第 44 卷　第 5 期
2024 年 5 月

爆　炸　与　冲　击
EXPLOSION AND SHOCK WAVES

Vol. 44, No. 5
May, 2024

DOI: 10.11883/bzycj-2023-0328

冲击载荷下蓄液结构动响应及防护机理的研究进展*

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摘要： 工程实际中，飞机油箱、船舶液舱、油液储罐等各类蓄液结构可能面临炸药爆炸冲击波、弹丸侵彻等冲击载荷的威胁。在冲击载荷作用下，蓄液结构的动响应受载荷特性、结构形式、充液方式等多种因素影响，相应的结构防护机理涉及多相介质的流固耦合、波在不同介质中的传播、液体介质的空化、结构动态力学特性等多个科学问题。针对冲击载荷下蓄液结构的动响应及防护机理，总结了工程领域中典型的蓄液结构形式，分析了各类蓄液结构在爆炸冲击波、弹体侵彻及其联合作用等载荷下的结构动响应过程、结构破坏模式、载荷耗散过程、能量转化与吸收过程，总结了蓄液结构的冲击动响应特性，归纳了蓄液结构对各类冲击载荷的防护机理，从结构构型、结构动响应、理论研究方法、抗冲击防护技术等方面对蓄液结构抗冲击防护研究进行了展望。

关键词： 冲击载荷；蓄液结构；动响应特性；防护机理；防护技术
中图分类号： O342　　　**国标学科代码：** 13015　　　**文献标志码：** A

A review of the dynamic response and protection mechanism of liquid filled structures under impact loads

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Abstract: Aircraft fuel tanks, marine liquid tanks, oil liquid storage tanks, and other types of liquid filled structures may be threatened by blast waves, projectile penetration, and other impact loads in engineering practice. The dynamic response of the liquid filled structure under impact load is affected by various factors such as the characteristics of the load, the configuration of the structure, and the way of liquid filling. Accordingly, the protection mechanism of the liquid filled structure against various types of shock loads involves the fluid-solid interaction of multiphase media, wave propagation in different media, cavitation of liquid media, dynamic mechanical properties of the structure, and several other scientific issues. In this paper, the dynamic response and protection mechanism of the liquid filled structures under different impact loads are reviewed, the typical forms of the liquid filled structures in engineering are summarized, and the dynamic response processes, damage modes, load dissipation processes, energy conversion and absorption processes of various types of the liquid filled structures under the loads of blast shock wave, projectile penetration and their combined effects are analyzed. Furthermore, the impact dynamic response characteristics of the liquid filled structures under the action of blast shock wave loading, projectile penetration loading, and the combined loads of blast shock wave and high-speed fragmentation group are summarized. The protection mechanisms of the liquid filled structures against various types of impact loads are summarized from the

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[*] 收稿日期：2023-09-14；修回日期：2024-02-19
基金项目：国家自然科学基金（51979277, 52371342, 52101378）
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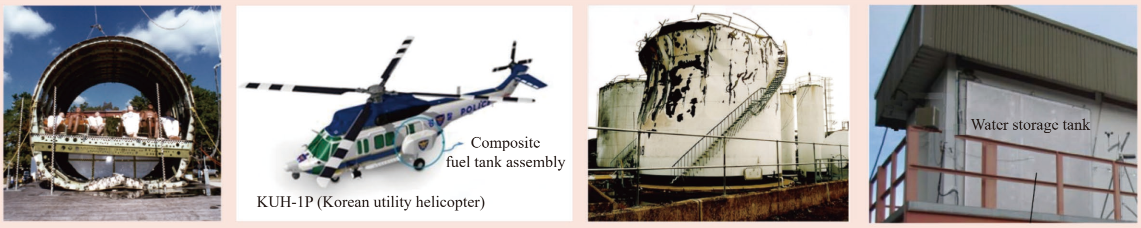
perspectives of attenuating and dissipating loads, as well as the energy transformation and conversion. In the end, the prospects of the investigation on anti-impact characteristics of the liquid filled structures are described from the aspects of dynamic response and protection characteristics of the multi-cell liquid filled structures, mechanisms for destruction of the liquid filled structures by combined loads, efficient numerical computation methods, as well as the dynamic response and protection mechanism of the liquid filled structures made of new materials.

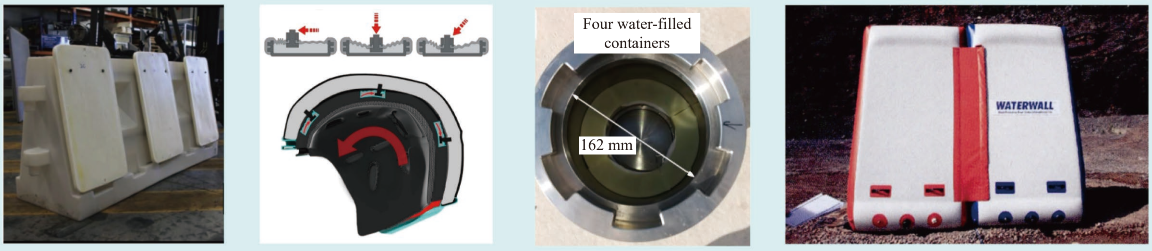
Keywords: impact load; liquid filled structure; dynamic response characteristic; protection mechanism; protection technology

蓄液结构指全部或部分储存液体介质的密闭或准密闭空间结构，由液体介质和空间结构构成，广泛存在于各类工程装备、工业设施中（图 1），如飞机油箱[1-2]、易燃或有毒液体储罐[3]、舰艇液舱[4]、储能水箱[5]等。在爆炸冲击波[6]、弹体侵彻[7]等冲击载荷及其联合作用下[8]，蓄液结构将经历复杂的流固耦合过程，导致空间结构大变形[9]和大面积破损、易燃或有毒液体介质外泄[10]，引发火灾和二次爆炸[11]，造成灾难性损失，如高速破片对飞机油箱的侵彻[12]、爆炸碎片或飞行器对有毒液体储罐的撞击[13]。另一方面，流固耦合过程将改变冲击载荷的时空分布特性，空间结构的变形与破损也将吸收冲击载荷的能量[14]。因此，蓄液结构又可作为抵御冲击载荷的防护结构，减小其后方结构或目标的损伤[15]，如蓄液防护路障[16]、头盔蓄液缓冲装置[17]、蓄液防爆服[18]、蓄液防爆罐[19]、防爆水墙[20]、舰船防护液舱[21]与双层船底[22]、防护水袋[23]等。探究蓄液结构在冲击载荷下的动响应特性与防护机理，提高蓄液结构的抗冲击防护性能，是船海工程[24]、航空航天[25]等多领域的热门研究方向。

冲击载荷下蓄液结构的动响应及防护机理十分复杂。一方面，气体、液体介质与结构之间会发生复



(a) Auxiliary fuel tank for passenger aircraft[1]　(b) External fuel tanks for helicopter[2]　(c) Storage tanks damaged by explosion[3]　(d) Water storage tank with blast-resistant features[15]



(e) Liquid filled protective barriers[16]　(f) Liquid filled buffer in helmets[17]　(g) Liquid filled anti-explosion tanks[19]　(h) Liquid filled anti-explosion water walls[20]

(i) Protective liquid cabin for vessel[21]　(j) Double-wall bottom grillage[22]　(k) Protective water bag[23]

图 1　冲击载荷下的各类蓄液结构

Fig. 1　Various types of liquid filled structures under impact loads

杂的流固耦合作用[26]、液体与气体介质之间会发生相变与多相流动[27]，结构也将发生弯曲[28]、鼓胀[12]、失稳[29] 等变形，以及穿孔[30]、边界撕裂[31]、花瓣开裂[32] 等破坏现象；另一方面，结构与液体、气体介质的属性差异很大[33]，空气中的冲击波[34]、结构中的应力波[35]、液体中的压力波[36] 将伴随结构动响应经历复杂的传播过程，并影响蓄液结构的动态力学性能[37]。本文中，针对爆炸冲击波、弹体侵彻及其联合作用下蓄液结构的动响应及防护机理，基于液、气介质属性和结构力学性能，从蓄液结构形式、冲击载荷传递与耗散机制、流固耦合作用过程、结构变形破坏与吸能等角度总结蓄液结构的冲击动响应特性与防护机理研究现状，展望冲击载荷下蓄液结构的研究发展趋势，以期为蓄液结构的抗冲击防护研究与设计提供参考。

