舰船结构舱内爆炸毁伤与防护研究进展

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摘要 舰艇是海军赖以生存和打击敌军的平台, 也是发生海上战争时敌军的主要攻击对象. 反舰导弹是舰艇面临的主要威胁之一, 其主要攻击模式是侵彻舰船甲板或舷侧外板进入舰船内部发生爆炸. 本文将舰船结构舱内爆炸毁伤与防护研究分为载荷特性、结构响应和防护技术三个方面, 分别论述了其研究进展. 首先介绍了舱内爆炸的载荷特性, 其次分析了舰船结构的毁伤效应, 然后总结了防护技术的研究现状, 最后对未来的研究工作提出一些建议.

关键词 舰艇结构, 舱内爆炸, 毁伤特性, 防护技术

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1 引言

舰艇是海军赖以生存和打击敌军的平台, 也是发生海上战争时敌军反舰武器的主要攻击对象^[1]. 反舰导弹是舰艇面临的主要威胁之一, 其主要攻击模式是侵彻舰船甲板或舷侧外板进入舰船内部发生爆炸, 对舰艇内部重要舱室形成严重毁伤^[2,3]. 如图1所示, 关于舰艇结构舱内爆炸的研究主要集中在舱内爆炸载荷特性、舰船结构动态响应和抗弹抗爆防护技术三个方面.

本文首先总结了反舰导弹战斗部内爆产生的载荷特性方面的研究进展. 反舰导弹战斗部内爆产生的主要毁伤元包括冲击波压力、准静态压力、高速破片群

等, 各种毁伤元之间互相耦合, 导致战斗部舱内爆炸载荷非常复杂. 其次总结了舰船结构在反舰导弹战斗部内爆作用下的毁伤特性方面的研究进展. 由于舱内爆炸载荷的复杂性, 舰船结构在战斗部舱内爆炸作用下的毁伤机理十分复杂, 造成舰船结构的严重毁伤. 然后总结了舰船舱内爆炸传统防护及新型防护技术的研究进展. 舱内爆炸产生的冲击波压力、准静态压力、高速破片群等每种毁伤元都有特定的毁伤作用, 针对特定的载荷开展防护设计对提高舰船的防护水平和生命力具有重要意义. 最后, 本文在梳理分析舰船结构舱内爆炸毁伤与防护的研究现状基础上, 对今后舰船防护结构设计及发展方向做了展望, 以期能够为后续的研究和工程应用提供一些参考.

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图 1 (网络版彩图)舰艇舱内爆炸毁伤与防护研究

Figure 1 (Color online) Research on damage and protection of the warship under internal blast.

2 舱内爆炸载荷特性研究现状

反舰导弹战斗部在舰船舱内发生爆炸时, 会形成复杂冲击波载荷、准静态压力及高速破片群等载荷, 舱内爆炸载荷的研究一直受到学者们的广泛关注. 本文将冲击波载荷和准静态压力统称为舱内爆炸压力载荷, 论述了舱内爆炸压力载荷和破片载荷的研究现状.

2.1 舱内爆炸压力载荷

半穿甲反舰导弹进入舰船舱室结构内发生爆炸, 爆距不同会导致舰船结构受到的冲击载荷有所区别. 对于近距离爆炸, 爆轰产物会直接作用于结构表面; 对于远距离爆炸, 爆轰产物不能直接到达, 而是由冲击波和破片作用于结构^[4].

关于爆炸载荷特性的研究可以追溯到第一次世界大战, Hopkinson^[5]提出了著名的Hopkinson比例定律, 即 $Z = \frac{R}{W^{1/3}}$, 其中 Z 为比例距离, R 为距爆源中心的距离, W 为炸药当量. Stoner和Bleakney^[6]通过试验研究了不同形状的TNT爆炸压力载荷特性. Brode^[7,8]采用有限差分法计算了自由场空爆冲击波的特征参数. Goodman^[9]统计了二战后进行的爆炸载荷特性测量情况, 随后Baker^[10]开展了大量爆炸试验, 并将试验结果整理成册, 以直观的形式表达出来. 后来, Henrych等人^[11]、Kingery等人^[12]、Smith等人^[13]基于模型和试验结果, 给出了一定爆距下的自由空气爆炸产生的爆炸

峰值超压和TNT当量表达式.

