DOI: 10.3969/j.issn.1673-3185.2017.01.015 **http:** // english.ship-research.com

Translated from: LI S Y, LI X B, ZHAO P D, et al. Research into energy absorption of water compartment subjected to close-range explosion[J]. Chinese Journal of Ship Research, 2017, 12(1): 101-106, 133.

Research into energy absorption of water compartment subjected to close-range explosion

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Abstract: In order to study the energy absorption of different parts of a water compartment under close-range explosion, a fluid-structure coupling model is built on the basis of experiments, and the deformation of the bulkhead and energy absorption ratio of different parts of the water compartment are analyzed, in which the influences of the water, bulkhead thickness ratio and water thickness are also discussed. The results show that the existence of a liquid medium can change the energy absorption model of a compartment. The total energy absorption is mainly affected by the front bulkhead thickness and water thickness, and alterations to the bulkhead thickness ratio or water thickness can also affect the deformation model of the bulkhead and energy absorption ratio of different parts of the compartment. A logical explanation of the energy absorption mechanisms of the water compartment is proposed, and some useful suggestions for designs are given.

Key words: close-range explosion; warship protective tank; shock; energy absorption

CLC number: U661.4; O38

0 Introduction

The warship protective tank is often set on the underwater side of large surface warships, which is mainly directed against the local contact and close-range non-contact explosion of torpedoes and mines, and explosion of armor piercing type and jet sunder armor type torpedoes inside the compartment to protect internal ammunition room, engine room and other important compartments from destruction. The study on energy absorption of water compartment under shock wave can provide suggestions for the design of warship protective tank.

The study on the antiknock problem of water compartment can be dated from the Second World War, but due to its military sensitivity, the references published abroad are few[1-2]. The study on this kind of question was carried out lately in China, Zhu et al.[3-4] performed a series of experimental study of underwater contact explosion model on the multilayer protective structures of warships. On the basis of suitable assumption, Du et al.[5] performed theoretical derivation of the response of bulkhead under close-range explosion load. Zhang et al.[6] analyzed the proportional relation between explosion load energy and total structural energy absorption, and the influence of explosive quantity and structural parameters on the distribution of total energy absorption through model experiment. Zhang et al.[7] studied the dynamic response of three-layer shell structure under the influence of underwater explosion through mathematical simulation, and also analyzed the effect of liquid level. Tang et al.[8] adopted fluid-structure coupling method to study the deformation and destruction of real compartment model under the influence of underwater contact explosion loading.

In order to study the absorption mechanism of water compartment against explosive shock wave energy, based on energy conservation, theoretical study on explosive energy absorption of water compartment

Received: 2016 - 07 - 04

Supported by: National Natural Science Foundation of China (11302259); Open Fund of State Key Laboratory of Nonlinear Mechanics (LNM201505)

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under close-range explosion is planned. On the basis of model experiment, the fluid-structure coupling model of a water compartment under close-range explosion load is built. The influences of water, bulkhead thickness ratio and water thickness on the deformation of the bulkhead and the change on the energy absorption ratio of different parts of the water compartment are also discussed, which will provide some useful suggestions for design of water compartment.

1 Explosive energy absorption of water compartment

The close-range explosion load acted on front bulkhead can be expressed as [9]:

$$p = p_m(1 - t/\tau)^{\mu - 1}$$
$$p_m = \bar{p}_w(R_w/R)\cos^2\alpha \quad (1)$$

where p_m is the maximum pressure on the external plate; μ is the charge shape coefficient, which is 3, 2 and 1 when the shape is sphere, cylinder and plane respectively; $\bar{p}_w$ is the average pressure of instantaneous detonation; R_w is the radius of charge; R is the vertical distance from the center of explosive to the external plate; α is the jet angle of explosion product; t is a certain moment; and τ is the duration time of positive pressure.