1　蓄液结构形式

根据承载能力与结构特性，可将蓄液结构分为柔性蓄液结构和刚性蓄液结构两大类（图 2）。

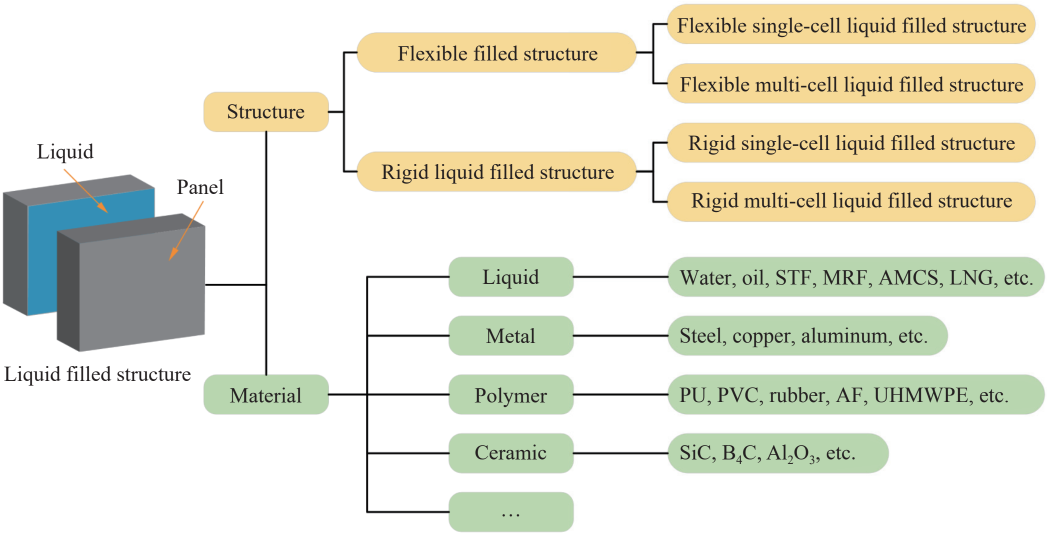


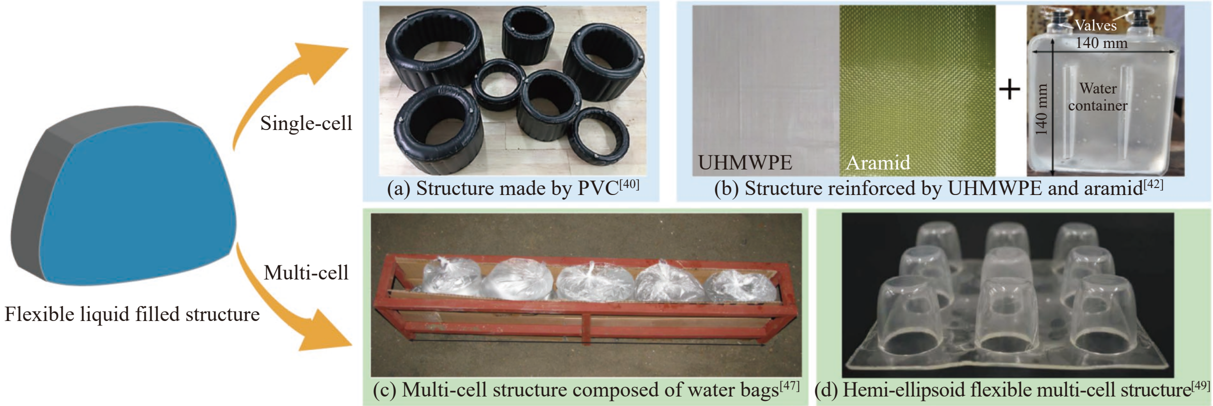
图 2　蓄液结构的分类

Fig. 2　Classification of liquid filled structures

柔性蓄液结构指壁面抗弯能力弱，仅依靠薄膜力约束内部液体介质的蓄液结构，其壁面常由聚氨酯（PU）[38-39]、聚氯乙烯（PVC）[40]、橡胶[41] 等聚合物材料制成，并可通过高分子量聚乙烯纤维（UHMWPE）[40]、芳纶纤维（AF）[18] 等进行加强，在冲击载荷作用下，结构主要以薄膜变形和材料的剪切、拉伸断裂为主[42-43]。结构形式上，柔性蓄液结构可进一步分为柔性蓄液单胞结构和柔性蓄液多胞结构（图 3）。其中，柔性蓄液单胞结构内液体介质的分布区域单一且独立，整体结构具有轻质、便携的特点，如蓄液软管[44]、储油囊[45] 等轻质、形状可变的蓄液结构，或蓄液防爆服[18]、蓄液冷却服[46]、蓄液防爆围栏[40] 等对轻质性、柔软度要求较高的蓄液防护结构。对柔性蓄液单胞结构进行规律排布即可形成柔性蓄液多胞结构[47]，其具有较强的结构可设计性[48]，可通过改变液体介质空间分布，显著改善结构刚度、强度与吸能特性[49]。

刚性蓄液结构的壁面抗弯刚度较大，对液体介质的约束能力较强，液体静压力下壁面不会发生明显变形。刚性蓄液结构壁面通常由钢[50]、铝合金[51] 等金属材料或纤维复合材料[52]、聚合物材料[53] 等构成，在冲击载荷作用下结构可能出现弯曲变形[54]、薄膜拉伸变形[55] 等多种变形与失效。结构形式上，刚性蓄液结构也可分为刚性单胞蓄液结构和刚性多胞蓄液结构，如图 4 所示，其中 HDPE 为高密度聚乙烯。刚性单胞蓄液结构常由多个壁面形成密闭或准密闭的蓄液连通空间，如油箱[56]、油液储罐[57] 等蓄液结构或防撞水箱[58]、抑爆水墙[59] 等蓄液防护结构，在此基础上通过喷涂聚脲[60]、设置缓冲橡胶层[61]、设置抗弹陶瓷层[32] 等方式，有针对性地增强蓄液结构在爆炸冲击波[62]、弹体侵彻[63] 及其联合作用下[64] 的结构防

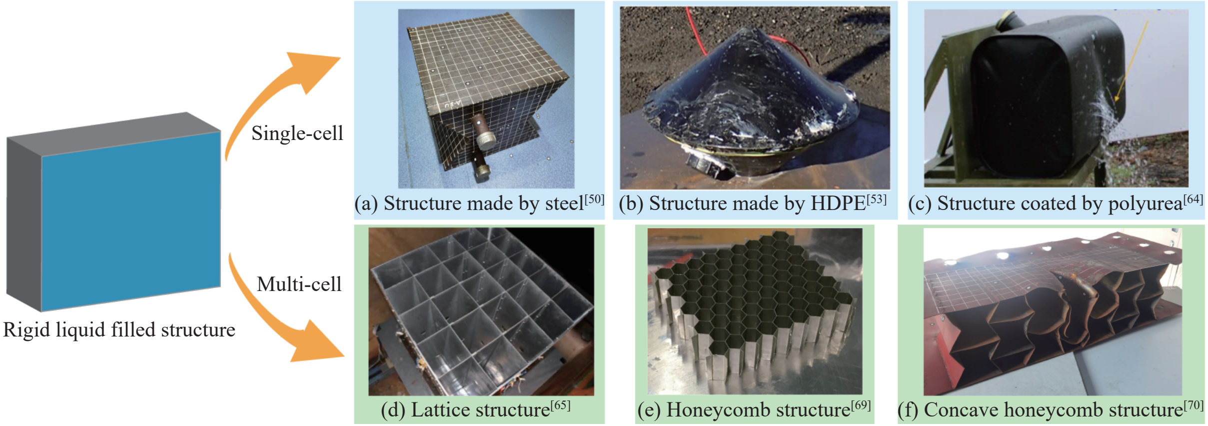
护性能，是结构防护领域的一大研究热点。刚性多胞蓄液结构的构型相对复杂，结构内部被壁板划分为多个相对独立的蓄液空间，每个蓄液空间均可视作一个蓄液胞元，包括格栅蓄液结构、蜂窝蓄液结构等诸多结构形式：格栅蓄液结构壁板主要为平面，易于加工成型，如格栅油箱[65]、水下多舱防护结构[66]、舰船双层底结构[22] 等蓄液结构；蜂窝蓄液结构由平直面板与弯曲面板构成，可设计性强，基于周期结构理论[67] 与力学超材料[68] 研究成果，可设计得到正六角蜂窝蓄液结构[69]、内凹蜂窝蓄液结构[70]、箭形蜂窝蓄液结构[71]、波纹蜂窝蓄液结构[72]、桁架蜂窝蓄液结构[73] 等种类丰富、力学特性各异的蓄液结构。



(a) Structure made by PVC[40]
(b) Structure reinforced by UHMWPE and aramid[42]
(c) Multi-cell structure composed of water bags[47]
(d) Hemi-ellipsoid flexible multi-cell structure[49]

图 3　柔性蓄液结构

Fig. 3　Flexible liquid filled structures



(a) Structure made by steel[50]
(b) Structure made by HDPE[53]
(c) Structure coated by polyurea[64]
(d) Lattice structure[65]
(e) Honeycomb structure[69]
(f) Concave honeycomb structure[70]

图 4　刚性蓄液结构

Fig. 4　Rigid liquid filled structures

蓄液结构内可储存丰富多样的液体介质。对于各类工程装备、工业设施中的蓄液结构，通常储存水[74] 以及各类油料[75]、液化气（LNG）[76] 等液体介质；对于各类蓄液防护结构，则可通过在结构内蓄入剪切增稠液体（STF）[77]、磁流变液体（MRF）[78]、甲基纤维素水溶液（AMCS）[79]、纳米材料功能液体[80] 等，将液体介质的功能特性赋予蓄液防护结构[81]，改善结构的变形[82] 与吸能[83] 特性，进而有效提升结构的抗冲击防护性能[84]，是目前蓄液结构抗冲击防护技术的一大热门研究方向。

2　蓄液结构冲击动响应特性

2.1　爆炸冲击波载荷作用

爆炸冲击波载荷的作用面积大、作用时间在毫秒量级[85]，可视作面冲击载荷，蓄液结构在此类载荷下主要经历凹陷和鼓胀变形过程（图 5）。

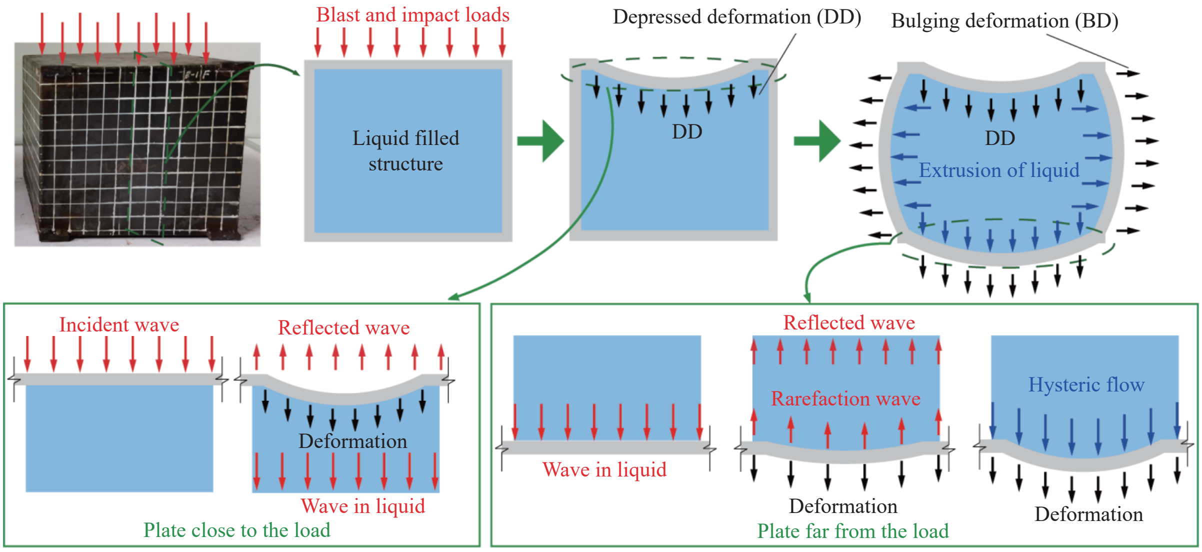


图 5　爆炸冲击波载荷作用下蓄液结构的动响应特性

Fig. 5　Dynamic response characteristics of liquid filled structures under blast shock wave

在载荷作用初期，入射冲击波接触结构的近爆面并形成透射波与反射波，透射波以压力波的形式在液体中传递，扰动液体介质使其发生运动，近爆面在背靠液体介质（背液）的情况下发生凹陷变形。对于近爆面的动响应问题，可将受到扰动的液体介质视为近爆面面板的附加质量，结合质量附加原理、动量守恒原理求解[86]，或将液体介质对面板的阻碍作用等效为面板的虚位移量[87]：

$$w(t) = w_{\mathrm{I}}(t) + w_{\mathrm{II}}(t) \tag{1}$$

式中：$w(t)$ 为面板的实际位移量，$w_{\mathrm{I}}(t)$ 为忽略液体介质时爆炸载荷所导致的面板位移量，$w_{\mathrm{II}}(t)$ 为液体介质的阻碍作用所导致的面板虚位移量，t 为时间。

水中压力波传播至远爆面后，同样将在流固耦合界面发生透射和反射，与此同时，远爆面在背靠空气（背空）的情况下与空气、液体介质发生双向流固耦合，并在鼓胀变形的过程中产生稀疏波。对于远爆面的动响应问题可参考 Taylor 理论求解[88]，即基于动量、质量守恒，围绕冲击波、耦合界面反射波以及结构面板运动所产生的稀疏波，建立水中压力波作用下背空刚性板的动响应理论模型，还可进一步将 Taylor 理论推广至背液刚性板[89] 中，求解得到水中压力波作用下的背液板和背空板的动响应解析式：

$$\left\{\begin{aligned} u^{\mathrm{w}}(t) &= \frac{2p_0\theta^2}{m_{\mathrm{a}}(\phi-1)\phi}\left[(\phi-1)+\mathrm{e}^{-\phi t/\theta}-\phi\mathrm{e}^{-t/\theta}\right] \\ u^{\mathrm{a}}(t) &= \frac{2p_0\theta^2}{m_{\mathrm{a}}(\psi-1)\psi}\left[(\psi-1)+\mathrm{e}^{-\psi t/\theta}-\psi\mathrm{e}^{-t/\theta}\right] \end{aligned}\right. \tag{2}$$

