水面舰艇舱内爆炸毁伤载荷研究进展

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摘要 随着大型水面舰艇防护结构的增强, 具有显著攻击优点的反舰导弹发展极为迅猛, 是各国海军研究的重点对象, 该武器能够穿透外层甲板, 在关键舱室内爆炸, 从而摧毁大型水面舰艇的关键系统, 因此掌握反舰导弹舱内爆炸的毁伤载荷特性对于舰船水上防护结构的设计至关重要. 本文系统地总结了反舰导弹在舱内爆炸后, 三类毁伤元的形成过程及其载荷特性的研究进展, 从三种舱内爆炸载荷——冲击波、准静态压力和高速破片群出发, 系统地回顾了三种载荷的形成机理、计算公式及其造成的损伤模式, 最后提出了舱室内爆毁伤的研究方向以及有待进一步深入研究的问题.

关键词 舱内爆炸, 冲击波, 准静态压力, 破片

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1 引言

近年来, 国内外的反舰武器迅猛发展, 产生了各类具有多样化攻击特点的反舰武器^[1], 其隐蔽性、命中精度和战斗部装药当量都在不断提高. 尤其是针对大型水面舰艇的半穿甲反舰导弹能够掠海飞行, 避开雷达的探测^[2], 对舰船产生严重破坏.

相比自由场爆炸, 反舰导弹在舱室内爆炸更加复杂, 其载荷形式主要有三种: 反射冲击波、破片以及准静态压力载荷. 其中, 反射冲击波载荷是由作用时间很短的脉冲波组成; 准静态压力载荷指的是振荡稳定后, 持续存在在密闭舱室内的压力载荷, 幅值相对

较小, 但作用范围广^[3]; 高速破片则是在战斗部完成轰爆后, 由导弹金属壳体碎裂产生, 尽管该类载荷持续时间短, 作用在舱室局部, 但穿透力强, 易产生设备和人员的损伤.

据文献[4-6]统计, 20世纪80年代以来的实战或试验中, 在反舰导弹作用下, 国内外各类舰船的损毁或沉没的主要原因是反舰导弹弹头穿透部分船体外部结构, 并在舱室内爆炸, 产生的冲击波、准静态压力、破片对内部结构造成了重大破坏^[7,8], 进而导致舰船严重毁伤. 因此, 为提高大型水面舰艇的防护能力, 对舱内爆炸后产生的冲击载荷特征及对结构的毁伤机理研究具有重要价值.

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2 冲击波载荷

在舱室内爆等效载荷的研究中, 美国标准UFC-3-340-02认为舱室内的载荷可分为两段: 第一段是三角形冲击波脉冲, 第二段是舱内空气趋于稳定后形成的低幅值、长脉宽的准静态压力载荷^[9]. 其中舱室内爆炸冲击波的形成过程为: 炸药在舱内爆炸后, 瞬间转变成高温、高压的爆轰产物, 并快速膨胀, 压缩空气形成冲击波; 冲击波遇到舱壁会发生反射, 形成反射冲击波, 各壁面形成的反射冲击波会在舱内相遇时或遇到舱壁而再次发生反射. 如此往复, 直到舱内压力趋于稳定(准静态压力阶段), 舱内爆炸冲击波加载阶段完成^[10-12].

对于舱室结构, 通常采用经典的“三波法”来描述舱内复杂的反射冲击波载荷, 但此方法理想化地将舱室板中心处的载荷应用到整个舱壁上, 且没有考虑反射冲击波在舱室角隅处的汇聚情况^[13,14].

在衡量爆炸冲击波的强度中, 一般是以霍普金森的爆炸相似律作为主要依据^[15], 计算冲击波峰值超压^[16-19]、正压作用时间^[20]以及比冲量^[21]. 尽管通过比较正压区时间与目标结构的谐振周期, 可选择合适的毁伤准则^[22], 但目前的冲击波正压时间多基于远场经验公式估算而来, 然而大量试验结果表明冲击波正压作用时间并不与经验公式完全相符^[23,24]. 因此, 姬建荣等人^[25]基于自由场静爆试验, 分析了经典经验公式在不同传播距离下的适用性, 并拟合了新的正压时间经验公式.