From Eq. (1), the specific impulse of any point on the front bulkhead can be obtained according to impulse theorem:

$$i(t) = \int_0^t p(t)\mathrm{d}t = p_m \frac{\tau}{\mu}\left[1 - \left(1 - \frac{t}{\tau}\right)^{\mu}\right] \quad 0 \leqslant t \leqslant \tau \quad (2)$$

When the front bulkhead surface of the water compartment is subjected to explosion shock load, the reverse side has water and the influence of water disturbance should be considered. The influence of water can be described by equivalent mass. The water disturbance develops to depth direction with time, and thus the increase of equivalent mass varies with time. It is supposed that the water of any point behind the plate synchronously moves with the plate and the response of water with thickness of $c_0\tau$ is considered, where c_0 is the sound velocity in water, and the mass of disturbed point is $(\rho_n h_n + \rho_0 c_0 t)$. The velocity response of the front bulkhead induced by reflected specific impulse can be obtained according to momentum conservation principle:

$$v(t) = \frac{i(t)}{\rho_n h_n + \rho_0 c_0 t} = \frac{p_m \tau}{\mu(\rho_n h_n + \rho_0 c_0 t)}\left[1 - \left(1 - \frac{t}{\tau}\right)^{\mu}\right]$$
$$0 \leqslant t \leqslant \tau \quad (3)$$

Supposing the pressure on structural surface is entirely absorbed and transformed into the initial kinetic energy of plate and water, total energy acted on the structure can be expressed as:

$$E = \int_0^{\tau}\int_0^{l} \frac{i^2(r, t)}{2(\rho_n h_n + c_0 \tau \rho_0)}\mathrm{d}t\mathrm{d}r \quad (4)$$

where r is the radius of load and the upper limit of integral is $l = 1/2L$ in which L is the length of short side of the plate. Eq. (4) indicates that the entire energy absorption decreases when the water disturbance is considered. The expression of total energy absorption of the water compartment can be obtained by the integral of Eq. (4):

$$E = \frac{\bar{p}_w^2 R_w{}^2 \tau^3 \arctan(l/R)}{R(1 + 3\mu + 2\mu^2)(h_n \rho_n \mu^2 + c_0 \tau \rho_0 \mu^2)} \quad (5)$$

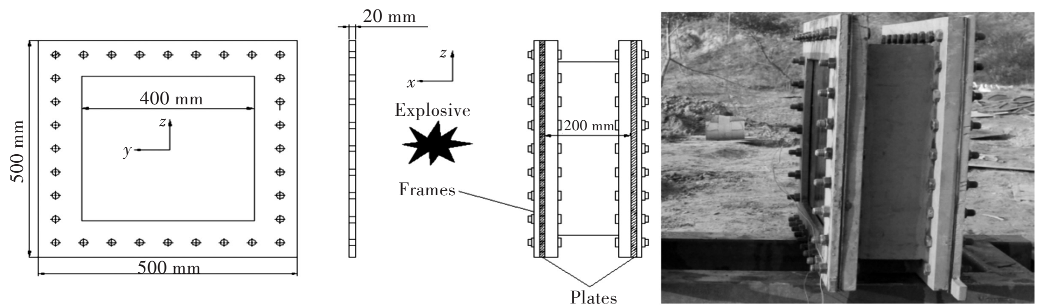
2 Simulation model and method validation

2.1 Experimental model

The experimental model is Q235 steel plate with a size of 500 mm × 500 mm. The steel plates are fixed on the sides of steel-made cubic explosive shell through bolts and frame fixture panels, and the dimension of the cubic shell is 400 mm × 400 mm × 200 mm. In order to simulate the water compartment of warship, it is necessary to fill water in the shell, thus a layer of rubber blanket is added between steel plates and side faces of the cubic shell to avoid liquid leakage. Each steel plate is connected to the cubic shell through 32 bolts so as to guarantee the fully clamped boundary conditions. A certain width is reserved in four sides of the fixture panels to fix the steel plates, so the actual explosive area of a steel plate is 400 mm × 400 mm. As shown in Fig. 1, the water compartment model is placed on the holder made in advance and the explosive is fixed on the center of the front bulkhead by ropes, with an explosion distance of 200 mm. The type of explosive is TNT, with the charge of 200 g, and the plate thickness is 2.5 mm.

2.2 Simulation parameters and method validation

Based on experimental model, nonlinear dynamic analysis software AUTODYN is adopted to build 1/2 symmetry model (Fig. 2). The ideal gas and water domain adopt Euler fluid element; the back and front bulkheads use Lagrange shell element; and a full fluid-structure interaction algorithm is used for calcula-



(a) Test model structure (b) Entity graph

Fig.1 Test model structure and entity graph

tion. Plates are fully clamped as boundary condition and outflow boundary condition is set in air domain. 11 measuring points are set with a spacing of 20 mm from the center of front bulkhead to boundary (Fig. 2). The material of bulkhead is Q235 steel, with consideration of strain rate strengthening effect. Dynamic flow stress of material adopts J-C strength model and the specific material parameters are shown in Table 1, where A, B, n, c and m are material parameters.