舱内爆炸压力载荷与空中自由场爆炸有明显不同, 反舰导弹战斗部在舰船舱室内发生爆炸时, 由于舰船舱室结构的反射和密闭作用, 冲击波在舱内会发生多次反射叠加, 并存在持续时间较长的准静态气体压力^[14-20]. Baker等人^[21]提出炸药在结构内部爆炸时产生的压力载荷存在两个阶段. 第一阶段由持续时间短的入射冲击波和反射冲击波组成, 反射冲击波由几个不规则反射脉冲叠加而成, 由于冲击波的不规则反射, 结构内部的反射过程较为复杂. 第二阶段是峰值较低但持续时间较长的准静态压力载荷作用阶段. 李营^[2]开展了舱内爆炸作用下准静态压力的试验研究, 明确了舱内爆炸准静态压力是舱内最为重要的压力载荷^[15]. Hu等人^[22]和Feldgun等人^[23]的研究表明, 炸药的大小、位置、形状、起爆点位置等参数会影响内爆压力载荷曲线. 孔祥韶等人^[24]开展了TNT在空气和氦气环境密闭空间中的爆炸试验, 对比了准静态压力、温度峰值及试件最终变形的区别, 分析了内爆载荷的燃烧增强效应.

舱内爆炸压力载荷曲线较为复杂, 因此学者们对内爆载荷曲线进行简化, 在简化的情况下可以得到压力载荷曲线的解析值^[21,25]. Feldgun等人^[26]提出了计算内爆冲击波压力变化的简化模型, 考虑了爆炸发生时通风口对冲击波流出的影响. Waymel等人^[27]、Karnesky等人^[28]、Ferrara等人^[29,30]、Janovsky等人^[31]、Wu等人^[18]采用通用或自主开发的程序计算了封闭空间内载荷特性.

2.2 舱内爆炸破片载荷

舱内爆炸产生的高速破片群是反舰导弹战斗部舱内爆炸毁伤舰艇结构的另一重要毁伤元. 在破片质量分布方面, 20世纪40年代, Mott^[32]研究了圆柱环爆炸破碎现象, 从理论上给出了破片质量分布公式. 此后对均质环/壳体产生破片的理论分析改进不大, 主要针对不同材料或含初始缺陷的结构碎裂特性开展了相关研究. 对于破片初速度计算方面, 学者们从动能的角度出发, 从理论上给出了破片初速度的计算公式. 其中的代表是Gurney公式, 可根据Gurney比能和炸药与金属壳质量比(C/M)计算破片初速度^[33].

在战斗部破片的空间分布方面, 尹峰等人^[34]对比了国内外常规爆炸武器产生破片的试验和理论研究成

果, 给出了常规武器爆炸产生破片的数量和质量分布、空间分布等特性, 并指出破片破坏效应研究的重点和方法. Arnold等人^[35]开展了破片空间及质量分布试验研究, 给出了4种不同厚度的壳体产生的破片相关特征. 在战斗部破片的质量分布研究方面, 李伟等人^[36]开展了破片的质量分布规律研究, 同时对破片等级进行了划分; 孔祥韶^[37]开展了复合多层防护结构在圆柱形战斗部内爆作用下的毁伤特性试验研究, 分析了破片的飞散特性, 并讨论了不同起爆方式对破片分布的影响; 吴震^[38]开展了战斗部自由场静爆试验, 分析了战斗部破片形成机理, 统计了破片形状及质量分布(图2). 在数值模拟方面, Glanville等人^[39]、Guilkey等人^[40]采用欧拉-拉格朗日耦合方法开展了战斗部和模拟战斗部的壳体碎裂过程. Kong等人^[41-43]采用SPH方法分析了起爆点位置对爆炸破片的速度及空间分布的影响, 给出了破片的速度、尺寸及分布特征. Liang等人^[44]根据破片的形态和断裂模式将不同缺口尺寸的圆环在爆炸载荷驱动下形成的破片分成四类: (1) 拉伸模式破片; (2) 剪切模式破片; (3) 混合模式破片; (4)

其他破片.

目前对舱内爆炸载荷特性已经有了一定的认识, 但相关研究工作开展相对较晚, 仍存在问题需要解决.

(1) 由于结构和冲击波的相互作用, 载荷特征较为复杂, 目前关于冲击波载荷的研究多数未考虑爆点位置、结构破损等因素的影响; 准静态压力的估算主要采用经验公式, 但目前只能估算峰值压力, 且结果误差较大, 因此舱内爆炸冲击波载荷的预测方法仍需改进.

(2) 预测战斗部爆炸产生的破片数量、质量及初速度时需要的计算参数较多, 但评估时各参数的取值缺少相关依据, 导致计算结果存在一定误差, 因此关于战斗部爆炸产生破片的相关经验公式仍需进一步修正.