3 准静态压力载荷

3.1 关键参数及经验公式

如前文所述, 在舱内爆炸的冲击波阶段结束后, 舱室空气趋于稳定, 进入到准静态阶段^[26,27], 该阶段的载荷特点是峰值小、脉宽长、冲量很大, 对舱室的整体毁伤起着极其重要的作用^[3]. 因此, 为获得能够在工程应用中准确预测准静态压力的方法, 李营等人^[28]基于实验验证了Feldgun预测准静态压力的理论公式^[29]. 同时, 总结了近年来国内外通过大量实验和理论获得的最大准静态压力计算公式, 如表1所示^[30-38].

从表1可以发现, 国内对准静态压力的研究已经取得了一些重要成果, 但受实验条件所限, 其适用范围仍

具有一定的局限性. 为准确计算密闭空间内爆炸准静态压力, 在图1所描述的示意图中, 张玉磊等人^[38]在考量影响准静态压力的药量-容积比后, 以爆炸罐(容积 26 m^3)和爆炸舱室(容积 2.013 m^3)为典型密闭空间环境开展了系列TNT内爆炸实验, 并拟合得到了场内爆炸准静态压力峰值的经验公式. 舱内爆炸时, 除准静态压力峰值外, 其衰减规律也是关注的重点, Baker在文献^[39]中给出准静态压力随时间衰减的经典计算方法, 并依据准静态压力的衰减公式, 进一步获得了准静态压力的总冲量表达式^[40].

3.2 影响准静态压力的环境因素

准静态阶段载荷受两个因素的影响, 一是爆炸自身释放能量, 特点是能量释放迅速, 在微秒量级; 二是爆炸产物发生化学反应释放能量, 该过程相对缓慢, 为毫秒量级. 基于准静态阶段的载荷形成过程, 除药量容积比外, 探究环境因素对化学反应的影响具有重要意义, 因此 Ornellas^[41]通过球形容器内爆试验, 发现真空中爆炸释放出来的能量小于爆炸发生在氧气环境中的能量; Kuhl课题组^[42-47]发现约束爆炸的气体产物中所包含的C和CO等易燃物在与空气中的氧气发生化学反应后, 会导致内压力明显上升. 由于爆炸产物与空间内的氧气等气体发生化学反应会对准静态压力造成影响, 说明后续燃烧效应对准静态压力有显著影响^[48].

基于燃烧效应, 国外研究人员通过实验得到了准静态压力和总燃烧热之间的关系, 并建立了基于准静态压力的炸药内爆炸效应评估方法^[49-51]. 国内的科研工作者同样通过试验得出在氧气存在下, TNT炸药的后燃烧效果较明显, 能够产生更大的准静态压力的结论^[52]. 徐维铮和吴卫国^[53,54]通过数值仿真表明, 后续燃烧效应是影响准静态压力的重要因素, 并基于冲量

图1 舱内爆炸试验. (a) 爆炸罐; (b) 爆炸舱

Figure 1 In-cabin explosion test. (a) Explosion vessel; (b) explosion chamber.