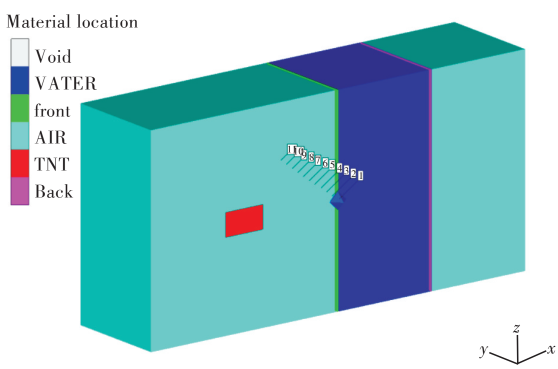


Fig.2 Simulation model

Table 1 Model parameters

ρ /(kg·m^{-3})	E /MPa	A	B	n	c	m
7 850	210	249.2	889	0.3	0.746	0.094

The actual deformation of front bulkhead is shown in Fig. 3. The contrast of simulation and experimental results of cross section deflection curve is shown in Fig. 4. It can be found that the simulation result is consistent with experimental curve, and the former is slightly larger than the latter, with the largest deflection error of 5.8%. The deflection difference of plate close to the boundary is large, which is because experimental boundary conditions cannot be fully clamped. This indicates that the obtained results are reliable when the simulation model proposed in this paper is adopted to study energy absorption of water compartment.

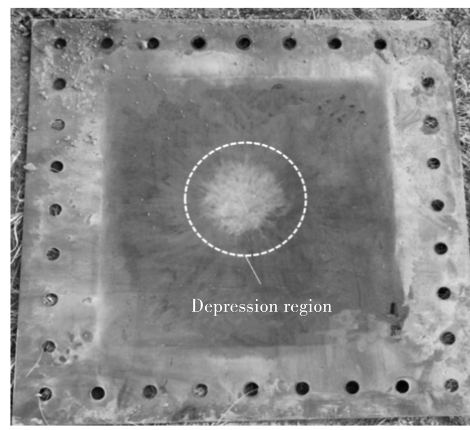


Fig.3 Deformation of front bulkhead

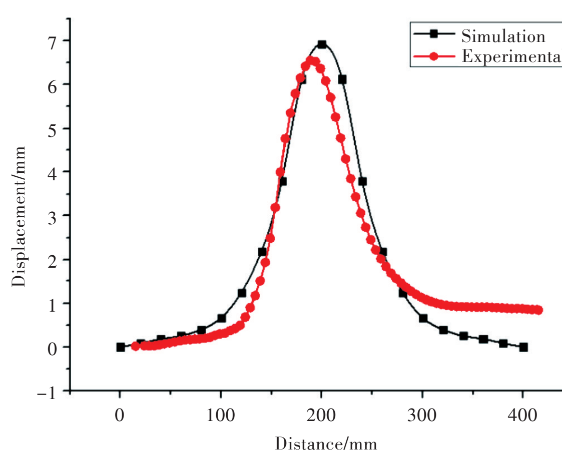
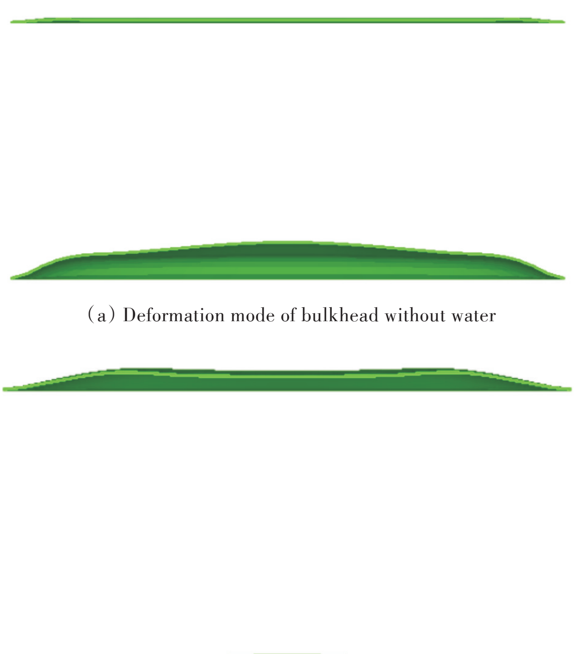