式中：$u^{\mathrm{w}}(t)$ 和 $u^{\mathrm{a}}(t)$ 分别为背液和背空下的面板位移，ϕ 和 ψ 分别为背液和背空情况下的流固耦合系数，p_0 为峰值压力，θ 为压力衰减时间，m_{a} 为板的单位面积质量。

在此基础上，众多学者围绕流体和固体介质对 Taylor 理论进行了补充与完善。对于流体介质：一是 Taylor 理论假定液体介质为不可压缩的理想流体，对此，Kambouchev 等[90] 和 Ghoshal 等[91] 考虑了流体介质的非线性可压缩特征，对流固耦合系数的计算方法进行了改进；二是 Taylor 理论中假定液体介质中的波速恒定为声速，不适用于接触爆炸等冲击波波速较高的情况，对此，刘晓波等[92] 对 Taylor 理论中的液体介质波速进行了修正，相关思想可用于水中强冲击波作用下的结构动响应问题（图 6）；三是 Taylor 理论未考虑液体介质环境压力的影响，对此，Schiffer 等[93-96] 考虑了液体介质的初始压力，针对刚性结构[93]、夹芯结构[94] 等开展了实验研究，并通过理论分析了初始环境压力对冲击载荷下刚性板[95]、夹芯板[96] 动响应特性的影响。

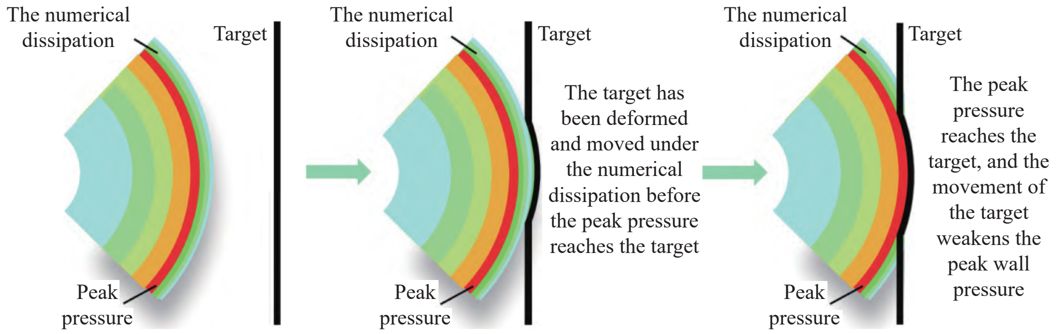


图 6　针对 Taylor 理论的完善与改进[92]

Fig. 6　Refinements and improvements for Taylor’s theory[92]

对于固体介质：一是 Taylor 理论将结构面板视为刚性体，不适用于夹芯结构问题求解，对此，Wang 等[97]基于 Taylor 理论提出了水下冲击波作用下夹芯板的动响应理论模型，Fleck 等[98]进一步将夹芯梁的冲击动响应过程分为了流固耦合、芯层压缩、整体弯曲拉伸 3 个阶段，联合采用 Taylor 理论、能量和动量守恒原理、改进的梁理论求解；二是 Taylor 理论中未考虑结构边界、液体滞后流等对结构动响应的影响，对于结构边界问题，可参考 Wang 等[15]对蓄液板架在长时程冲击载荷下的结构响应研究，其将蓄液板架的面板简化为梁模型，基于 SDOF 单自由度系统进行了理论推导：

$$K_{\mathrm{LM}} m_{\mathrm{eq}} \ddot{y} + R(y) = F(t) \tag{3}$$

式中：K_{LM} 为载荷-质量等效系数，m_{eq} 为等效质量，y 为位移量，$R(y)$ 为抗力-位移关系，$F(t)$ 为系统所受外载荷。对于液体滞后流问题，Kishore 等[99]考虑了滞后流和冲击波经过面板时的透射问题，对 Taylor 理论的流体速度进行了修正，提出了一种针对滞后流的改进模型（表 1），其中，p_{k} 为流体压力，ρ_{w} 和 ρ_{p} 分别为液体和弹体的密度，c_{w} 为流体中的波速，R 为爆距，v_{p} 为面板中心点速度，v_{i} 为入射压力导致的流体速度，v_{r} 为反射压力导致的流体速度，v_{t} 为透射压力导致的流体速度。对于未蓄满液体的结构，其近爆面的动响应还可能受“气垫效应”[100]的影响。研究表明：曲面楔形体[101]、波纹板[102]等结构入水时均存在“气垫效应”，而对于蓄液结构在爆炸冲击波等强动载作用下的“气垫效应”问题仍有待进一步探索。

表 1　Taylor 模型与改进模型的比较

Table 1　Comparison between Taylor’s model and the improved model

模型类型	Taylor模型	针对滞后流的改进模型
流体速度	$\dfrac{p_{\mathrm{k}}}{\rho_{\mathrm{w}} c_{\mathrm{w}}}$	$\dfrac{p_{\mathrm{k}}}{\rho_{\mathrm{w}} c_{\mathrm{w}}} + \dfrac{1}{\rho_{\mathrm{w}} R}\int_0^t p_{\mathrm{k}} \mathrm{d}t$
连续条件	$v_{\mathrm{p}} = v_{\mathrm{i}} - v_{\mathrm{r}}$	$v_{\mathrm{p}} = v_{\mathrm{i}} - v_{\mathrm{r}} = v_{\mathrm{t}}$

2.2　弹体侵彻载荷作用

弹体侵彻载荷的作用面积较小，作用时间在微秒量级[103]，可视为点冲击载荷，蓄液结构在此类载荷下通常发生穿甲破坏与鼓胀变形（图 7）。

在侵彻过程中，弹体将动能传递给液体介质，冲击载荷以液体中压力波的形式作用于结构面板，并引发结构动响应，该过程被称为“水锤效应”[104]。Chen 等[105]将水锤效应划分为侵入、初始冲击、拖曳-空腔、侵出、空腔振荡和空腔收缩共 6 个阶段，并给出了典型的水锤效应载荷（水锤载荷）时程曲线（图 8）。

可以看出，初始激波压力与空腔挤压压力、空腔溃灭压力是典型的水锤载荷，也是蓄液结构动响应研究中的重点关注对象。在侵彻初期，侵彻体受阻减速并释放动能，在液体介质中引发峰值较高、作用时间较短的初始激波。Dear 等[106]基于应力波理论给出了初始激波压力 P_{i} 的理论解法：

$$P_{\mathrm{i}} = \frac{v \rho_{\mathrm{w}} c_{\mathrm{w}} \rho_{\mathrm{p}} c_{\mathrm{p}}}{\rho_{\mathrm{w}} c_{\mathrm{w}} + \rho_{\mathrm{p}} c_{\mathrm{p}}} \tag{4}$$

式中：c_{p} 为弹体中的波速，v 为侵彻速度。结构面板、自由液面、破片形状等均可能影响初始激波的传

播。对于结构面板，Chen[107] 等基于反射定律提出了一种预测初始激波在封闭结构内传播的理论方法（图 9）；对于自由液面，Varas 等[51] 通过理论计算初始激波与自由液面相互作用后反射稀疏波的过程，发现这会显著削弱初始激波的强度；对于破片形状，Huang 等[108] 研究了弹头形状对初始激波压力峰值及其衰减特性的影响。此外，陈晨[109] 还发现在考虑气、液、固体介质的可压缩性时，初始激波显著受到了“气垫效应”等因素的影响，相应的理论解析方法则有待进一步的探索。

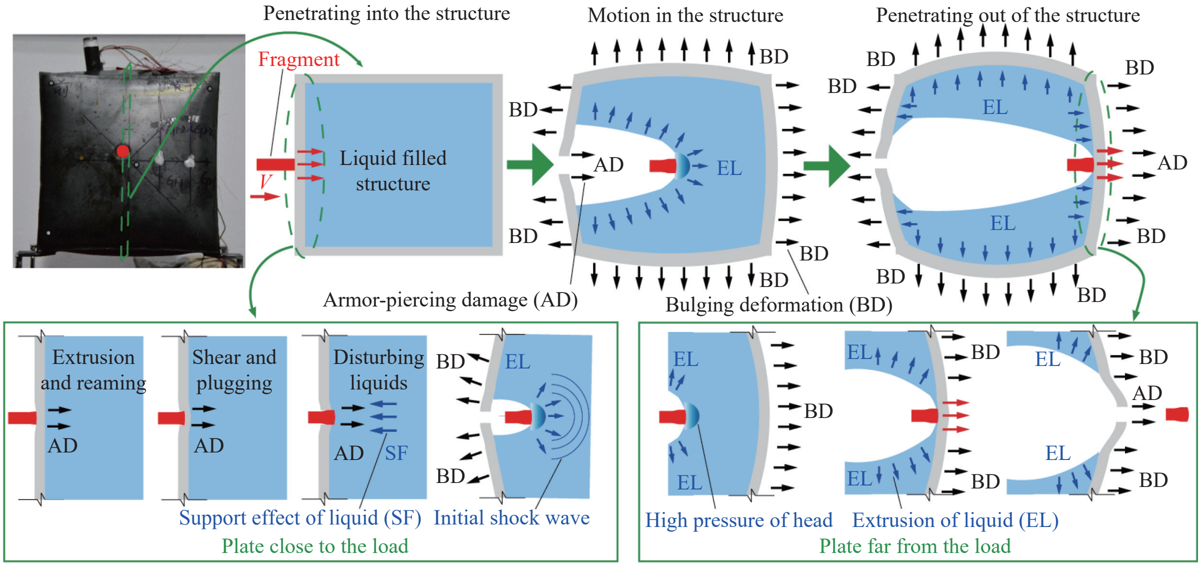


图 7　弹体侵彻载荷作用下蓄液结构的动响应特性

Fig. 7　Dynamic response characteristics of liquid filled structure under penetration

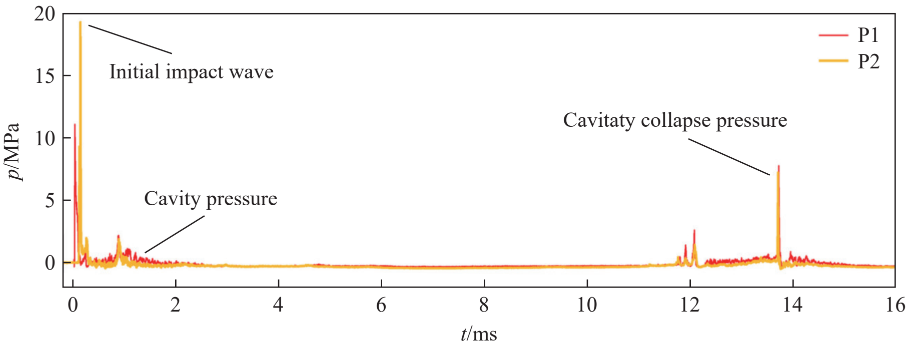


图 8　典型的水锤效应时程曲线[105]