3 舱内爆炸结构动态响应研究进展

板架是舰船结构的基本组成单元, 由于舱内爆炸

图 2 (网络版彩图)战斗部破片的形成过程(a)和破片模式统计(b)^[38]

Figure 2 (Color online) Warhead fragment. (a) Formation process; (b) fragment mode statistics [38].

载荷复杂, 早期关于舱内爆炸结构动态响应的研究多数是对舱内爆炸载荷进行解耦, 分别研究单一毁伤元(爆炸冲击波或高速破片群)作用下的结构响应, 近些年破片与冲击波耦合作用下的毁伤效应才引起了人们的注意.

3.1 冲击波作用下的结构响应

关于板架在冲击波载荷作用下的动态响应的研究起源较早, 20世纪90年代以前的有关研究, 已有文献[45–47]进行了综述, 本文不再赘述. 近些年爆炸荷载作用下不同形状的板架的动态响应也得到了广泛的研究, 如圆形板^[48]、方形板^[49–51]、加筋板^[52,53]等. 无量纲数是预测板架在冲击波作用下的结构响应的重要理论方法, Zhao^[54]在分析理想刚塑性梁和板在冲击作用下的动态响应问题时提出了一个无量纲数 Rn , 该无量纲数中同时考虑了惯性效应、材料抵抗变形的能力以及

结构的几何效应, 已被广泛地用于预测强动载荷作用下结构的动态响应和失效. Yao等人^[55–57]分析了内爆作用下舱室的变形, 提出了一个无量纲数用于预测箱体结构在舱内爆炸作用下的动态响应, 并给出了舱内爆炸板的典型变形模式(图3).

类似于其他工程研究领域, 板架在冲击波载荷作用下的动态响应最可靠的研究方法是试验方法. 在理论上, 为了研究爆炸荷载作用下结构的真实响应, 有必要进行实尺度的爆炸试验. 然而, 由于安全限制和较高的试验成本, 开展实尺度模型试验难度较大. 为了得到实尺度原型的物理现象, 缩比模型试验具有操作简单、重复性高的优点, 是非常理想的选择. Snyman^[58]通过各种爆炸载荷试验, 研究了钢板的几何缩比相似定律, 利用钢板中点挠度估算值与几何缩比因子进行比较, 指出了材料特性对挠度“相似”的重要性. Zhao等人^[48]通过对两个按比例缩小的试件在按

图 3 (网络版彩图)内爆舱壁变形模式^[55]. (a) 舱壁大变形; (b) 花瓣形破口; (c) 边缘撕裂; (d) 整体失效

Figure 3 (Color online) Damage figure for different failure modes [55]. (a) Plastic deformation; (b) petalling break; (c) edge tearing; (d) overall failure.

比例爆炸装药作用下的变形试验, 对圆形板的变形进行了分析, 结果表明, 在整个测量过程中, 对结构进行适当缩比的结果是满足相似定律的. Yao等人^[59]等通过试验和数值计算, 研究了三组不同尺度的几何相似的箱形结构在内爆荷载作用下的变形规律, 并给出了挠度修正公式. Kong等人^[60]提出了一种修正爆炸荷载作用下加筋板原型与缩比模型的相似方法, 可使用缩比模型试验预测爆炸荷载作用下全尺度结构动力响应. Ren等人^[61]研究了缩比舱室结构在舱内爆炸载荷作用下的动态响应, 讨论了不同尺度的模型挠厚比不一致的原因, 并提出了考虑尺寸和应变率影响的修正公式.

3.2 高速破片作用下的结构响应

关于破片侵彻与穿甲的研究已取得较多研究成果, 形成了较为完善的理论体系. 文献^[62,63]系统总结了国内外侵彻与穿甲问题的研究成果, 但这些工作大多是对普通弹丸的侵彻行为进行研究, 战斗部内爆产生的破片数量多、速度快、破片之间的耦合作用造成的毁伤比单个破片造成的毁伤更加严重, 破片群造成的穿孔会相互贯穿, 形成更大的破口. Qian等人^[64]设计了一种基于定向驱动原理的密集破片发生器, 随后采用理论方法, 对比了密集破片群耦合毁伤效应与单一破片叠加毁伤效应之间的差异^[65]. 同时, 基于靶板在单个破片的破坏模式给出了靶板在破片群作用下的裂纹扩展-剪切损伤模型, 并提出了密集破片群耦合毁伤效应出现的两种临界条件. 此外, 为了验证理论方法的正确性以及探索靶板的主要毁伤模式, Qian等人^[66,67]还开展了数值仿真研究, 结果表明, 破片群密度和打击时间间隔对目标靶的损伤模式有显著影响,

且破片群密度对靶板毁伤模式的影响程度高于打击时间间隔. 李典等人^[68]给出了一种密集破片侵彻能力估算方法, 解决了现有弹丸穿甲效果模拟方法中破片群侵彻防护结构时缺乏计算方法的问题.