Fig.4 Contrast of simulation and experimental results

3 Energy absorption of water compartment

3.1 Influence of water

The contrast of deformation mode of bulkhead at 3 ms is shown in Fig. 5 considering the existence of water or not. It can be found that when no water exists, large global plastic deformation of front bulkhead is produced, which is similar to the deformation mode of empty back, while the deformation of back bulkhead is small and the contribution to energy absorption is very low. When water exists, only local plastic deformation of front bulkhead happens and the back bulkhead of compartment produces global plastic deformation under the influence of water disturbance. In addition, the deformation of back bulkhead is larger than that of front bulkhead, but the total deformation is smaller than that of compartment with no water. At this time, the back bulkhead still has velocity, and with the kinetic energy gradually transferring into deformation energy, the back bulkhead ultimately develops into "center uplift" form [10]. The reason lies in that when no water exists, the explosion energy absorption of compartment mainly depends on the deformation of bulkhead, in which the front bulkhead plays a "blocking effect" on shock load and can easily produce tensile and tear failure [11]. When there exists water, the compressibility of water makes pressure on part of media transmitted to other particles in the form of high-speed and finite wave. In this way, lots of energy is absorbed by water and part of energy is transmitted to the back bulkhead. The results show that the water reduces the deformation of bulkhead by energy absorption and changes the deformation mode of bulkhead. Thus, the back and front bulkheads are organically connected through absorption and dispersion of shock load.



(a) Deformation mode of bulkhead without water

(b) Deformation mode of bulkhead with water

Fig.5 Deformation mode of bulkhead

The energy transformation curve of a water compartment under close-range explosion is shown in Fig. 6 with consideration of water effect. It can be found that when there exists no water, the explosion energy is mainly absorbed by the front bulkhead and transformed into kinetic energy and deformation energy. When there exists water, the whole energy absorption of water compartment decreases by about 60% and the explosion energy adsorbed by bulkhead is only about 11% of that when there exists no water. More than 70% energy is absorbed by water, and the energy absorbed by the front bulkhead is less than 4%, and 26% by the back bulkhead. The absorbed energy is mostly transformed into kinetic energy and potential energy of water, and part is transformed into kinetic energy and deformation energy of bulkhead. This indicates that the water changes the dispersion effect of explosion energy in water compartment, which is initially born by the front bulkhead and now commonly born by back bulkhead, front bulkhead and water. Through interaction among back bulkhead, front bulkhead and water, most energy is ultimately dissipated in the form of heat energy induced by vibration and agitation of water.

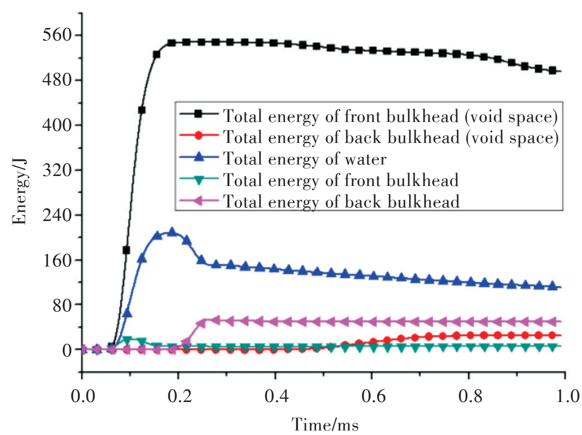
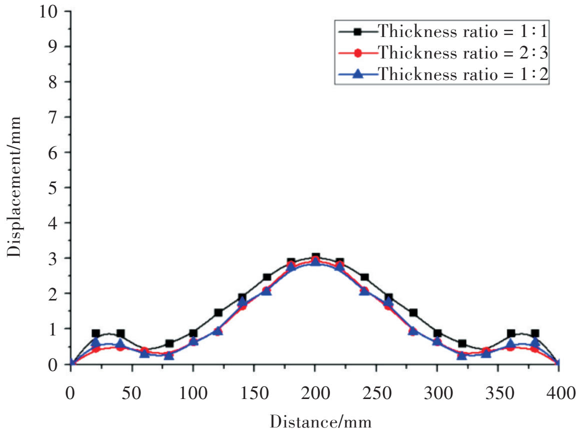