表 1 最大准静态压力峰值计算公式

Table 1 Maximum quasi-static pressure peak calculation formula

作者	时间	实现方式	实验条件	公式内容	使用范围
Carlson ^[31]	1945	试验	两半球合成的球体(直径约为25 inch), 单发最大18磅	$P_{qs}=1.30m/V$ P_{qs} 为压力峰值(MPa), m 为炸药质量(kg), V 为容器体积(m^3)	对于多数的HE(早期)
Moir ^[32]	1979	试验	—	$P_{qs}=(1.34\pm0.19)m/V$ m 为炸药质量(kg), V 为容器体积(m^3)	对于多数的HE(早期)
Anthony和Foster ^[33]	1985	试验	3个合金钢容器, 以容纳预由LX-13重量体积比(0.06:1至3.50:1 lb/ft)产生的压力	$P_{qs}=0.97m/V$ m 为炸药质量(kg), V 为容器体积(m^3)	仅适用于LX-3(早期)
英国劳式军规 ^[30]	1960至今	试验	—	$p_{qs} = 2.25 \left(\frac{W}{V} \right)^{0.72}$ W 装药质量(kg), V 密闭空间体积(m^3)	适用于大部分情况
Anderson等人 ^[34]	1983	试验	—	$P_{qs} = \begin{cases} 1.336p_0 \left(\frac{E}{p_0 V} \right)^{0.6717} - p_0, & \frac{E}{p_0 V} \leq 350 \\ 1.388p_0 \left(\frac{E}{p_0 V} \right) - p_0, & \frac{E}{p_0 V} > 350 \end{cases}$ E 单位重量炸药所含能量, p_0 大气压强(MPa), V 密闭空间体积(m^3)	适用于HE
Lee等人 ^[35]	2005	试验	—	$P_{qs} = 0.146 + 0.193\Delta H$ ΔH 为炸药的总燃烧热(J)	认为准静态压力是炸药总燃烧热的单值函数, 限制了它的适用范围
王等旺等人 ^[36]	2012	试验	容器内径195 mm, 总长1380 mm, 药量8/27/133 g TNT当量	$P_{qs} = \begin{cases} 1.48 \frac{Q}{V}, & \frac{Q}{V} < 1.8 \text{ kg/m}^3 \\ 1.7 + 0.5 \frac{Q}{V}, & \frac{Q}{V} > 1.8 \text{ kg/m}^3 \end{cases}$ Q 为爆炸TNT当量(kg), V 密闭空间体积(m^3)	特定条件(未体现氧化剂含量和炸药的氧平衡对准静态的影响)
李鸿宾等人 ^[37]	2014	试验	爆炸罐(0.5 m^3)药量35/80/100 g TNT当量	$p_{qs} = 0.117 \frac{\Delta H}{V} = 3.947W$ $W \leq 0.185 \text{ kg}$ ΔH 炸药爆炸能量, 包括爆炸能和后燃烧能(J), V 密闭空间体积(m^3)	适用于特定条件下的计算
张玉磊等人 ^[38]	2018	试验	爆炸罐(26 m^3)和舱室(2.013 m^3)药量分别为0.5/1/2/4 kg和30 g TNT当量	$P_{qs}=1.394(m/V)^{0.679}$ m 为炸药质量(kg), V 为容器体积(m^3)	0.019≤ m/V ≤8.87的TNT内爆

等效原则, 提出爆炸载荷的简化计算公式^[55]. 钟巍等人^[56]基于爆炸后产物膨胀过程的等压假设模型, 建立了密封容器中发生的爆炸准静态压力计算公式, 为预测约束爆炸后的准静态压力提供估算方法.

4 破片载荷

4.1 破片的形成机理

反舰导弹穿甲进入船体内部舱室爆炸, 除冲击波

和准静态压力外, 战斗部爆炸后产生的爆轰压力会作用于反舰导弹壳体的内壁面, 周向壁面会在径向压力的作用下膨胀, 最终形成飞散的破片, 会对船体结构、设备、人员造成很大的破坏^[57].

Taylor^[58]最早提出壳体断裂的拉伸应力准则, 但所假设的模型受限于低应变率条件. 对于高应变率情形, Hoggott和Recht^[59]对该准则进行了改进, 提出壳体内壁面剪切带向外扩展形成裂纹的观点, 但其适用范围仍具有一定的局限性. 因此, 考虑应变率效应的圆

柱壳半经验断裂准则^[60]、应变和应变率的双变量断裂准则^[61]的应用更为广泛. 除圆柱形装药外, Al-Hassani等人^[62]将Taylor理论应用到球形装药的类型中.