3.3 冲击波与破片耦合作用下的结构响应

冲击波和破片是战斗部舱内爆炸产生的两个重要毁伤元, 其对舰船结构的耦合毁伤效应与两者单独作用时的毁伤效应有显著差别, 也不是二者毁伤效应的简单叠加, 而是存在特殊的破坏机理和作用规律^[4], 二者对结构的耦合毁伤效应远大于单独毁伤效应的简单叠加^[38].

舰船结构的基本组成元素是金属薄板, 由于金属板架厚度较小, 高速破片很容易穿透, 而破片的速度下降并不显著. 破片的作用会造成靶板的密集穿孔, 降低了靶板的损伤容限, 这些密集穿孔会在冲击波载荷作用下出现应力集中, 从而成为裂纹扩展的源头. 李茂等人^[69,70]近年来开展了不少舰船舱室结构在冲击波和破片耦合作用下响应方面的研究, 给出了一种模拟战斗部冲击波和破片耦合作用的等效试验方法和耦合作用判据(图4), 并运用试验及仿真方法开展了冲击波和破片耦合作用下的典型舰船板架的变形和毁伤模式研究^[3,71-75]. Li等人^[76]给出了一种模拟爆炸与冲击耦合作用的实验室试验技术, 该方法使用嵌有模拟破片的圆柱状泡沫铝子弹作为输入载荷. Kong等人^[77,78]研究了爆炸与破片载荷协同作用下多层防护结构的毁伤特性, 给出了舰船舱室结构在战斗部舱内爆炸载荷作用下的毁伤模式. 杜志鹏等人^[79]和吴震等人^[80]开展了舰船板架在两种非标准圆柱形战斗部爆炸载荷作用下的毁伤效应试验和数值模拟, 研究了舰船板架在破片

图 4 爆炸与破片联合作用的实验技术^[70]

Figure 4 Experimental technique of combined action of explosion and fragment ^[70].

与冲击波耦合作用下的变形及破损. 李勇等人^[81]和段新峰等人^[82]运用数值模拟方法研究了典型夹层板在冲击波与破片耦合作用下的响应过程, 分析了当量、爆距等因素对靶板变形和破坏模式的影响. Grisaro等人^[83]研究了爆破冲击与破碎冲击的复合载荷特性, 提出了一种评估密集破片冲击的简化方法, 以评估其相对于爆炸的重要性. 另外, 复合材料层合板^[84,85]、泡沫铝板^[86]和夹层板^[87]在冲击波和破片耦合作用下的毁伤情况近几年也吸引了学者们的注意.

因此要准确评估舰船结构在战斗部舱内爆炸作用下的毁伤效应(图5^[88]), 首先, 需要明确输入载荷特性, 包括破片和冲击波载荷特性; 其次, 需要确定结构在舱内爆炸复杂载荷作用下的动态响应, 由此来评估舰船

结构的毁伤效应.

目前关于战斗部舱内爆炸载荷作用下结构动态响应的研究仍然较少, 多数研究未考虑冲击波破片的耦合毁伤作用, 破片和冲击波的耦合毁伤效应不是两者简单的叠加, 而是会加重结构的毁伤, 尤其是战斗部近距离爆炸的情况下. 除此之外研究目标多为均质靶标或缩比模型试验, 但目前尚无可靠方法将此类试验结果换算到实际模型, 可靠的等效试验方法仍需解决.

4 舰船防护技术研究进展

由于舱内爆炸载荷的复杂性和严酷性, 舰艇的防御技术的研究显得尤为重要, 其对提高舰艇抗冲击毁

图 5 (网络版彩图)舰船结构在冲击波和破片联合作用下的毁伤情况. (a), (b) 试验布置及典型毁伤模式^[80]; (c)–(e) 舱段模型及舱段结构典型毁伤模式^[88]

Figure 5 (Color online) Damage of warship structure under combined blast and fragments loading. (a), (b) Test layout and typical damage patterns [80]; (c)–(e) cabin models and typical damage modes of cabin structures [88].