Fig. 8　Typical time course of hydrodynamic ram loads[105]

在侵彻中期，侵彻体在结构内作减速运动，同时将动能传递给周围液体介质并使其发生运动，空腔随之在结构内部发展。对于此阶段的研究主要围绕侵彻体的速度衰减、空腔运动两大问题。对于侵彻体的受阻减速问题，可基于能量守恒建立侵彻体的速度衰减公式[110]：

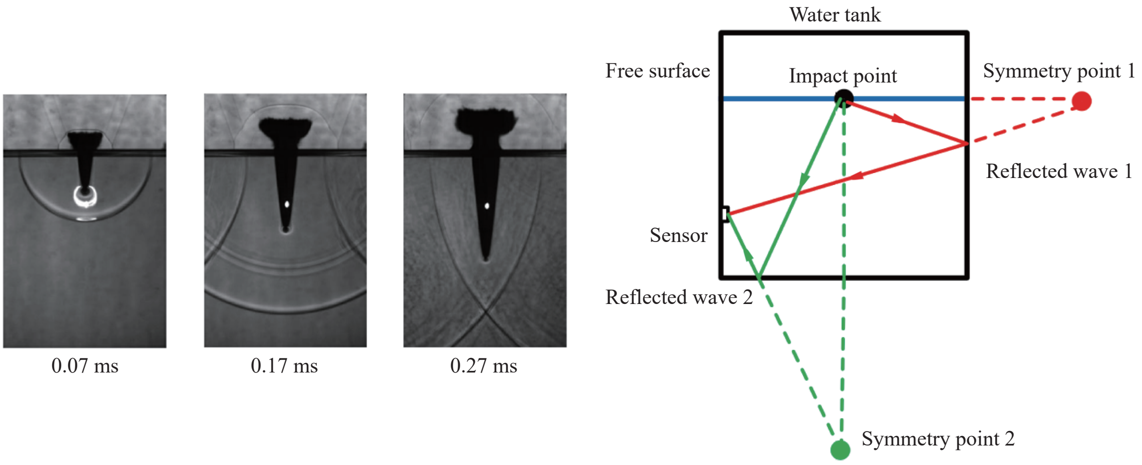
$$m_{\rm q}\frac{{\rm d}v}{{\rm d}t}=-\frac{1}{2}\rho_{\rm w}A_0C_{\rm D}v^2 \tag{5}$$

式中：$m_{\rm q}$ 和 A_0 分别为侵彻体的质量和横截面积，与侵彻体的规格尺寸有关；$C_{\rm D}$ 为阻力系数，受多方面因素影响。一方面，侵彻体迎流面积的变化将影响阻力系数，如沈晓乐等[111] 考虑了弹体入水后的墩粗现象，提出了相应的阻力修正系数，孔祥韶等[112] 同时考虑了弹头形状与侵彻速度对阻力系数的实时影响，对阻力系数进行了拟合计算研究；另一方面，空化数[113]、雷诺数[113]、马赫数[114] 等也会对阻力系数产生影响，如 Zhao 等[115] 发现，当马赫数较低时，阻力系数主要受雷诺数影响，随着马赫数的提高，阻力系数

与马赫数逐渐呈现出相关性，对此还提出了阻力系数理论模型。对于空腔运动问题，Truscott 等[116]依据入水速度将空腔的成因分为了空气夹带（低速入水）和超空化（高速入水）。对于空腔运动发展规律的研究则主要围绕空腔生长速度变化规律和流场压力分布特性：一方面，可基于实验结果与合理假设建立空腔生长模型，如 Held[117]提出的假设中认为空腔生长速度与侵彻体速度成正比；另一方面，可基于势流原理，将侵彻体的运动过程视为“点源”在移动中不断向外辐射“弹道压力波”的过程，通过求解势函数进而依据伯努利方程得到流场压力分布，如 Lee 等[118]将“弹道压力波”分解为轴向与径向“点源”响应的卷积，基于能量守恒将侵彻体损失的动能视为液体介质增加的动能和势能，建立了相应的空腔运动模型，并通过空腔径向速度与源强度的数理关系简化了模型[114]：

$$u_{\mathrm{c}}=\frac{2S_{\mathrm{c}}}{w_{\mathrm{L}}} \tag{6}$$

式中：u_{c} 为空腔生长速度，w_{L} 为腔壁距轴线的距离，S_{c} 为点源强度。上述理论中假设“点源”在运动过程中均匀辐射弹道波，Liu 等[119]指出，侵彻体尾部辐射的弹道波会受到空腔影响，“点源”向四周辐射的弹道波实际上并不均匀，并针对点源强度 S_{c} 提出了相应的修正方法。

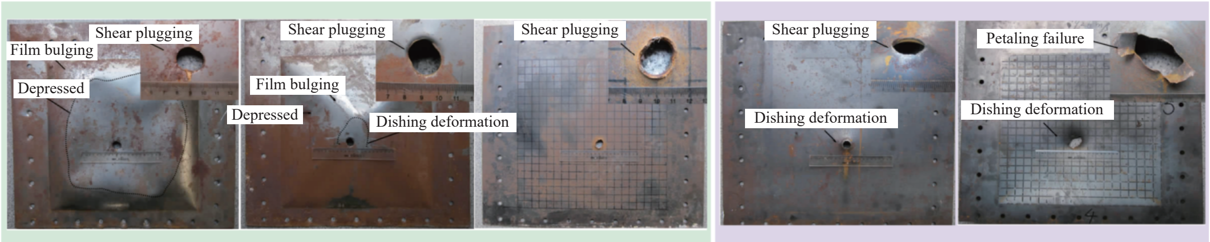


(a) Shock wave shadowgraphs　　(b) Schematic diagram of the path of the reflected waves

图 9　初始激波在封闭结构内部的反射过程[107]

Fig. 9　Reflection process of the initial shock wave in the interior of a closed structure[107]

伴随空腔的运动过程，蓄液结构在空腔挤压载荷作用下发生大挠度的整体鼓胀变形，对此，Guo 等[120]将侵彻体损失动能等效为液体介质动能、势能增量以及结构的弹性能增量，提出了圆柱形蓄液结构约束下的空腔动力学模型，并进一步[121]表征了空腔对蓄液结构面板的挤压作用，可用于指导蓄液结构的抗侵彻防护设计。然而，对于结构弹塑性响应、复杂结构边界等因素对空腔运动的影响则有待进一步的探索。在弹体侵彻作用下，受水锤效应影响，蓄液结构外板与内板的动响应模式也有所不同（图 10）。根据



(a) Deformation modes of the outer panels　　(b) Deformation modes of the inner panels

图 10　弹体侵彻下蓄液结构面板的变形和破坏形貌[32]

Fig. 10　Deformation and failure morphology of liquid filled structure panel under projectile penetration[32]

仲强等[32] 的实验研究，蓄液结构外板在弹体侵彻作用下可能发生剪切冲塞、碟形变形、薄膜鼓胀和失稳凹陷等多种变形模式，内板则可能发生剪切冲塞、碟形变形或花瓣开裂。此外，外板和内板的实际变形模式还受到面板刚度影响，与面板厚度、材料等因素有关。根据吴晓光等[12] 的研究结果，随着外板与内板厚度比的增加，外板的凹陷变形和内板的碟形变形程度有所降低，剪切充塞破坏、花瓣开裂破坏逐渐分别成为外板与内板的主要变形破坏模式。

对于外板的动响应，可将其视为弹体侵彻背液面板过程，通过能量守恒定律和应力波理论求解。例如，徐双喜等[122] 将破片侵彻背水面板过程划分为挤压扩孔、剪切冲塞、液体扰动 3 个阶段并建立了相应的能量模型：

$$\begin{cases} E = E_{\mathrm{r}} + E_{\mathrm{c}} \\ E_{\mathrm{r}} = \dfrac{1}{2}\left(m_{\mathrm{p}} + m_{\mathrm{f}} + m_{\mathrm{s}}\right) v_{\mathrm{r}}^{2} \\ E_{\mathrm{c}} = E_{\mathrm{p}} + E_{\mathrm{s}} \end{cases} \tag{7}$$

式中：m_{p} 和 m_{f} 分别为破片质量和冲塞块质量，E、E_{r} 和 E_{c} 分别为破片的初始动能、剩余动能和穿透能，v_{r} 为破片与冲塞块联合体的剩余速度，E_{p} 为破片与靶板的塑性变形能，E_{s} 为面板剪切塑性变形能，m_{s} 为扰动水体的质量。陈长海等[123] 则采用应力波理论，给出了剪切冲塞阶段吸能量的理论计算方法，并基于板厚等效原则将理论模型推广至斜侵彻问题[124] 中。对于内板的动响应特性研究，需要考虑侵彻体在液体中运动所产生的水锤载荷对结构的预加载作用。相关研究表明，内板所受的冲击波峰值、冲量[125] 和面板变形量[31] 均显著大于外板。李典等[126] 认为，内板最先受初始激波和侵彻体头部高压的作用发生变形，侵彻体的穿甲过程则导致内板的变形进一步扩展。孔祥韶等[127] 针对此问题提供了理论计算方法，将内板所受到的等效压力 p_{e} 视为两部分载荷的叠加：

$$p_{\mathrm{e}} = p_{\mathrm{n}} + p_{\mathrm{c\text{-}t}} \tag{8}$$

式中：p_{n} 为液体介质对内板产生的冲击压力，$p_{\mathrm{c\text{-}t}}$ 为不考虑液体介质的情况下侵彻体与内板接触时的接触压力。在此基础上，可将初始激波的预加载作用等效为内板的初始挠度[128]，运用水中压力波作用下的结构动响应理论表征内板的位移响应。

可以看出，目前针对弹体侵彻下蓄液结构动响应的理论研究主要围绕弹体对外板、内板的局部穿甲破坏过程，对于水锤载荷作用下外板、内板乃至蓄液结构整体的薄膜鼓胀、失稳凹陷等整体变形破坏过程则有待进一步的理论探索。此外，在侵彻体穿出蓄液结构后，空腔还将发生振荡[129] 并导致液体介质向外喷溅[130]。陈安然等[131] 对此开展了深入研究，发现空腔的振荡过程改变了腔内的压力分布，从而影响了液体喷溅速度，并基于空腔运动模型得到了液体喷溅理论模型[132]，分析了液体介质的喷溅特性与弹体侵彻速度、侵彻破口形状等因素的内在联系。总的来看，目前蓄液结构的抗侵彻防护研究仍主要聚焦于拖曳-空腔阶段[133]，事实上当蓄液结构内存储易燃液体时，空腔运动后期的振荡和收缩过程还可能导致液体介质喷溅并同时产生雾化产物，甚至诱发液体介质及其雾化产物的燃烧甚至爆炸[134]，相关理论问题值得深入研讨。

2.3　联合载荷作用

爆炸冲击波与高速破片群的联合载荷（联合载荷）同时包含面冲击载荷和多个点冲击载荷，涉及冲击波载荷与高速破片群载荷在时间维度和空间维度的多重叠加与联合作用[135]，通常导致蓄液结构经历密集穿孔破坏与凹陷、鼓胀变形过程（图 11）。