4.2 关键参数及相关公式

破片形成的过程可简单描述为在爆轰产物作用下, 导致壳体结构剧烈膨胀变形, 进而产生了大量高速破片并以一定的初速度向周围飞散, 形成极具穿透力的高动能点群载荷, 在对其进行毁伤效能评估时, 需要重点考虑以下关键参数: 决定破片穿透船体板能力的破片尺寸、速度和质量, 影响着结构破坏程度的破片质量以及空间分布.

对于破片的周向分布, 其破片尺寸的计算有两种方法: 一是可基于平均尺寸的Mott公式^[63], 二是从能量的角度出发, Grady和Hightower^[64]提出了钢质壳体形成破片的理论模型, 基于试验数据, Arnold和Rottenkolber^[65]也进一步讨论了该理论的适用性.

在推算破片初速度上, Gurney能量法应用最为广泛, 如式(1)所示^[66]:

$$v_0 = \sqrt{2E} \sqrt{\frac{\beta}{1+0.5\beta}}, \quad (1)$$

其中, $\beta = \frac{C}{M}$ 为战斗部的爆炸载荷系数, $\sqrt{2E}$ 为Gurney能量常数.

随后, 大部分对破片初速度的研究, 都是对Gurney

公式进行的改进或修正^[67], 如采用几何等效修正 β ^[68,69]、对Gurney能量 $\sqrt{2E}$ 进行修正^[70,71]、基于实验数据提出修正函数^[72]以及端面单点起爆情况下, 获得破片速度的计算公式^[73,74].

在破片载荷特征的研究中, 破片质量以及空间分布是破片群打击能力的重要依据, 常用的破片质量分布形式共有7种^[75], 如表2所示^[76-80].

国内外关于破片的空间分布的研究, 主要是分析破片飞散角度, 按照战斗部外形, 可分为柱形壳体^[81,82]和非柱形壳体飞散角度^[83,84].

5 爆炸载荷对结构的毁伤研究

5.1 破片、冲击波联合作用下的损伤模式

早期, 对于战斗部空中爆炸的毁伤研究主要是将其解耦成冲击波^[85]和破片^[86]单独的作用. 随后的研究发现, 两种毁伤元冲击波和破片的耦合破坏不是二者破坏效应的简单叠加, 而会对结构产生更严重的破坏^[87,88]. 国外对于两种毁伤元耦合破坏效应的研究对象以建筑结构及混凝土构件居多^[89,90], 但舰船板架与建筑结构区别较大, 为更真实地模拟冲击波及破片的耦合毁伤效果, 杜志鹏、吴震等人^[91,92]采用SPH-FEM模拟了破片与冲击波对固支方板的耦合毁伤过程, 并进行了耦合毁伤效应试验, 如图2所示, 最终给出了光板在破片与冲击波联合作用下主要的2种破坏模式: 花

表 2 常用的破片质量分布形式^{a)}

Table 2 Commonly used fragment mass distribution forms^{a)}

分布类型	Mott分布 ^[76]	普适的Mott分布	对数正态分布 ^[77]
公式	$N(m) = \exp\left[-\left(\frac{m}{\mu}\right)^2\right]$	$N(m) = \exp\left[-\left(\frac{m}{\mu}\right)^\lambda\right]$	$N(m) = \frac{1}{2}\left[1 - \operatorname{erf}\left(\frac{\ln m - \mu}{\sqrt{2}\sigma}\right)\right]$
特点及适用性	薄壁	考虑了厚壁	以对数正态分布描述破片分布
分布类型	Grady(普适Mott分布中特例即 $\lambda=1$) 和普适的Grady分布	Weibull分布 ^[78,79]	Hled分布 ^[80]
公式	$N(m) = f \exp\left(-\frac{m}{\mu_1}\right) + (1-f) \exp\left(-\frac{m}{\mu_2}\right)$	$N(m) = \frac{1}{\Gamma\left(1-\frac{1}{\lambda}\right)} \Gamma\left(1-\frac{1}{\lambda}, \left(\frac{m}{\mu}\right)^\lambda\right)$ 其中 $\lambda=1$, $\Gamma(a, x) = \int_x^\infty t^{a-1} e^{-t} dt$	$M(n) = M_0[1 - \exp(-Bn^\lambda)]$
特点及适用性	考虑了破片的非均匀性	双参数Weibull分布可准确描述 三维破碎中弹壳的质量分布	忽略大约1%~2%的最重碎片

