rD}(x, y)=(I_{rD}, P_{rD})$ on the P-I diagram and selected an optimized curve among positions on the upper side of L_{rD} (see Fig. 14).

5.2 Design target pressure

The design target pressure P_D is equivalent to the static pressure applied directly to the bulkhead. It is conventionally estimated using two correction factors and the gas quasi-static pressure from the UFC manual (23, 24), written as,

$$P_D = \gamma_d \times \gamma_s \times P_{gUFC} \tag{2}$$

in which γ_d is a dynamic loading factor, γ_s is the safety margin factor, and P_{gUFC} is the gas quasi-static pressure on UFC manual. For example, γ_d=1.5 and γ_s=2.9 are suggested (according to the experimental results) for use with conventional curtain type BHBs. These factors should be newly derived to include the pressure reduction effect of the respective Al-form panels. We suggest that the dynamic loading factor and the safety margin factor for each Al-foam panel be decided using the experimental and numerical results (see Table 6).

5.2 Design method for bulkheads

The conventional design formulae for bulkheads are based on the beam theory and the ultimate strength analysis method (Noh *et al.* 2014, Søreide 1981, Seo and Choi 1996). The bulkheads are modeled by assemblage of beams which contains a stiffener, as shown in Fig. 15. Also, they assume uniformly distributed pressures and arc-shaped plastic deflection. Then, the design criteria based on the cross-sectional area of the beam model is given as

$$A_b > A_{cr} \quad \text{with} \quad A_b = w_b t_m + A_{stiffner}$$
$$\text{and} \quad A_{cr} = P_D \cdot \frac{w_b l_b (1+\varepsilon_f)^{3/2}}{2\sigma_Y \sqrt{6\varepsilon_f}} \tag{3}$$

where A_b is the cross-sectional area of the beam model, A_{cr} is the cross-sectional area of the design criteria, w_b is the width of the beam model, t_m is the thickness of the bulkhead, $A_{stiffner}$ is the cross-sectional area of the stiffener, l_b is the length of the beam, ε_f is the failure strain of the material, and σ_y is the yield stress of the material. From these design formulae, Al-foam BHBs can be optimized with respect to weight by adjusting the thickness of the structural parts.

We can also estimate the remaining deflection of a bulkhead from the following formulae, given by,

$$\delta_{\max} = \frac{\alpha - \sqrt{\alpha^2 - l_b^2}}{2} \quad \text{with} \quad \alpha = \frac{2A_b \sigma_Y}{w_b \gamma_d P_{gUFC}} \tag{4}$$

As mentioned above, the dynamic loading factor γ_d is suggested for each Al-foam panel (see Table 6). Therefore, we can estimate the remaining deflection of Al-foam BHBs by substituting the values of the dynamic loading factor γ_d for each panel. We compared the analytic estimations from Eq. (4) with experimental results in Section 3. As a result, the estimations of deflections were similar to the experimental results (±20 mm, see Table 4).

6. Conclusions

In this paper, we presented a novel design concept for reinforcing bulkheads of naval warships against damage from internal blasts. The new concept can significantly reduce the forces transferred to bulkheads even using simple attachment without special installation techniques. Thus, it can be quickly and easily equipped in operating warships. Furthermore, the Al-foam panels naturally have a number of the properties considered necessary for bulkheads of naval warships such as sound and vibration absorption, heat insulation, and electromagnetic shielding. The excellent performance of the Al-foam was well demonstrated using chamber model internal blast test experiments and numerical simulations. Finally, we presented a preliminary design method for practical usage of Al-foam BHBs.

In future studies, it would be valuable to determine weight-optimization for more efficient use, after which it might totally replace conventional BHBs in new warships. In addition, we need to investigate various types of Al-foam panels, for example high-performance Al-foam panels, because the present work is limited to the normal type of

Al-foam panel.

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