联合载荷在空气中的传播过程可分为 3 个阶段[136]：爆炸冲击波加速破片群阶段，冲击波波阵面先于破片群、冲击波速度（v(F)）逐渐低于破片群速度（v(E)）阶段，破片群先于冲击波波阵面、冲击波速度低于破片群速度阶段。联合载荷作用下蓄液结构的动响应问题还涉及联合载荷在液体介质中的传播过程，即爆炸冲击波透射进入液体并形成压力波、破片群高速入水引发水锤效应的过程。由于各破片的速度与空间分布不同[137]，破片群高速入水过程还涉及多个破片以不同次序进入液体的问题，具体可分为串

联式侵彻（图 12(a)[138]）与并联式侵彻（图 12(b)[139]），其中并联式侵彻还可根据破片作用时序进一步分为同步并联式侵彻和异步并联式侵彻[139]。

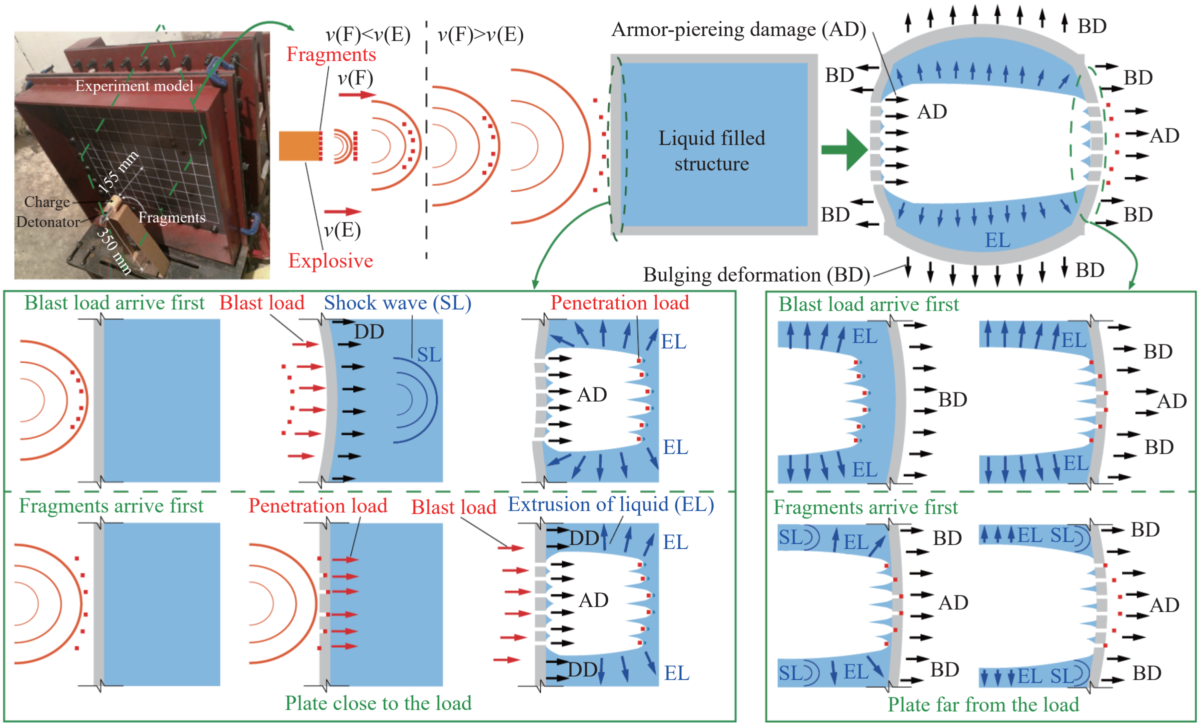


图 11　联合载荷作用下蓄液结构的动响应特性

Fig. 11　Dynamic response characteristics of the liquid filled structures under the combined loads

在侵彻过程中，破片及其引发的空腔的运动均可能受到相邻破片的影响。在串联式侵彻时，前序破片所产生空腔的扩展、闭合与溃灭过程改变了后序破片进入液体介质时的流场环境[140]，进而影响了其运动过程及空腔发展过程[141]。根据 Yun 等[142] 的研究，破片入水时间间隔与空腔运动时程的相对关系决定了串联入水特性。对此，Rabbi 等[143] 提出使用套娃系数（matryoshka number）表征后序球体入水时受到的冲击强度。采用并联式侵彻时，破片群的入水时间顺序及间距均可能影响局部流场，进而导致破片运动姿态和空腔运动过程发生变化。对此，宋武超等[144] 基于势流理论分析了双空腔的运动特性，通过有势面表征了空腔之间的相互作用，以破片头部的空腔扩展合速度势 $\varphi_{\rm bsum}$ 为例：

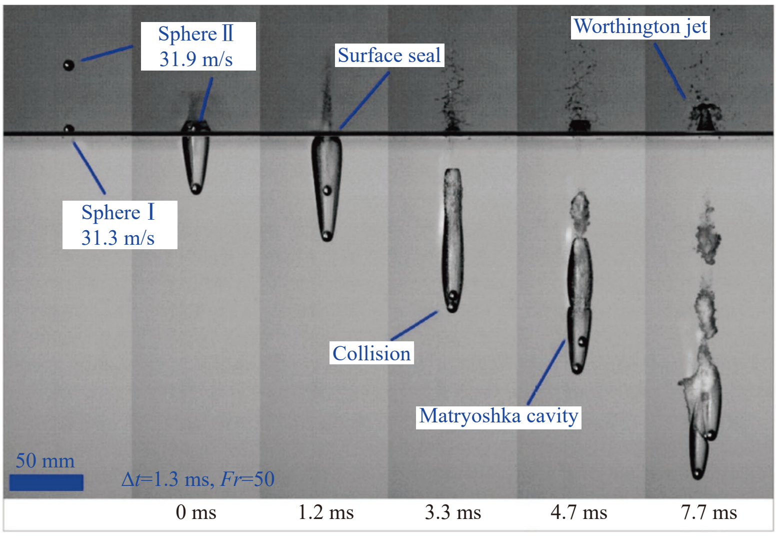
$$\varphi_{\rm bsum}=\varphi_{\rm b}+\varphi_{\rm bs} \tag{9}$$

式中：$\varphi_{\rm b}$ 为不考虑相邻空腔作用时的点源速度势；$\varphi_{\rm bs}$ 为考虑相邻空腔作用时的点汇速度势，用于表征相邻空腔产生的抑制作用。

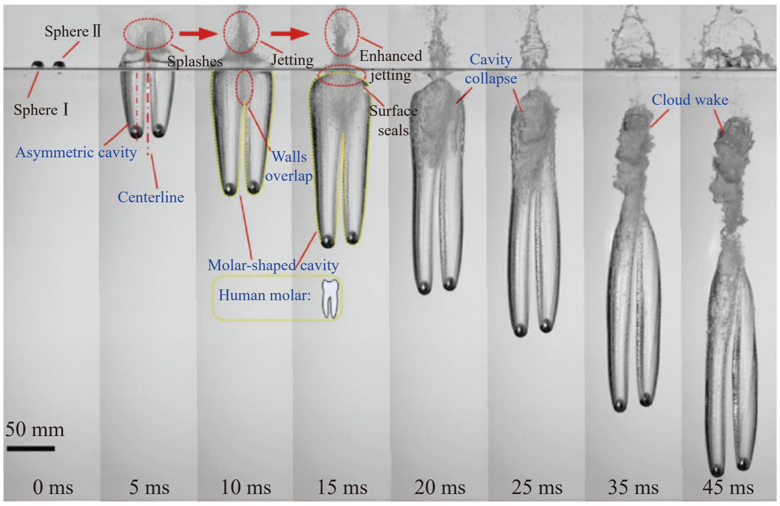
在联合载荷作用下，蓄液结构近爆面与远爆面所受到的载荷形式、载荷作用方向有所不同，导致两者的变形破坏模式也有所区别。近爆面的变形破坏以密集穿孔与鼓胀变形为主（图 13(a)[145]），且由于爆炸冲击波载荷与高速破片群所导致的水锤载荷方向相反，蓄液结构近爆面的变形挠度较未蓄液结构有所减小[146]；对于远爆面，由于爆炸冲击波载荷与水锤载荷作用方向相同，远爆面所受冲击载荷显著增强，面板因而发生了显著的鼓胀变形（图 13(b)[147]）。

联合载荷对蓄液结构存在独特的联合毁伤效应[135]，即联合载荷对蓄液结构的作用强于单一的爆炸冲击波和破片群对蓄液结构的作用之和。联合毁伤效应主要体现在两方面。

一是破片群的联合毁伤效应，即破片群对结构面板的穿甲过程以及破片群侵入结构后所引发的水锤效应。对于破片群对结构的穿甲过程，可参考 Qian 等[148] 的研究，将破片群的联合毁伤效应分为围聚



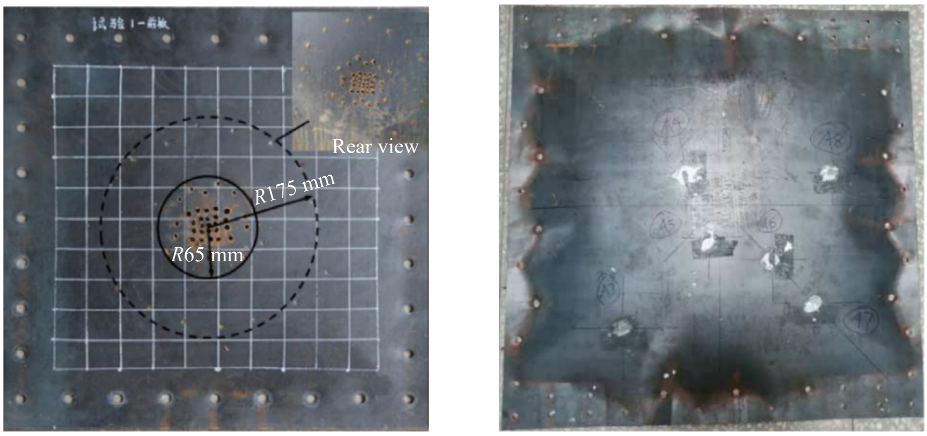
(a) Tandem entry[138]



(b) Parallel entry[139]

图 12　多破片串联式[138] 与并联式[139] 侵彻入水

Fig. 12　Tandem water-entry[138] and parallel water-entry[139] of fragments



(a) Deformation of front panel[145]　　(b) Deformation of rear panel[147]

图 13　联合载荷作用下蓄液结构近爆面[145] 与远爆面[147] 的变形破坏模式

Fig. 13　Deformation and damage modes of the front[145] and rear[147] panels of liquid filled structure under the combined loads

效应（cumulative effects）和累积效应（additive damage），联合毁伤效应的发生条件受破片群侵彻密度、侵彻同步性的影响[149]。对于破片群引发的水锤效应，Ji 等[150-151] 对双破片侵彻下的水锤效应及蓄液结构动响应特性开展了研究，发现 2 枚破片入水后产生的初始激波发生了叠加和增强，双破片对蓄液结构的毁伤效应主要受破片间距和破片作用时间间隔影响。此外，由于装药驱动下各破片的飞散姿态有所不同[152]，蓄液结构还可能遭受来自多个方向破片的同步侵彻。对此，王旭阳[153] 研究了破片以不同角度同时侵彻时蓄液结构的动响应特性，相应的理论模型则有待进一步的探索。