伤能力, 提升舰船生命力具有重要意义. 参照舰船防护技术的发展历程, 本文回顾了舰船舱内爆炸防护结构的研究成果, 将现有的舰船舱内爆炸防护技术归纳为载荷削弱技术、抗弹抗爆防护材料、新概念防护材料等3个方面(如图6所示), 总结了舰船防护结构的发展情况.

4.1 载荷削弱

4.1.1 舷侧泄爆技术

舷侧泄爆技术是通过舷侧外板或者舰船的长通道等使爆炸冲击波传播距离和范围明显增大, 因此准静态压力也会相应降低, 可使爆炸冲击波及爆轰产物泄出爆炸当舱, 降低重要舱室结构的损伤.

美国新研制的DDG1000型驱逐舰已经在舷侧采用了新型双层壳防护结构以及牺牲外壳的泄爆技术, 泄爆结构的相关细节参见参考文献[1]中的图10和参考文献[89]中的图6. 关于排气口对密闭舱室内爆炸冲击波超压的影响的研究多数集中在氢气^[90,91]、甲烷^[92,93]爆炸等方面, 其压力载荷特性对战斗部舱内爆炸泄爆技术的研究有一定的参考意义. 目前关于有泄爆口的舰船结构在爆炸载荷下的响应及压力载荷特性

方面的研究较少, 刘晓明等人^[94]开展了有泄爆口的防爆舱在爆炸载荷下的响应研究, 分析了不同泄爆口大小和相同泄爆口大小下加筋高度对泄爆效果的影响. 赵鹏铎等人^[95]运用有限元分析软件建立泄爆舱室的仿真模型, 研究了不同泄爆舱壁厚度下舱室破坏及舱内载荷的变化情况. Kong等人^[77,78]开展了多层防护结构舱内爆炸试验, 对比分析了开有泄爆孔一侧的临舱舱壁的毁伤情况, 表明爆炸产生的冲击波和准静态压力通过开有泄爆孔的舱壁而直接作用在相邻舱室的舱壁上. Zheng等人^[96]开展了内爆载荷作用下钢板动力响应的试验与数值研究, 研究了泄爆口对板的变形模式的影响, 表明泄爆口可以有效降低作用在板上的冲量, 从而降低板的变形.

4.1.2 水雾抑爆技术

水雾喷淋在军事上一般用来消防^[97]和红外隐身^[98]. 水雾抑爆技术(图7)其实质是采用气液两相混合介质衰减耗散冲击波的新兴防护技术, 对于一定尺寸的水雾微粒, 其抑制冲击波的效果明显^[99]. 其抑爆机理包括以下方面: (1) 将较大的液滴分解成更细的水雾, 分解过程可从冲击波中提取能量; (2) 直接削弱冲击波; (3) 减小周围舱壁和其他物体的反射冲击波压力; (4) 减缓或熄灭炸药后续燃烧的化学反应; (5) 降低舱室内爆炸性气体的浓度, 从而防止二次气体爆炸或火灾.

细水雾多应用在消防领域, 并且有较多的研究成果, 但其在抑爆方面的应用和研究较少. 学者们在试验和数值模拟方面都开展了相关研究, 在试验方面, Joseph等人^[100]通过开展激波管试验, 研究了冲击波和液滴的相互作用, 给出了液滴破碎的机理. 液滴破碎的模式可按照液滴形貌的变化进行分类^[101,102], 黄熙龙等人^[103]开展了高速气流中的液滴变形破碎的试验研究, 通过高速摄影测试技术获得了液滴的3种典型变形破碎模式: 振荡变形、剥离破碎和爆炸破碎. 在低速气流作用下, 液滴发生振荡破碎; 在低马赫数激波作用下, 液滴的破碎模式为剥离破碎; 在高马赫数激波作用下, 液滴发生爆炸破碎. Willauer等人^[104]开展了舱内水雾抑爆试验, 测定了有无水雾下的舱内超压的区别, 结果表明冲击波超压、冲量和准静态超压分别衰减了40%, 33%和35%. 李营等人^[105]和陈鹏宇等人^[106]均开展了水雾对舱内爆炸载荷抑制作用的试验研究, 表明

图6 (网络版彩图)舰船舱内爆炸防护技术

Figure 6 (Color online) Defense technology of warship under internal blast loading.

