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Capacity of surface warship's protective bulkhead subjected to blast loading

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Abstract: The protective bulkhead of the large surface warship need to be designed working in the membrane mode. In this paper, a formula is derived for calculating the plastic deformation of the protective bulkhead subjected to blast loading by the energy method, and the ultimate capability of the protective bulkhead can be calculated. The design demand of the protective bulkhead is discussed. The calculation is compared with external experiments, which indicates that the formula is of great application value.
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1 Introduction

The survivability of naval vessel to blast loading is one of its main performance factors. A warship should have not only proper initiative but also passive protective capability. The passive protective capability is sometimes called "anti-blast capability". The power of modern anti-ship weapon is increasing; traditional armored protector alone is not enough for the survivability demand. Using protective structure is becoming necessary. It is a style of protection with space and structural strength. The developing trend of surface warship towards bigger and bigger has made it possible to use this protective structure[1].

Protection includes air protection and underwater protection. Air protection is mainly against bombs and missiles and underwater protection is mainly against torpedoes and mines. Because of the performance of concealment of submarine and heavy power of underwater explosion, the underwater protection is most important. The special cabins have been set almost in all large surface warships[2]. It includes expansion cabin and absorption cabin, and except these, there is a special longitudinal protective bulkhead as a final protector, which is a pure plate actually and sometimes it is called "the main armor plate".

The design of protective bulkhead is much different from the other ship structures. For most of ship structures, such as shell, rib, etc., the main design requirement is that these structures are not allowed to fail because they support total hull strength; even if they have failed, they should not bring about the loss of the survivability. But it is different for the protective bulkhead. In normal condition, it is a useless plate. Only subjected to blast loading, it starts to absorb the energy of shock by large deformation or fail itself, thus the other structural damage can be reduced.

So the protective bulkhead is a pure anti-blast structure with a special design. For obtaining the highest capacity against the blast loading, the bulkhead should be designed working in the membrane stress mode, because the membrane can make heavy deformation and not crack. As heavily deformed bulkhead does not affect strength and performance of the ship, this kind of design is possible.

In this paper a formula is derived for calculating the bulkhead capacity against the blast loading by the energy method. The demands of the bulkhead design are also discussed.

2 The membrane effect of a rectangular plate

In the general design of ship structures, the rectangular plates of ships subjected to the lateral loading are not allowed to appear plastic deformation. In this case, the deflection of the plates is small, and the stress of the plates is mainly the bending stress. But if the boundary is very strong to restrict the moving toward center of the plate, and the plate is soft ($\beta = \frac{b}{t}\sqrt{\frac{\sigma_s}{E}} \geq 2.4$), the membrane effect of the plate will be obvious when the deflection of the plate becomes large. When the deflection is more than 1.5 times of the thickness of the plate, the most of lateral loading is

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supported by extension of the membrane and not by bending of the plate[3].

3 Solution method

The calculation of rigid plates with small elastic deflection is standard. There are relevant analytic methods for circular, square and rectangular plates. Many studies have been made for the plastic deformation of common plates subjected to blast loading. Bounding theorems and mode approximation solutions are used usually, and the suitability has been tested by model experiments[4-5].

The elastic deflection can be ignored and rigid-plastic material is assumed when investigating the large deformed plate in which the membrane stress is the dominant component. Moreover, as there is only extension stress and not bending stress in the plate, the analysis of the plate with traditional "plastic hinge" method is unsuitable.

As the complex deforming process does not need to be considered in the energy method, using similar formula of energy, a solution suitable for the approximation of the adopted model can be got, and the result is concise and practical. Therefore, an energy method is adopted for the analysis of membrane effect of rectangular plates in this paper.