二是破片群与冲击波的联合毁伤效应，即冲击波与高速破片群在时空上的叠加与联合毁伤过程。郑红伟等[154] 认为，联合载荷对结构的毁伤与结构响应周期有关，不论冲击波与破片群以何种载荷最先到达近爆面，当载荷作用时间间隔 Δt 小于结构固有振动周期 T 的 0.25 倍，即可认为存在联合毁伤效应，该理论对于蓄液结构的适用性仍有待进一步研究。参考联合载荷作用下蓄液结构动响应特性的相关研究成果[145-155]，爆炸冲击波透射入水后所引发的水中压力波强度通常远小于水锤载荷强度，因而难以对爆炸冲击波与水锤载荷的联合毁伤效应进行定量表征。由此可见，亟需一种可精确控制爆炸冲击波、高速破片群载荷强度以及时空分布的实验方法。对此，可参考金属泡沫圆柱弹体内嵌 FSP（fragment simulating projectile）的实验方法[156]，通过金属泡沫圆柱弹体和金属实心弹体分别形成爆炸冲击波与高速破片载荷。然而，受金属泡沫圆柱弹体直径的限制，该方法模拟爆炸冲击波载荷的作用范围有限，相关实验方法有待进一步的探索与改进。

3　蓄液结构防护机理

蓄液结构抵御冲击载荷的核心思想是载荷耗散与能量吸收（图 14）。所谓载荷耗散，即通过液体介质的传递，降低载荷的时间、空间密集度，将峰值高、作用时间短的点冲击载荷耗散为峰值低、作用时间长的面冲击载荷或准静态载荷。所谓能量吸收，即将冲击能量转化为液体介质的压力势能和动能，其中：压力势能将以波的形式在液体介质中传播，并作用于结构壁面，部分转化为壁面的变形能；由于壁面的约束作用，液体动能也将部分转化为壁面的变形能。

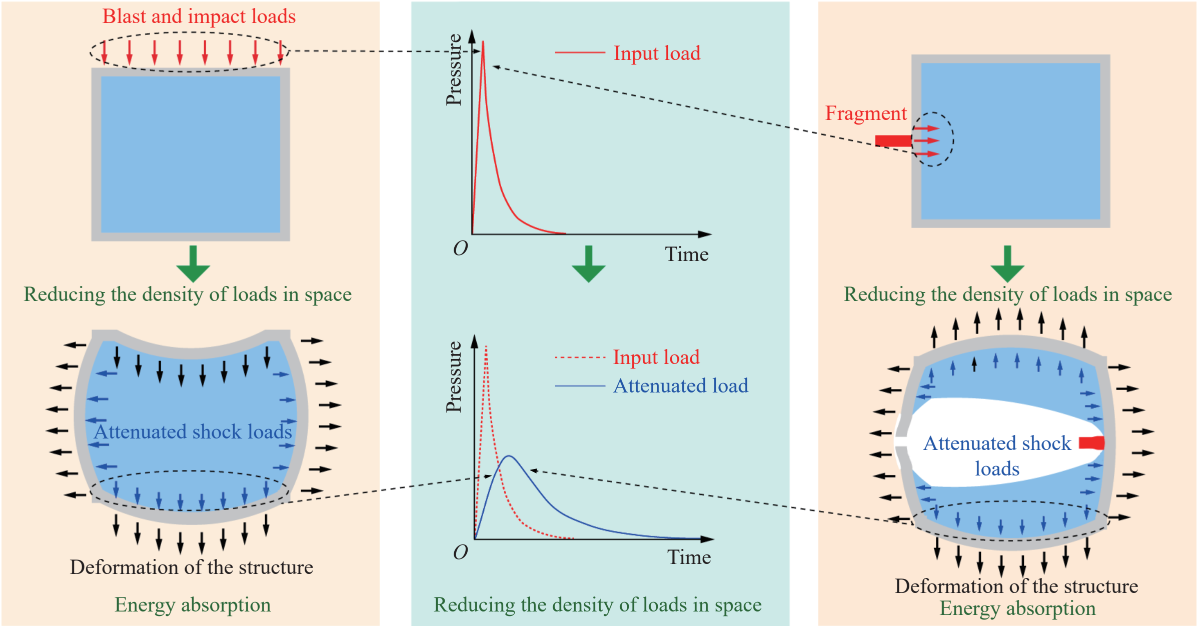


图 14　蓄液结构抗冲击防护机理

Fig. 14　Mechanisms of anti-impact protection for liquid filled structures

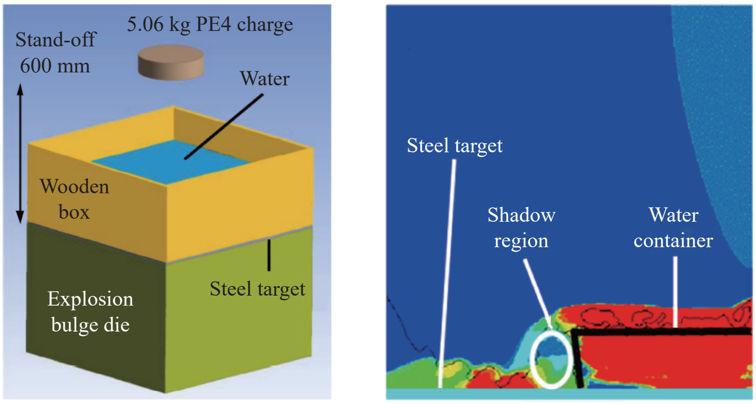
3.1　爆炸冲击防护

对于蓄液结构的抗爆防护：一方面，可充分发挥液体介质的惯性效应与波阻特性，削弱爆炸冲击波载荷峰值，延长载荷作用时间，扩大载荷作用范围，在时空维度上降低载荷分布密集度；另一方面，可利用液体介质的承压特性与载荷均匀化特性，在改变结构变形破坏模式的同时优化结构力学特性，进而充分转化载荷能量，达成结构抗爆防护的目标。

3.1.1　载荷削弱与耗散

通过贮蓄液体介质提升结构的等效质量与惯性，可实现结构对爆炸冲击波载荷的削弱与耗散。Thiyahuddin 等[16] 在对蓄液防护路障的研究中发现，液体作为防撞路障的压载物，可阻碍防撞路障在外部冲击载荷作用下的惯性运动，且这一阻碍效应随着液体蓄贮量的增加而增强。利用液体介质的惯性效应，可实现对爆炸冲击波等高频冲击载荷的有效削弱。例如，张琳等[157] 在对蓄液结构的抗冲击特性研究中发现，较未蓄液结构而言，蓄液结构可有效抑制冲击载荷的高频响应成分。Li 等[158] 在对爆炸冲击波载荷下液舱结构的动响应特性研究中也有类似的发现，在爆炸冲击下，受扰动的液体介质伴随近爆面面板一同运动，提高了近爆面面板的等效质量，并延长了面板的响应周期。

利用液体介质与固体、气体介质的波阻差异，亦可实现对爆炸冲击波载荷的削弱与屏蔽。一方面，爆炸冲击波在传递至液体与空气介质的交界面时将发生反射、衍射和绕射，冲击载荷因而受到屏蔽。如 Chen 等[159-160] 发现在防护目标和爆炸物之间设置水墙可促使爆轰波绕射，显著降低载荷的峰值和冲量，并延迟载荷到达防护目标的时间。Bornstein 等[161] 也有类似的发现（图 15[161]）：冲击载荷在介质交界面的反射与衍射过程形成了低压力区域（shadow region），并减小了防护目标的变形。他们认为，液体介质通常无法在结构达到最大变形时充分破碎和蒸发吸能，此时蓄液结构对爆炸载荷的防护机理主要为屏蔽效应[162]。在此基础上，Bornstein 等[53] 还研究了蓄液单胞结构构型对屏蔽效应的影响，发现在等质量条件下蘑菇型蓄液容器具有更好的载荷屏蔽特性。



(a) Schematic of experimental setup　(b) Pressure contours from water container

图 15　液体介质对爆炸冲击波载荷的屏蔽作用[161]

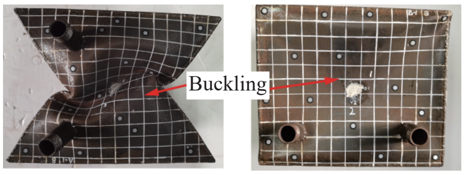
Fig. 15　Shielding of explosive shock wave loads by liquid media[161]

3.1.2　能量传递与转化

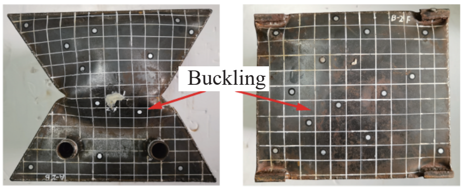
液体介质中的应力波速通常大于空气介质。较未蓄液结构而言，载荷在蓄液结构内可以更均匀地传递，进而导致结构的变形模式发生改变（图 16[50, 72]），同时提高了结构各面板的吸能均匀程度。

由于液体介质对载荷的均匀化传递特性，结构近爆面所受的冲击能量被其余面板分担，蓄液结构近爆面发生大挠度变形和局部破坏的风险较未蓄液结构显著降低。例如：Wang 等[163] 在对水箱的冲击实验中发现，液体介质使得冲击载荷更易从近爆面传递至其余面板，有效减小了近爆面的变形量；Zhang 等[164] 针对蓄液半球壳的抗冲击性能研究、Cheng 等[165] 针对蓄液圆管的抗爆性能研究以及 Jamali 等[166] 针对蓄

液双层圆柱壳结构的研究中均得到了类似的结论，蓄液柱壳结构较未蓄液柱壳结构有着显著的抗冲击性能优势，液体介质使得结构近爆面的局部变形挠度显著下降。值得注意的是，蓄入液体可能提升远爆面的变形挠度和破坏风险，如 Zhou 等[167] 发现液体介质置于爆炸物与结构面板之间时，结构面板受液体挤压作用过早发生了拉伸和剪切破坏。因此，在蓄液结构抗冲击防护设计中，需重点考虑远爆面强度、刚度以及面板边界连接等问题，通过对结构各面板的强度、刚度的合理配置，得到出色的蓄液防护结构形式。

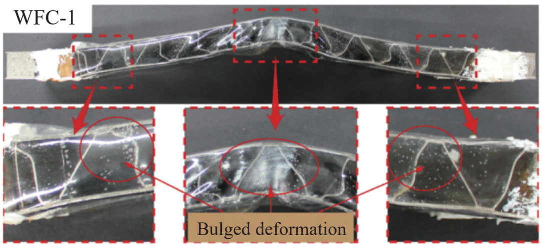


(a) Unfilled single-sell structure[50]



(b) Liquid filled single-sell structure[50]

(c) Unfilled multi-cell structure[72]



(d) Liquid filled multi-cell structure[72]