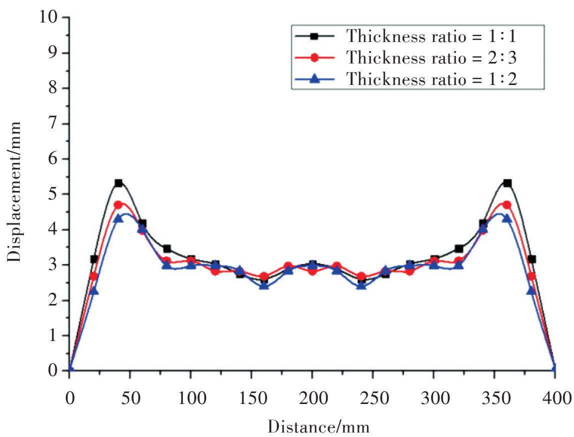
Fig.6 Energy transformation

3.2 Influence of thickness ratio

Both Reference [5] and this study indicated that the deformation of back bulkhead was larger than that of front bulkhead under close-range explosion, and thickening treatment on back bulkhead should be considered. The thickness ratio is defined as the ratio of thickness between back and front bulkheads. The bulkhead realizes energy absorption by deformation and the increase of thickness of back bulkhead inevitably influences the dispersion effect of explosion energy in water compartment. Thus, the influence of thickness ratio needs to be deeply studied. The contrast of deformation mode of bulkhead at 1 ms with different thickness ratios is shown in Fig. 7. It can be found that the change of thickness ratio does not change the whole deformation trend of bulkhead. Although at this time the bulkhead does not reach the ultimate deformation, with the increase of

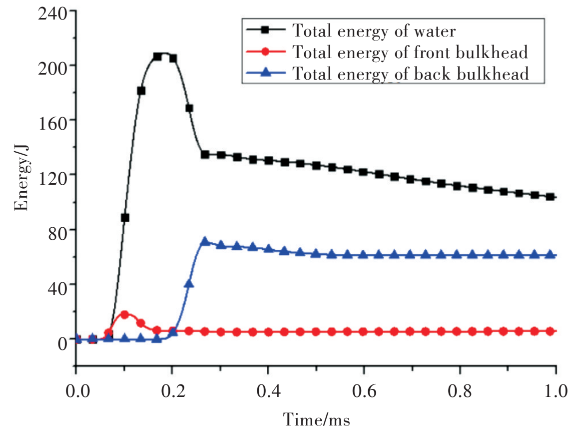


(a) Deformation mode of front bulkhead

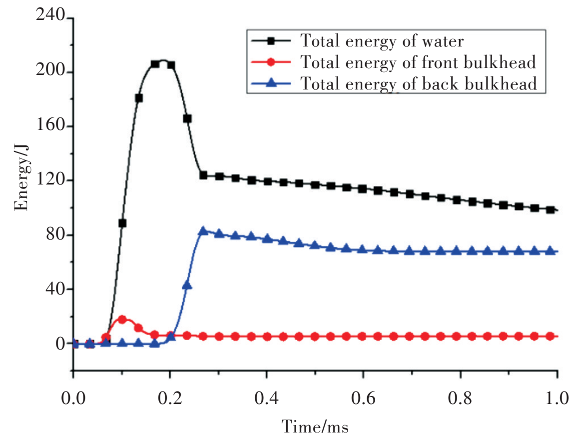


(b) Deformation mode of back bulkhead

Fig.7 Contrast of deformation mode of bulkhead



(a) Thickness ratio of 2∶3



(b) Thickness ratio of 1∶2

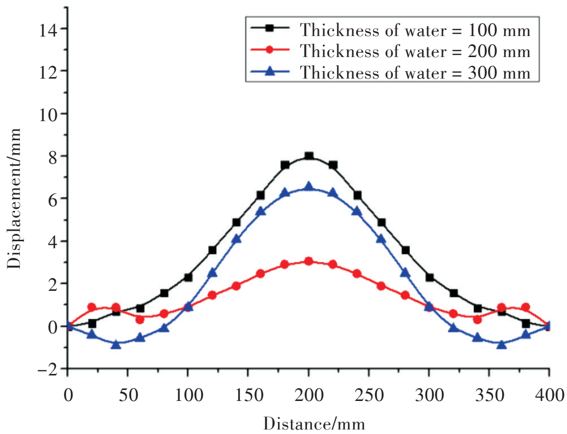
Fig.8 Contrast of energy absorption mode of liquid tank

thickness ratio, the deformation speed of back bulkhead becomes slower. Total deformation of front bulkhead of water compartment also decreases slightly, but because the thickness of front bulkhead is constant, the influence on energy absorption is small.