a) $N(m)$ 为质量大于 m 的破片总数, μ 为破片的平均质量; $M(n)$ 为累积破片质量, B 比例参数, λ 为形状参数.

图 2 (网络版彩图)光板背爆面的毁伤情况^[91](图片来自文献, 已获得授权). (a) 爆距0.25 m; (b) 爆距0.75 m; (c) 爆距1 m; (d) 爆距1.5 m

Figure 2 (Color online) Damage of back plane plates. Adapted from ref. [91]. (a) Distance 0.25 m; (b) distance 0.75 m; (c) distance 1 m; (d) distance 1.5 m.

瓣弯曲破坏和拉伸断裂破坏.

冲击波和破片联合作用时, 哪种毁伤元更先作用于舱室结构是研究损伤效应的关键. 国外对两者联合作用的研究中, 一般假设破片先于冲击波到达, 仅适用于远距离爆炸的情况^[93,94]. 但舱室内爆多为近距离爆炸, 为探讨破片式战斗部空中爆炸下冲击波与破片的先后作用机制, 陈长海等人^[95]建立了冲击波与破片先后作用临界爆距的理论计算模型, 得出战斗部装填系数、装药类型、壳体厚度对临界爆距值的影响较大.

5.2 结构毁伤的研究进展

舱内爆炸对舰船的损伤一直备受关注. 早期, 研究局限于梁和板等简单结构的非线性大变形问题^[96]. 20世纪90年代起, 人们开始研究加筋板结构在爆炸载荷下的动态响应, 并提出变形和破损的计算公式^[97-99]. Menkes和Opat^[100]通过对固支铝制金属梁的实验研究, 首先提出了爆炸载荷下梁的3种失效模式. 随后, 在爆炸冲击载荷下圆板^[101]和方板^[102,103]的失效中也观察到了类似的失效模式. 在对纵横比 $\gamma > 1$ 的矩形板架变形模式的研究中, Yuan和Tan^[104]总结了近40多年来矩形板架爆炸变形破损的研究成果, 采用平板的无量纲位移 w_0/h 和无量纲冲量 I^* 作为表征参数, 从而获得矩形板

架的毁伤模式. 但没有考虑近距离爆炸的能量远大于板架弯曲塑性变形能量时板架的损伤模式, 如花瓣破口.

图3中, 杜志鹏等人^[105]通过实尺度舰船舱内炮弹静爆试验(爆距为0-0.5 m的实弹和等效裸炸药)对文献^[104]进行了补充. 舱室结构在近距离爆炸产生的非均匀冲击波和破片的共同作用下, 发生了局部花瓣破口损伤模式, 如图4所示.

为进一步提高水面舰船在舱体内爆载荷作用下, 舱内结构的抗爆性能, 国内科研人员同样进行了许多研究. 早期国内则多采用缩比模型方法开展研究, 如侯海量和朱锡等人^[106,107]对1:4缩比舱室模型进行了静爆试验, 研究了舱内爆炸产生过的冲击载荷及其作用过程, 提出了内爆载荷在角隅处聚集、结构在角隅处撕裂的失效模式; 王佳颖等人^[108]提出双层横舱壁的抗爆形式, 分析了在舱内冲击波载荷下, 板架结构的失效

图 3 (网络版彩图)局部花瓣破口损伤模式^[105](图片来自文献, 已获得授权). 爆距0 m (a)和0.1 m (b)的破口

Figure 3 (Color online) Failure mode of partial petal crevasse. Adapted from ref. [105]. Breach with distance 0 m (a) and 0.1 m (b).