图 7 (网络版彩图)水雾抑爆技术. (a) 冲击波作用下典型液滴变形过程^[103]; (b), (c) 水雾抑爆效果及抑爆机理^[105]

Figure 7 (Color online) Water mist explosion suppression technology. (a) Typical droplet deformation process under shock wave ^[103]; (b), (c) the effect and mechanism of water mist explosion suppression ^[105].

水雾对舱内爆炸冲击波的衰减作用明显; 另外, 由于两位学者采用的水雾形成方式不同, 关于随着炸药当量的增加, 水雾对冲击波的衰减效果的结论存在一定差异. 目前研究均表明水雾对冲击波的抑制作用明显, 但对其抑爆机理的研究尚不明确, 对水雾的液滴尺寸、喷出时机、舱室尺寸等影响因素的作用效果还不明确, 还需进一步开展相关研究.

4.2 抗弹抗爆防护材料与结构

4.2.1 抗爆材料与结构

基于能量吸收的防护方法是舰艇抗爆抗冲击领域中的一种重要方法. 常用的吸能结构是轻质夹芯结构, 其结构一般由两个强度和刚度较大的薄面板, 一个较

为轻质、较厚的芯材组合而成. 从宏观上的轻质夹芯结构而言, 本质上都是属于多孔材料, 多孔微结构又可以分为有序结构和无序结构, 有序结构即胞元在结构空间内呈某种有序排布的规则结构, 如蜂窝结构、点阵结构; 无序结构即胞元在结构空间内呈任意分布的无规则结构, 如泡沫结构.

关于夹层结构静动态力学性能的研究一直是学者们研究的热点, 已有文献综述了轻质夹芯结构的冲击动力学性能^[107-109]和金属夹层结构的舰船应用情况^[110]. 近些年, 学者们主要关注夹层结构的冲击动力学性能和吸能特性. Wu等人^[111]通过试验和数值的方法研究了由蜂窝铝芯层和碳纤维增强板组成的仿生夹层结构的冲击响应, 认为该结构可以显著降低传入结

构的冲击波的强度, 可以显著提高结构的能量吸收特性. 李汶蔚等人^[112]研究了水下爆炸冲击载荷作用下金属夹芯结构的抗冲击性能问题, 建立了反映金属蜂窝夹芯结构抗冲击性能随冲击强度和芯材相对密度变化的结构-载荷-性能量化关系. Li等人^[113]研究了夹层结构在冲击载荷作用下的解析解, 并与有限元模拟结果较好地吻合. 针对传统桁架点阵性能受限和极小曲面结构构型设计单一的问题^[114], Cao等人^[115-119]提出了新型的节点增强的点阵结构, 并系统性地研究了所提出结构的静动力学性能. 研究表明, 所提出的新型结构具有更为优异的静动力学特性, 刚度、强度和能量吸收可以提高约40%.

从现有研究成果来看, 轻质夹芯结构种类众多, 与传统的单层结构相比, 在抵抗爆炸载荷方面具有明显的优势, 主要表现为芯层可以通过较好的塑性大变形能力缓冲并吸收较多的冲击能量. 目前轻质夹芯结构静力学性能的研究已经较为完善, 其动力学性能的研究仍有问题需要解决, 相关动态理论模型仍需完善. 另外, 轻质夹芯结构制造工艺复杂, 成本较高, 目前在大型水面舰艇上实现应用难度较大, 其工艺水平仍需优化.

4.2.2 抗弹材料与结构

高速破片群是战斗部舱内爆炸产生的另一重要毁伤元, 关于高速破片群的防护一直是各国海军重点关注的对象. 由于重量限制, 舰船舱壁板的厚度范围约为4-20 mm, 关于高速破片侵彻金属靶板的研究已有文献进行了综述^[120], 其理论模型、仿真方法和试验方法已经较为成熟. 非金属装甲材料在抗侵彻领域相对金属材料更具有优势. 现代复合装甲最常用的非金属装甲材料是陶瓷材料和纤维增强复合材料.

陶瓷材料硬度高且压缩强度高, 可以在抗侵彻时钝化、侵蚀和碎裂破片, 但陶瓷的脆性和低抗拉强度使得陶瓷在抗侵彻过程中没办法吸收较多能量^[121]. 高速破片侵彻作用下陶瓷材料的典型破坏形式主要是侵彻时子弹发生大变形, 甚至破碎; 陶瓷材料中裂纹从弹着点开始发生扩展, 最终形成近似锥形的破坏区域, 破碎的陶瓷碎块发生飞溅, 行成二次破片^[122]. 由于陶瓷材料缺点较为明显, 且不具备抗重复打击的能力, 因此其应用范围较为局限.