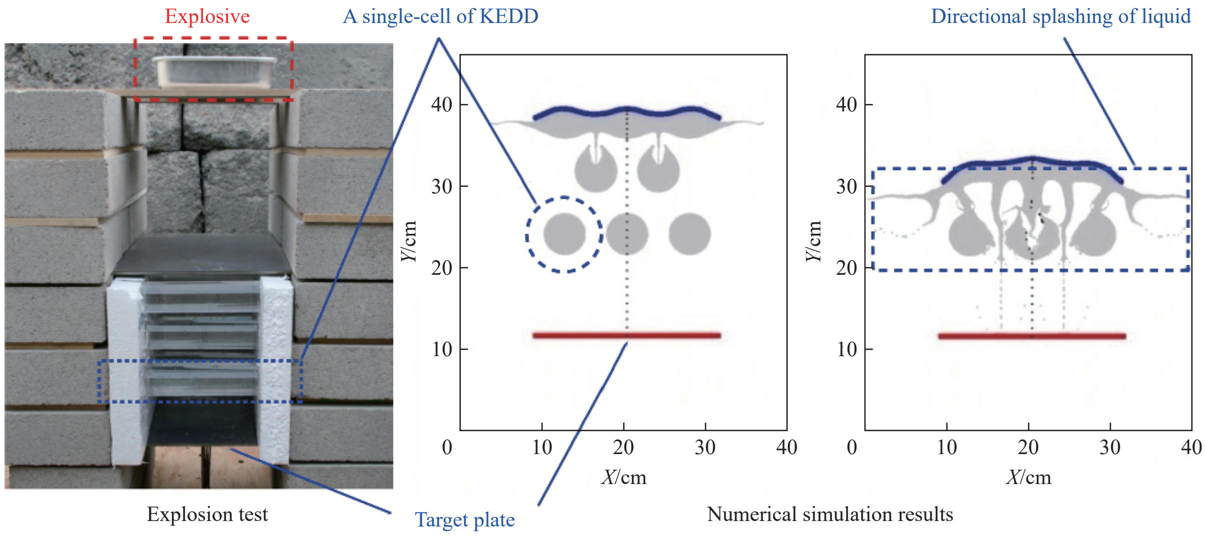
图 16　通过蓄液改变单胞[50] 和多胞结构[72] 的变形与吸能模式

Fig. 16　Modifying the deformation and energy absorption modes of single-cell[50] and multi-cell structures[72] by liquid filling

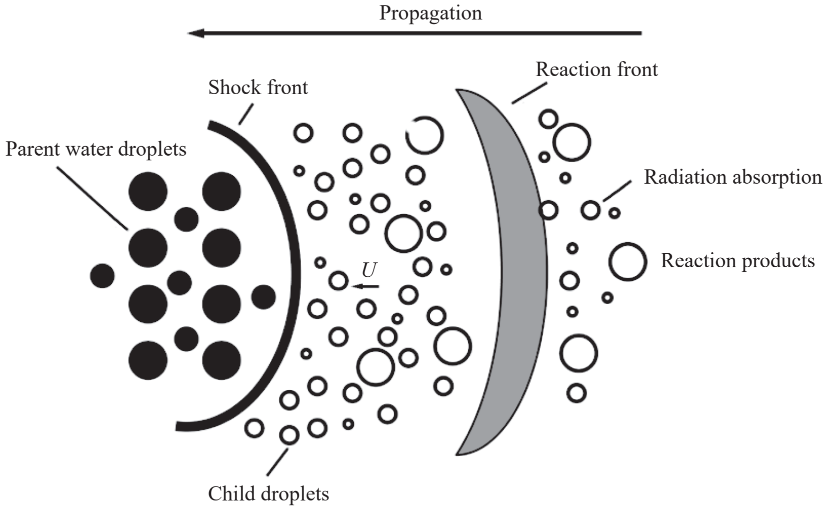
液体介质具有良好的流动特性和分散特性，其在爆炸载荷下的运动和汽化过程可有效转化载荷能量，提高蓄液结构的抗爆防护性能。一方面，液体介质的破碎和飞散可将载荷能量转化为液体介质自身的动能和势能。根据李思宇等[168] 对于蓄液结构抗爆性能的研究，液体介质吸收了近 7 成的爆炸能量，此部分能量随后以液体介质的动能、势能和结构的动能、变形能逐步耗散。Bornstein 等[169] 和 Baragetti 等[170] 也观察到液体介质在蓄液结构内的径向扩散过程和泄露后的飞散过程中将大量载荷能量转化为自身的动能和势能。Jenson 等[171] 设计了一种抗冲击蓄液结构，其包含内、外双层壳体，由内壳体上的孔洞连接内、外层蓄液区域，液体介质经孔洞的运动过程可有效传递和耗散能量。受益于液体介质的流体运动特性，在蓄液结构内合理布置液体介质可实现对载荷能量的定向释放。例如，Wolfson[172] 设计了一种多胞蓄液装置，通过控制液体介质的飞散运动方向偏离载荷作用方向，将载荷能量以液体介质动能的形式定向偏转耗散，实现对目标结构的防护（图 17(a)）。另一方面，液体介质与爆轰产物接触后将发生能量交换，抑制爆轰过程，并削弱载荷强度。如 Sugiyama 等[173] 研究了液体介质的抑爆过程，认为爆轰产物与液体介质的温度及压力差异致使两者之间发生内能传递，这一过程有效衰减了爆炸载荷。Grujicic 等[174] 对此进行了进一步的理化分析，发现液体介质的雾化和蒸发过程耗散了载荷能量，并通过降低温度抑制了爆轰产物的反应过程。李营等[175] 也有类似的发现：爆炸冲击波载荷强度与液体介质的汽化蒸发程度呈正相关，汽化过程明显阻碍了炸药的爆轰反应。在上述研究的基础上，Adiga 等[176] 通过理论分析了液滴破碎吸能与汽化吸能对耗散载荷的贡献率，发现液滴的比表面积及汽化时间量级直接影响其对爆炸载荷的削弱特性（图 17(b)）。可见，对于蓄液结构而言，蓄贮方式决定了液体介质的集中程度、比表面积等，进而影响能量的转化与耗散特性，是蓄液结构防护设计的重点研究对象。

液体介质较难被压缩，在外部冲击载荷作用下，液体介质将对结构面板产生内压作用，这在改变结构吸能模式的同时提升了蓄液区域的结构动刚度[177] 与抗力[178]。如 Mittal 等[179] 在对爆炸冲击载荷下

蓄液圆柱壳结构的动响应特性研究中发现，液体的内压作用提高了结构的局部刚度，液位以下面板的环向应力显著小于液位以上结构面板。利用液体介质的上述特性，可实现对蓄液多胞结构的定制化力学设计。如赵著杰等[180]对蓄液多胞结构进行部分的蓄液，将蓄液胞元和未蓄液胞元分别等效为大刚度弹簧和小刚度弹簧（图 18[180]），由此解释了蓄液方式对蓄液多胞结构宏观力学性能的影响机理，研究发现，蓄液胞元的不同布置方法可显著改变结构的变形与吸能模式。在此基础上，还可使用剪切增稠溶液（STF）、涂覆聚脲等方法进一步改善蓄液结构的宏观力学特性。STF 在高剪切速率下的黏度显著高于常规液体介质[181]，有助于提升材料的耗能效率[182]和抗冲击性能[183]，如 Lam 等[184]发现 STF 在高速冲击载荷下的增稠行为可有效改善蓄液结构的宏观力学行为，并进一步将 STF 运用至蓄液多胞结构中[185]，有效提高了结构的动态平台应力、抗冲击性能和能量吸收效率。Rijensky 等[186-187]则通过实验和数值模拟研究了涂覆聚脲对面板抵御水动力冲击的防护机理，发现涂覆聚脲有利于协助结构面板分担冲击载荷和吸收能量，有效改善蓄液结构的宏观力学性能。



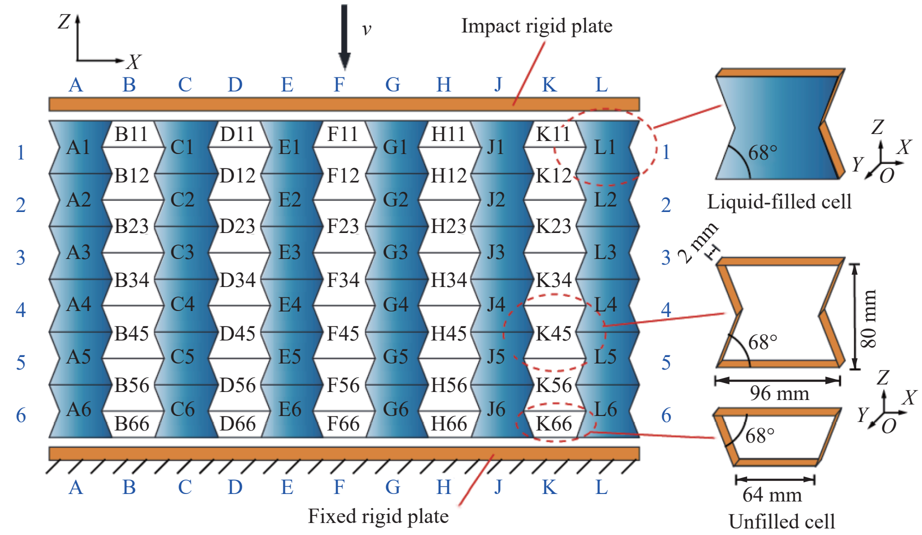
(a) Absorbing impact energy through the flow of liquid[172]



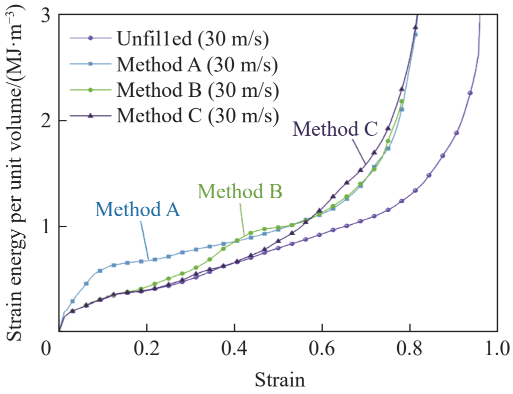
(b) Interaction of water droplets in detonation process[176]

图 17　利用液体介质的运动[172]、破碎与汽化过程[176]转化载荷能量

Fig. 17　Conversion of load energy through the process of motion[172], breakup and vaporization[176] of liquid media



(a) Impact test of multi-cell liquid filled structure



(b) Energy absorption modes under different filling modes

图 18　通过调整蓄液方式定制化设计结构吸能模式[180]

Fig. 18　Customized design of energy absorption modes by adjusting the liquid filling method[180]