图 4 (网络版彩图)均布加载下的平板损伤^[105](图片来自文献, 已获得授权)

Figure 4 (Color online) Flat plate damage under uniform load. Adapted from ref. [105].

模式, 并提出了相应的结构改进方案. 李营等人^[109]以固支金属方形板为研究对象, 基于试验和仿真分析, 阐明了舱内爆炸作用下水密舱壁破坏模式和失效机理.

从冲击载荷的能量角度出发, 考虑到爆炸冲击波对目标的毁伤效能与冲击波各频段的能量分布密切相关^[110], 李丽萍等人^[111]采用分析爆炸冲击波能量谱的方式来进行战斗部的毁伤效能评估.

除板架和舱室局部结构响应研究外, 对多舱室的毁伤模式研究中, 李营等人^[112]开展了多舱结构在舱内爆炸作用下的毁伤特性实验, 探讨了多舱室结构的毁伤特点, 如图5所示. 同时, 研究爆炸对结构损伤的重要方法-量纲理论, 如梁板塑性动力响应无量纲数^[113], 被广泛用于毁伤模式的研究中, 姚术健等人^[114]研究了多箱室结构在内部爆炸载荷作用下的损伤特性, 基于JOHNSON-COOK^[115]模型的ANSYS/LS-DYNA仿真和多箱体内爆试验, 总结了箱体的5种破坏模式, 并采用量纲理论得出预测破坏模式的经验公式. 焦晓龙等人^[116]基于仿真与量纲理论, 研究了不同药量TNT内爆下多舱室毁伤模式临界转换判据的无量纲毁伤数.

6 结论

由于舰船舱室内战斗部爆炸过程的复杂性, 在目前的研究中至少还存在以下问题, 需要进一步展开

图 5 (网络版彩图)多舱室爆炸实验^[112](图片来自文献, 已获得授权)

Figure 5 (Color online) Multi-cabin explosion experiment. Adapted from ref. [112].

研究.

(1) 多数舱室内爆毁伤研究仅针对于板架或单舱室结构, 并不能满足大型水面舰船毁伤评估的工程需求. 因此, 在未来展开对多舱室内爆毁伤机理的深入研究具有重要价值.

(2) 现阶段少量对多舱室毁伤的研究中, 通过量纲分析方法, 建立结构毁伤模式的临界转换判据-无量纲毁伤数时, 研究对象均是规则舱室, 忽略了不同舱室体积比等无量纲参量对毁伤模式的影响, 故有必要结合实际典型舱室的结构形式展开进一步研究.

(3) 由于舱室内爆试验成本较高, 所以研究人员往往利用仿真软件获得结构的动力响应, 但计算时间较长. 因此, 如何结合三类毁伤元的载荷特点与结构响应的关键点, 提出简化模型或公式, 形成便捷、准确的快速算法, 仍是未来重要的研究方向, 值得进一步探索.

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Research advance of damage load of surface ship cabin explosion

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With the enhancement of the ship's protective structure, the development of anti-ship missiles with significant attack advantages is extremely rapid. This type of weapon can penetrate the outer deck and explode in crucial compartments, thus destroying the functional systems of the ship. Therefore, it is very important to master the load characteristics of anti-ship missile cabin explosion for the design of ship's protective structure. This paper systematically summarizes the research progress of the formation and characteristics of three types of explosion loads after the anti-ship missile explodes in the cabin. Starting from the types of explosive loads in the cabin-shock wave, quasi-static pressure and high-speed fragment group, we systematically review their formation mechanism, calculation formula and structural damage modes, and finally propose the research direction of cabin blast and the problems to be further studied.

cabin explosion, shock wave, quasi-static pressure, fragment

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