4 Solution process

4.1 Strain energy of heavily deformed rectangular plate

The strain energy per unit in a plate is

$$\mathrm{d}U_p = \sigma_{xx}\mathrm{d}\varepsilon_{xx} + \tau_{xy}\mathrm{d}\gamma_{xy} + \tau_{yx}\mathrm{d}\gamma_{yx} + \sigma_{yy}\mathrm{d}\varepsilon_{yy}\,. \quad (1)$$

The strain energy of heavily deformed rectangular plate consists of bending strain energy U_1 and extensional strain energy U_2.

$$U_p = U_1 + U_2\,.$$

For U_1, the normal bending strains and shearing strain are

$$\begin{cases} \varepsilon_{xx} = -Z\dfrac{\partial^2 w}{\partial x^2} \\ \varepsilon_{yy} = -Z\dfrac{\partial^2 w}{\partial y^2} \\ \gamma_{xy} = -2Z\dfrac{\partial^2 w}{\partial x\partial y} \end{cases}.$$

A rigid-plastic material is assumed, according to Von.Mises yield criteria:

$$\sigma_{xx} = \sigma_s\,,\ \ \sigma_{yy} = \sigma_s\,,\ \ \tau_{xy} = \tau_{yx} = \sigma_s/\sqrt{3}\,.$$

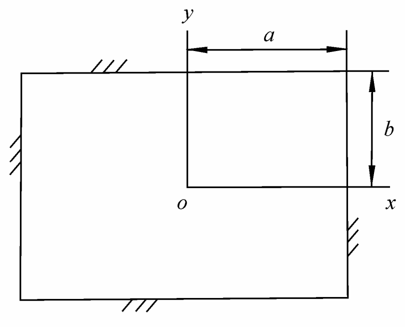

Fig.1 Configuration of the plate

The thickness of the plate is h, according to Fig.1,

$$U_1 = 4\int_0^a\int_0^b\int_{-h/2}^{h/2}[\sigma_s(-Z\frac{\partial^2 w}{\partial x^2} - Z\frac{\partial^2 w}{\partial y^2}) + \frac{2}{\sqrt{3}}\sigma_s(2Z\frac{\partial^2 w}{\partial x\partial y})]\mathrm{d}x\mathrm{d}y\mathrm{d}z. \quad (2)$$

The normal extensional strains and shearing strain are

$$\begin{cases} \varepsilon_x = \dfrac{1}{2}(\dfrac{\partial w}{\partial x})^2 \\ \varepsilon_y = \dfrac{1}{2}(\dfrac{\partial w}{\partial y})^2 \\ \gamma_{xy} = \dfrac{\partial w}{\partial x}\dfrac{\partial w}{\partial y} \end{cases}. \quad (3)$$

The deduction process of Eq.(3) can be found in Ref.[6].

The extensional strain energy is given by

$$U_2 = 4h\int_0^a\int_0^b\{\sigma_s[\frac{1}{2}(\frac{\partial w}{\partial x})^2 + \frac{1}{2}(\frac{\partial w}{\partial y})^2] + \frac{2}{\sqrt{3}}\sigma_s(\frac{\partial w}{\partial x}\frac{\partial w}{\partial y})\}\mathrm{d}x\mathrm{d}y. \quad (4)$$

A deformed shape function of the form is given by

$$.\ w = \frac{w_0}{4}(1+\cos\frac{\pi x}{a})(1+\cos\frac{\pi y}{b})\,. \quad (5)$$

Then the strain energy of the plate is

$$U_1 = [\frac{\pi}{2}(\frac{b}{a}+\frac{a}{b}) + \frac{4}{\sqrt{3}}]h^2\sigma_s w_0\,, \quad (6)$$

$$U_2 = [\frac{3\pi^2}{32}(\frac{b}{a}+\frac{a}{b}) + \frac{8}{\sqrt{3}}]h\sigma_s w_0^2\,, \quad (7)$$

where w_0 is the deformation of the plate center.

Actually, when the plate is heavily deformed, the bending strain energy is much lower compared with the extensional strain energy. Taking square plate as an example, the ratio is

$$\frac{U_2}{U_1} \approx 1.5\frac{w_0}{h}\,.$$

If $w_0 = 10h$, then U_2=15U_1. So the analysis of the capacity of protective bulkhead can neglect the bending strain energy of the plate completely. Thus $U_p \approx U_2$.