纤维增强复合材料密度小, 强度与模量高, 抗拉性

能较好, 抗侵彻性能优异. 纤维增强复合材料目前在抗侵彻领域发展较快, 已经经历了高性能玻纤复合装甲材料、芳纶纤维复合装甲材料、高性能聚乙烯纤维复合装甲材料等几个阶段^[89]. 高速破片侵彻作用下纤维增强复合材料的典型破坏形式包括纤维剪切破坏和拉伸破坏、纤维-基体脱黏、基体开裂等. 纤维材料的强度、纤维与基体之间的界面强度是影响其抗侵彻性能的主要因素^[123].

由于不同抗弹材料力学特性的优劣势不同, 单一材料的抗弹装甲往往难以满足使用要求, 为了充分发挥各种抗弹材料的性能优势, 一些学者通过结构合理优化设计, 将单一材料组合成复合装甲结构. 常见的复合装甲结构主要是由陶瓷、纤维增强复合材料和金属材料组成的两层^[124-126]、三层^[127-129]或多层^[130,131]复合结构, 近些年其抗侵彻性能得到了学者们的广泛研究, 多层复合装甲的理论模型和抗侵彻机理还需要进一步探索. 舰船抗弹防护和其他装备的抗弹防护原理相似, 抗弹材料/结构的选择也可参考其他防护装备, 但舰船结构复杂, 舱室众多, 防护结构复杂, 如何合理地将抗弹防护和抗爆防护相结合, 将防护结构和舰船结构设计相结合, 也是舰船抗弹防护设计的关键问题.

4.3 新概念抗爆抗弹防护材料与结构

关于载荷削弱、能量吸收、抗弹材料的研究多数基于舱内爆炸产生的单一载荷进行防护, 随着现在工业和科技的发展, 舰船防护装甲设计领域出现了很多新思路, 典型的代表有超材料、仿生材料、柔性边界等.

4.3.1 抗爆抗弹防护超材料

超材料概念广泛, 涉及声、光、电、磁、热、力等各个领域, 目前抗冲击领域研究较为广泛的超材料有负泊松比超材料、弹性超材料等.

传统材料在承受冲击载荷时会呈现横向膨胀的特点, 负泊松比超材料(图8)在压缩时则呈现横向收缩而不是膨胀的特点. 当负泊松比结构受到局部挤压时, 由于负泊松比效应的汇聚原理, 结构会向挤压点收缩, 使结构局部等效密度增加, 结构抗压性能明显提高^[132,133]. 负泊松比结构的抗冲击性能相比传统结构会更高, 其性能不仅和基体材料性质有关, 还取决于结构的拓扑构型, 目前研究较多的有内凹六边形结

图 8 (网络版彩图)负泊松比超材料. (a) 变形机制^[133]; (b) 内凹六边形^[17]; (c) 星型结构^[136]; (d) 手性结构^[144]. (a)来自CC By Iris Publishers LLC; (b)和(c)来自文献^[17,136], 已获得授权; (d)来自CC By Elsevier

Figure 8 (Color online) Metamaterials with negative Poisson's ratio. (a) Deformation mechanism ^[133]; (b) concave hexagon ^[17]; (c) star-shaped structure ^[136]; (d) chiral structure ^[144]. (a) is adapted with CC By Iris Publishers LLC; (b) adapted with permission from ref. ^[17], Copyright 2019, Elsevier; (c) adapted with permission from ref. ^[136], Copyright 2021, Elsevier; (d) adapted with permission from ref. ^[144], CC By Elsevier.

构^[16,17,134,135]、星型结构^[136,137]、双箭头结构^[138,139]、手性结构^[140-144]等。

近些年关于超材料的研究十分火热, 超材料的出现颠覆了传统材料中某些固有力学性能, 打破了材料和力学性能之间的耦合关系, 超材料在未来爆炸防护领域中会得到广泛研究和应用。

4.3.2 抗爆抗弹仿生防护材料

前文中的层合板、夹芯结构都显现了优秀的能量吸收的性能, 但是很多结构并没有得到优化. 与此同时, 自然界中的生物为了生存, 其自身结构为了适应各种极端环境而进化出了低密度、高强度、高韧性的结构. 抗冲击的仿生材料从结构上可分为板层状^[145-147]、管壁状^[148,149]、梯度^[150,151]、多孔^[152-154]、缝合线^[155,156]等结构. 图9^[157-160]列举了几种典型的仿生吸能材料, 目前的研究表明仿生材料的比吸能较为优异, 是未来抗爆领域值得关注的材料。