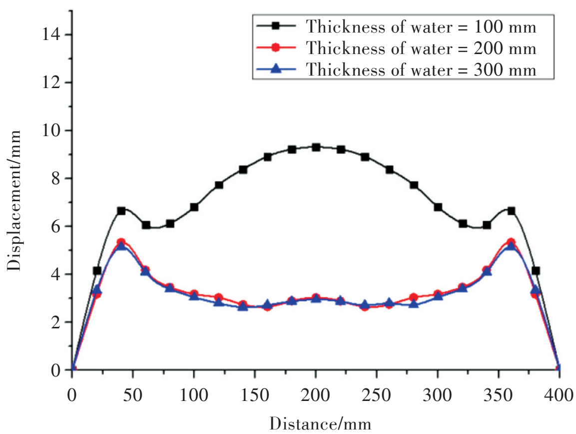
The contrast of energy absorption mode of water compartment with different thickness ratios is shown in Fig. 8. As can be noted in the figure, both change laws are basically consistent. Taking the energy curve with thickness ratio of 2∶3 as an example, under close-range explosion, the energy of front bulkhead increases firstly and reaches the peak at 0.1 ms. The kinetic energy is completely transformed at about 0.18 ms and only deformation energy exists. The energy of water begins to increase rapidly at 0.06 ms and reaches the peak at about 0.18 ms. At this moment, the shock load has reached the back bulkhead and the energy of the back bulkhead begins to increase. At 0.26 ms, energy transformation between water and back bulkhead is completed and the energy of back bulkhead basically keeps stable, while the energy of water shows stable decrease trend. When the thickness ratio is 1∶1, the increase of thickness ratio has little influence on total energy absorption of water compartment and energy absorption of front bulkhead, but the energy absorption of back bulkhead increases by about 32%. When thickness ratio increases to 1∶2, the energy absorption of back bulkhead increases by about 54%. The results indicate that thickness increase of back bulkhead contributes to deformation decrease of back bulkhead and meanwhile improves the energy absorption effect of back bulkhead, so thickness ratio shoud be considered in the design of water compartment.

3.3 Influence of water thickness

The contrast of energy absorption mode of water compartment with different water thicknesses at 1 ms is shown in Fig. 9. It can be seen that water thickness has large influence on the deformation of bulkhead. When the water thickness increases from 100 mm to 300 mm, the deformation of front bulkhead firstly decreases and then increases, and the deformation mode also changes. When water layer is thin, the bulkhead shows the trend of large global plastic deformation. With the increase of water thickness,



(a) Deformation mode of front bulkhead

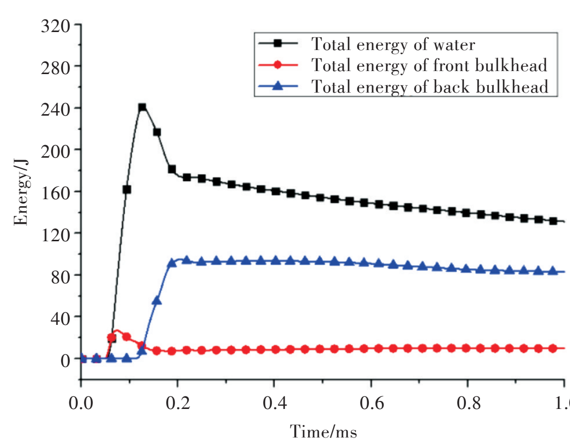


(b) Deformation mode of back bulkhead

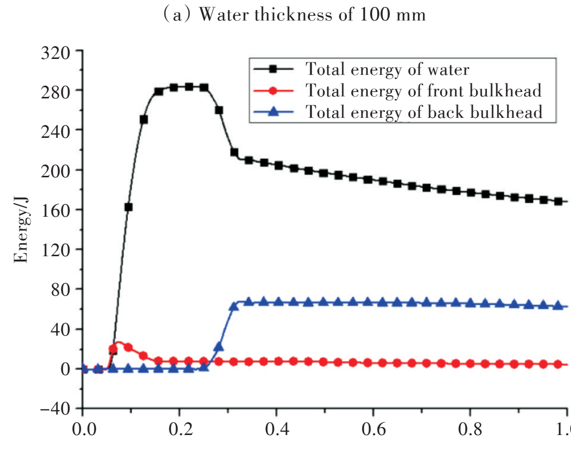
Fig.9 Contrast of deformation mode of bulkhead