4.2 Kinetic energy of the plate

The kinetic energy of the rectangular plate is given by

$$E_k = \frac{\rho h}{2}\int_{-a}^{a}\int_{-b}^{b}\dot{w}^2\,\mathrm{d}x\mathrm{d}y = \frac{\rho h}{2}ab\,\dot{w}_0^2 . \tag{8}$$

In Eq.(8), ρ is density of the plate.

4.3 Blast loading and shock wave kinetic energy

Assuming blast loading $p(t)$ is uniformly distributed among the plate vertically, the generalized force is decided by the virtual work which is done by the pressure $p(t)$ along the virtual displacement.

$$\delta W = p(t)\mathrm{d}x\mathrm{d}y\delta w . \tag{9}$$

Substituting w by Eq.(5), Eq.(9) modifies to

$$\delta W = \frac{1}{4}(1+\cos\frac{\pi x}{a})(1+\cos\frac{\pi y}{b})p(t)\mathrm{d}w_0 . \tag{10}$$

Integrating Eq.(10),

$$W = \int_0^{w_0}\int_{-b}^{b}\int_{-a}^{a}\frac{1}{4}(1+\cos\frac{\pi x}{a})(1+\cos\frac{\pi y}{b})p(t)\mathrm{d}x\mathrm{d}y\mathrm{d}w = w_0 abp(t). \tag{11}$$

4.4 Calculation of the plastic deformation

When dealing with problems of dynamic mechanics, Lagrange function can be used. Lagrange function is defined as follows:

$$L = k_e - U_p . \tag{12}$$

The Lagrange equation is given by

$$\frac{\mathrm{d}}{\mathrm{d}t}(\frac{\partial L}{\partial \dot{w}_0}) - \frac{\partial L}{\partial w_0} = \frac{\partial W}{\partial w_0} . \tag{13}$$

The motion equation of center of the plate is deduced:

$$\ddot{w}_0 + \frac{3\pi^2\sigma_s}{16\rho ab}(\frac{b}{a}+\frac{a}{b})w_0 = \frac{p(t)}{\rho h} . \tag{14}$$

The damage effect of the bulkhead by the shock wave is associated with the loading time t_+. If t_+ is much shorter than the vibration period T of the structure itself, i.e. $t_+ << T$, the damage effect of the structure is dependent on the impulse i of the shock wave, otherwise if $t_+ >> T$, then it depends on the maximum pressure ΔP_m of the shock wave.

For the protective bulkhead, $t_+ << T$, so the blast loading can been simplified to a rectangular impulsive loading in Eq.(14).

The loading can be given as follows:

$$p(t) = \begin{cases} p & 0 \le t \le \tau \\ 0 & t \ge \tau \end{cases} . \tag{15}$$

So the deformation of the plate center is

$$w_0 = \frac{32}{3}\frac{a^2b^2p}{\pi^2\sigma_s h(a^2+b^2)}\sin(\frac{\pi\tau}{8ab}\sqrt{\frac{3\sigma_s}{\rho}(a^2+b^2)}) . \tag{16}$$

When $\tau \to 0$, $\sin\omega t \approx \omega t$. As $i = p\cdot\tau$, it can be deduced that

$$w_0 = \frac{4}{\pi\sqrt{3}}\frac{abi}{h\sqrt{\sigma_s\rho(a^2+b^2)}} . \tag{17}$$

4.5 Limiting value of the plate

For this kind of bulkhead in the complete membrane mode, the ultimate capability depends not only on the allowable maximum stress but also on the allowable maximum deformation or allowable maximum strain.

It is very difficult to propose the ultimate deformation of the structure, which involves the loading form, feature of material and structural strain rates, all of them are non-linear.

Assuming ε_{mn} is the maximum dynamic strain of the bulkhead and when one of the two-dimensional strains ε_x and ε_y reaches ε_{mn}, the bulkhead is cracked.