除吸能材料外, 仿生材料在抗弹领域同样给出了相关参考(图10). 自然界中存在一些有优异力学性能和微观结构的生物盔甲, 常见的有犰狳盔甲^[161,162]、贝壳^[163]、龟壳^[111,164,165]、鱼鳞^[166-169]等. 此类盔甲在结构和组成上有很大的差异, 但也有明显的共同点: 外部盔甲是高度矿化的硬质材料, 再由胶原纤维/肌肉

连接到身体组成的. 外部的鳞片是高度矿化的, 为外部攻击提供了一个硬质屏障, 而内部的骨层及其胶原纤维提供了一个“软/缓冲”层, 以提高韧性. 当这些外部的鳞片按照一定规律排列时, 鳞片会根据载荷进行调整, 并在接近表面的地方重新分配应力, 增大受力面积, 从而起到抗侵彻作用。

生物材料往往会集成多种抗冲击策略, 以防止灾难性破坏. 从这些结构中, 我们可以发现生物体的优良力学性能来自于其独特的多层次的力学结构, 向大自然借鉴灵感发展仿生材料的研究是今后爆炸防护领域的重要方向。

5 结语

关于舰船结构舱内爆炸毁伤与防护的研究是舰船结构设计的重要组成部分, 是提升我国舰艇生命力的重要前提, 其涉及爆轰基本理论、材料动力学行为、动态载荷作用下裂纹的产生与扩展、材料设计、增材制造等, 涉及学科广、理论深、还存在很多挑战和机遇。

(1) 关于舱内爆炸载荷特性方面, 舱内爆炸载荷最典型的载荷特征是存在持续时间较长的准静态压力和冲击波破片的耦合效应. 关于带壳战斗部内爆压力等

图 9 (网络版彩图)仿生吸能材料. (a) 仿竹子吸能结构^[157]; (b) 仿仙人掌吸能结构^[158]; (c) 仿牛角吸能结构^[159]; (d) 仿甲虫翅吸能结构^[160]

Figure 9 (Color online) Bionic energy absorbing materials. (a) Bamboo-like energy absorbing structure [157]; (b) cactus-like energy absorbing structure [158]; (c) horn-like energy absorbing structures [159]; (d) beetle wings like energy absorbing structures [160].

图 10 (网络版彩图)仿生抗弹材料. (a) 贝壳类结构^[163]; (b) 龟壳^[164]; (c) 鱼鳞^[166]. (a)来自文献[163], 已获得授权

Figure 10 (Color online) Bionic bullet-resistant materials. (a) Shellfish structure [163]; (b) tortoise shells [164]; (c) fish scales [166]. (a) is adapted with permission from ref. [163], Copyright 2019, AAAS.

效载荷、冲击波和破片联合作用的机理和等效载荷形式、等效评估方法等还需要进一步关注和研究。

(2) 关于结构的动态响应研究方面, 对典型舰用材料的动态力学行为和失效特征、高速破片群作用下的结构响应、冲击波破片联合作用下的结构响应、大尺度多舱室的结构响应等问题的认识还有待提高。

(3) 关于舱内爆炸防护技术研究方面, 吸能材料、

抗弹材料近几十年已经取得了长足的进步, 载荷削弱技术也得到了实际的应用, 但此类防护多数是基于舱内爆炸产生的单一载荷进行防护。随着现代工业和科技的发展, 舰船防护技术研究领域出现了很多新思路, 将抗爆、抗弹、隐身、承载等功能相结合, 设计多功能一体化的复合装甲是防护装甲领域未来发展的必然趋势。

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Review of the damage and protection of warship structures under internal blast loading

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Warships are naval platforms to launch and survive attacks, and they are the main target of the enemy in a sea war. Antiship missiles are one of the main threats to warships. The main attack mode of an antiship missile is to penetrate into the ship deck or side plate and explode inside the cabin. The main damaging elements of an internal blast loading through a warhead include shock wave and quasistatic pressures and high-speed fragments. All the damaging elements are coupled, resulting in a serious damage to the warship structure. Therefore, research on warship defense technology is particularly important to improve the ability of warships to resist impact damage and enhance the vitality of warships. In this paper, advances in research on the explosion damage and protection of ship structures in cabins are systematically discussed. Moreover, the load characteristics of an explosion in the cabin and damaging effects to the ship structure are introduced, and the status of defense technology research is summarized. Finally, some suggestions for future research are proposed.

warship structure, internal blast, damage characteristic, defense technology

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