central uplift deformation of bulkhead becomes more evident, which indicates that the increase of water thickness makes the local deformation effect of front bulkhead become more prominent. When water layer is thin, the deformation of back bulkhead develops rapidly into the form of center uplift. When water thickness increases, the deformation developing trend slows down, but when water thickness continues to increase, the deformation trend does not have evident change. When water layer is thick, the shock wave acted on back bulkhead is approximately plane wave and with the decrease of propagation distance, the local effect of load becomes gradually stronger, which causes the change of deformation mode of back bulkhead and thus influences the ultimate deformation.

The contrast of energy absorption of water compartment with different water thicknesses is shown in Fig. 10. When water thickness increases, energy transformation process between water and back bulkhead is gradually delayed. When water thickness is 100 mm, total energy absorption of water compartment increases by about 28.4%, in which the proportion of energy absorption of back bulkhead increases by about 10% and that of water decreases slightly. When water thickness increases to 300 mm, total energy absorption increases by about 35.3%, while the influence on energy absorption of different parts of water compartment is little, with a fluctuation error less than 3%. Although both thin and thick water layers increase the overall energy absorption of water compartment, the reasons of energy absorption increase are different. The water absorbs explosion energy through the movement of particle and when water thickness is small, water disturbance is more violent. In addition, the deformation of back bulkhead develops rapidly and thus causes the increase of energy absorption of back bulkhead. The increase of water thickness actually increases the number of disturbed water particles and then increases the total energy absorption of water compartment. From Eq. (5), when water thickness is more than $c_0\tau$, the redundant water will not influence energy absorption any more. Therefore, suitable water thickness should be selected in design of water compartment by comprehensively considering the energy absorption effects of bulkhead deformation and water disturbance.



(a) Water thickness of 100 mm



(b) Water thickness of 300 mm

Fig.10 Contrast of energy absorption mode of liquid tank

4 Conclusions

The above research shows that:

1) When water exists, explosion energy absorbed by compartment decreases compared with that with no water. When charge and explosion distance are given, explosion energy absorbed by compartment is mainly related to the thicknesses of front bulkhead and water.

2) The liquid medium reduces the deformation of front bulkhead through energy absorption and changes its deformation mode. The liquid medium changes energy absorption mode of compartment from energy absorption solely depending on the deformation of front bulkhead to that depending on deformation of front and back bulkheads as well as the movement of liquid particles.

3) The increase of thickness of back bulkhead does not affect the total energy absorption of water compartment and the energy absorption effect of front bulkhead, but increases energy absorption of back bulkhead and decreases its deformation speed at the same time, which is conducive to protect the inner structure of compartment.

4) The water thickness influences the total energy absorption of water compartment and the deformation mode of bulkhead, and when the thickness is $c_0\tau$, the maximum energy absorption effect of water compartment can be guaranteed. When water layer is thin, the overall energy absorption of water compartment can be improved through agitation of water and deformation of back bulkhead. When water layer is thick, the increase of vibrated water particles is the reason changing energy absorption of water compartment.

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近爆载荷作用下液舱的吸能研究

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摘　要: 为研究近距爆炸载荷作用下液舱各部分的吸能情况,根据实验建立数值仿真模型,研究在有无液体、不同厚度比和不同水层厚度条件下舱室变形和各部分吸能的占比情况。结果表明,液体介质的存在改变了液舱的吸能模式,液舱总吸能主要受到舱室外壁厚度和水层厚度的影响,厚度比和水层厚度的变化对舱壁变形模式和爆炸能量在液舱各部分的占比有一定影响。对液舱各部分吸能机理的阐述,可作为液舱设计的参考依据。

关键词: 近距爆炸; 防护液舱; 冲击; 吸能