The extensions of the bulkhead in two-dimension x and y are respectively

$$\delta_x = \int_{-a}^{a}\frac{1}{2}(\frac{\mathrm{d}w}{\mathrm{d}x})^2\mathrm{d}x = \frac{\pi^2 w_0^2}{8a}(1+\cos\frac{\pi y}{b})^2 , \tag{18}$$

$$\delta_y = \int_{-b}^{b}\frac{1}{2}(\frac{\mathrm{d}w}{\mathrm{d}y})^2\mathrm{d}y = \frac{\pi^2 w_0^2}{8b}(1+\cos\frac{\pi x}{a})^2 . \tag{19}$$

Obviously, the two-dimensional maximum deformations appear at the center of the plate:

$$\delta_{x0} = \frac{\pi^2 w_0^2}{8a} , \tag{20}$$

$$\delta_{y0} = \frac{\pi^2 w_0^2}{8b} . \tag{21}$$

The ultimate extension of the bulkhead can be given as

$$\delta_{x0} = \frac{\pi^2 w_0^2}{8a} \le 2a\varepsilon_{mn} , \tag{22}$$

$$\delta_{y0} = \frac{\pi^2 w_0^2}{8b} \le 2b\varepsilon_{mn} . \tag{23}$$

The minimum of a, b is adopted, assuming it is b, then:

$$w_0 \le \frac{4b}{\pi}\sqrt{\varepsilon_{mn}} . \tag{24}$$

The suggested value of ε_{mn} given in Ref.[1] is 0.2888, and ε_{mn} given in Ref.[10] is 0.23 for the steel that σ_y =400 MPa.

4.6 Examples

Calculation is done using the test data given in Ref.[8]. The results of calculation and experiment are compared as shown in Table 1.

The length of the square plate is 508 mm, the explosive is 14.5 kg in weight.

The comparison shows that the theoretical results comply well with the experimental results, which indicates that the theoretical method is of engineering practical value.

Table 1 Results of calculation and experiment

Thickness/mm	Distance/cm	Yield stress/MPa	Central displacement of the plate (experimental)/mm	Central displacement of the plate (theoretical)/mm
3.4	305	260	26	26.6
1.5	305	285	62	57.5
3.4	244	260	34	33.2
1.5	244	285	73	71.9

5 Demands of the bulkhead design

1) The design concept of protective longitudinal bulkhead is not the same as that of a normal panel of ships. The traditional method that adding beams on the plate to form a panel to enhance the stiffness so as to increase the protective capability is not used anymore. The plate is designed working in the membrane mode, the energy is much more absorbed by the heavy deformation of the plate, and the protection is carried out by the failure of the plate itself. As to the protective capability, slender plate is better. The elastic connection between the plate and the adjacent longitudinal bulkhead is necessary.

2) Making the plate work in membrane mode, the conditions of both size and supporting must be satisfied. For the plate size, although when $\beta = \frac{b}{t}\sqrt{\frac{\sigma_s}{E}} \geq 2.4$ the plate has a good membrane effect, it is said that if the pure membrane mode is expected, $b/t \geq 100$ is necessary. Deduced from it, $\beta \geq 13.8$ is necessary for the steel whose yield stress is 400 MPa and $\beta \geq 19.5$ for 800 MPa. Moreover, the normal welding which can not prevent the heavy deformed plate from moving toward center is insufficient for the boundary conditions of the plate. The special reinforcement of the boundary is necessary, so it is a feasible method to thicken the four ends of the plate.

6 Summary and conclusions

In this paper the response of protective bulkhead subjected to blast loading is investigated by energy method, from which the final deflection and the ultimate deflection are obtained. The theoretical results show good concordance with experimental results. The demands in protective bulkhead design are also discussed in details. So this paper will lay good theoretical foundation for the protective bulkhead design.

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爆炸荷载作用下的舰船防护舱壁的承载能力

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摘　要：大型水面舰船的防护舱壁需要设计成工作在薄膜应力状态下. 利用能量法推导了在爆炸荷载作用下防护舱壁塑性大变形的计算公式、探讨了防护舱壁的最大承载能力，对防护舱壁的设计要求进行了讨论. 与国外发表的有关试验结果进行了计算比较，结果表明该方法具有一定的应用价值.

关键词：防护舱壁；爆炸荷载；能量法