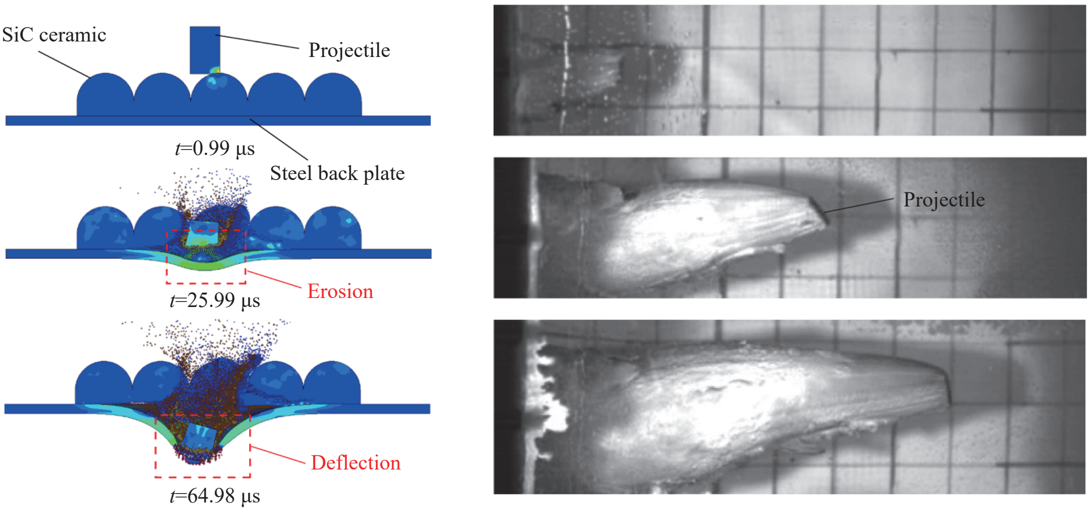
3.2　弹体侵彻防护

对于舰艇防护液舱等蓄液防护结构，其防护目的是确保后方结构和舱室的安全，即保证液舱内壁不发生水密性破坏。与此不同的是飞机燃料箱等蓄液结构，其防护目的是尽量减小结构的变形破损程度，保持结构的完整性，相关防护技术主要围绕如何衰减和削弱弹体侵彻导致的水锤载荷、合理加强箱体结构。在实现途径上，前者应尽量吸收弹体的冲击动能、衰减弹体的速度，将弹体的冲击能转化为弹体变形能、液舱前壁变形破坏能、液体的压力波能和动能等，从而分散冲击能量的密集度，确保液舱内壁不产生穿甲破坏和大面积破口；后者则应反其道而行之，即尽量减少液体介质对弹体动能的吸收，或者降低已传递给液体介质的冲击能量对箱体结构的破坏程度。

3.2.1　弹体冲击动能的衰减与耗散

弹体进入蓄液防护结构前，使之发生变形、碎裂、翻转运动，增大其与液体的接触面积，降低其运动稳定性，可以有效减小其对蓄液结构内壁的侵彻能力。一方面，可选用陶瓷[188]等高硬度材料加强蓄液结构面板，如仲强等[189]在针对陶瓷/液舱复合结构的研究中发现，陶瓷与液体介质使弹体发生了显著的墩粗变形及侵蚀。另一方面，可改变弹体侵彻姿态进而降低其运动稳定性，如 Wang 等[190]和王浩杰等[191]均研究发现，合理设置弹体进入液体时的攻角可降低其在液体中的运动稳定性，有效衰减弹体侵彻速度。可以看出，通过在蓄液结构的外板外置陶瓷体等刚性偏转结构[192]（图 19(a)），促使弹体在侵彻期间

发生破损与变形[193]，同时降低弹体的运动稳定性并使其在液体内发生姿态偏转与大变形[194]（图 19(b)），可实现对弹体速度的有效衰减。



(a) Projectile deflected by solid media[192]　　(b) Projectile deflected by liquid media[194]

图 19　使用陶瓷体[192] 和液体介质[194] 衰减与耗散弹体冲击动能

Fig. 19　Attenuation and dissipation of projectile impact kinetic energy by ceramics[192] and liquid media[194]

弹体进入蓄液防护结构后，通过增加液体介质阻力促使弹体减速，可进一步衰减和耗散弹体动能。根据弹体在液体中的速度衰减规律，可通过改变黏度、流速等方式改变液体介质的雷诺数，进而提升弹体阻力。一方面，可采用 STF 提升液体介质黏度，如张朴等[195] 在研究蓄液单胞结构时发现，STF 的固化特性导致液体介质的局部密度增大，显著降低了弹体速度；另一方面，可促使液体介质连续流动以增加其流速，如 Chen 等[196] 提出了一种使液体介质自行流动的防护技术（图 20[196]），发现流动的液体介质可有效增加弹体阻力，动态蓄贮结构较静态蓄贮结构拥有更好的抗侵彻能力。

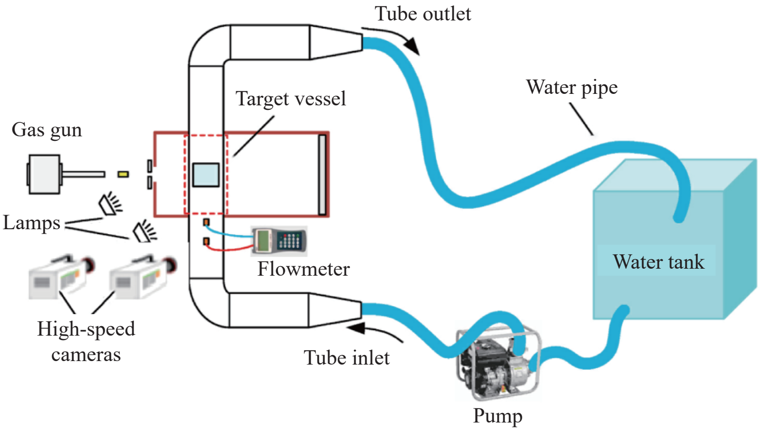


图 20　通过提高液体流速提升蓄液结构的抗侵彻能力[196]

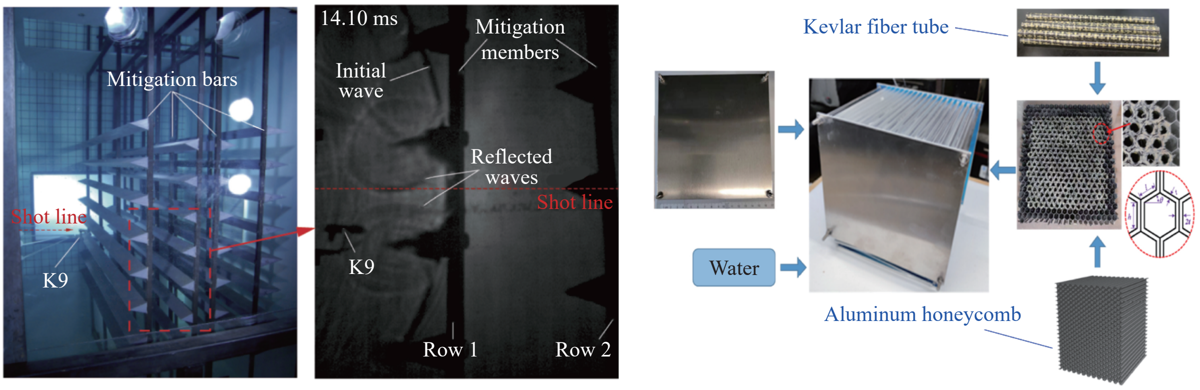
Fig. 20　Enhancement of the resistance of liquid filled structure to penetration by increasing the fluid flow rate[196]

3.2.2　水锤载荷的衰减和耗散

通过设计合理的结构构型和蓄液方法，实现蓄液结构对水锤载荷的定向传递，可降低结构重要壁面所受的水锤载荷强度，达到对水锤载荷衰减和耗散的目的。相关的防护技术可分为如下两类。

第一类是通过在载荷传递路径上设置刚性体、蜂窝结构等方法，阻碍水锤载荷对液舱内壁、油箱箱

体等重要面板的直接作用，实现对水锤载荷的衰减与耗散。(1) 在水锤载荷的传播路径上设置刚性体[197]，阻碍水中压力波传导至结构内壁，如 Disimile 等[198] 在蓄液结构中阵列布置了刚性棱柱群，显著阻碍和扰乱了初始激波的波阵面，降低了结构内板所受到的压力载荷强度（图 21(a)）。(2) 在水锤载荷的传播路径上设置蜂窝结构，如 Wang 等[65] 和 Artero-Guerrero[199] 等分别针对内含铝制格栅芯层和蜂窝铝芯层的单胞蓄液结构开展了侵彻实验，均发现芯层的变形吸能过程削弱了水锤载荷，并有效降低了蓄液结构外侧面板的鼓胀程度；Xu 等[200] 在此基础上对蜂窝芯层内嵌芳纶纤维管（图 21(b)），通过芳纶管和铝蜂窝共同吸收水锤载荷能量，进一步削弱了水锤载荷，提升了结构的抗侵彻能力。

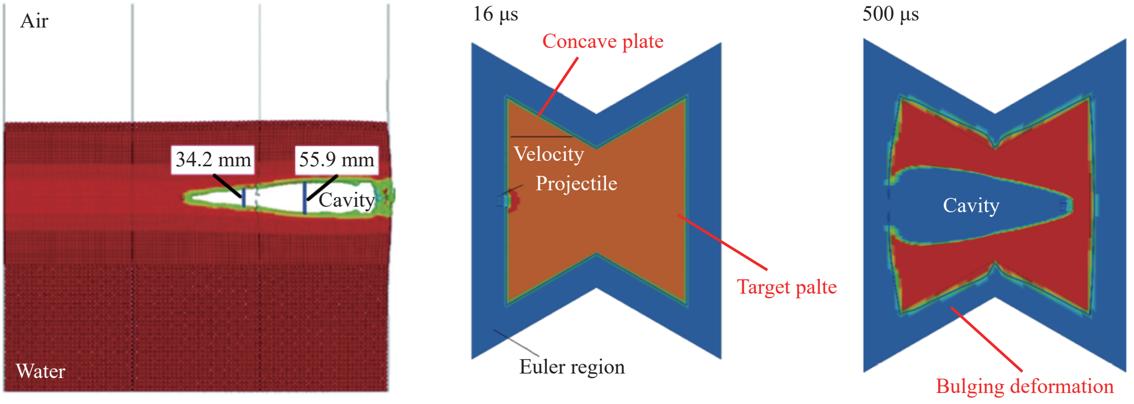


(a) Array liquid filled structure[198]　(b) Honeycomb liquid filled structure[200]

图 21　通过设置阵列刚性体[198] 和蜂窝结构[200] 削弱水锤载荷

Fig. 21　Weakening hydrodynamic ram loads by built-in arrayed rigid bodies[198] and honeycomb structure[200]

第二类是可通过在结构内预留空气或结构不等强度设计等方法形成一定的低强度区域，引导水锤载荷朝低强度区域定向传递，进而实现对水锤载荷的衰减和耗散。(1) 在结构内预留空气，即通过预置自由液面或气泡等方法形成低强度区域。例如，张宇等[201] 研究了蓄液量对蓄液格栅结构抗侵彻性能的影响，发现蓄液量的降低导致空腔更易膨胀，削弱了作用于内板的空腔挤压载荷强度（图 22(a)）；Townsend 等[202] 研究了在蓄液结构内预置低压压缩空气气泡的防护技术，同样发现气泡显著降低了水锤载荷强度。(2) 对结构进行不等强度设计，通过设置若干低强度、低刚度壁面形成结构的低强度区域。例如，李营等[203] 在液舱结构内设置了夹芯芯层，发现适当降低芯层强度可有效缓解结构外壁受到的水锤载荷强度；Guo 等[204] 针对弹体侵彻蓄液容器问题，提出了有限边界约束下的空腔动力学模型，发现容器对空腔膨胀过程的约束效应显著增加了空腔压力载荷的强度，小容器中的截面压力峰值显著大于大容器。针



(a) Preset free surface in the liquid[201]　(b) Design of variable strength structure[30]

图 22　通过预制自由液面[201] 及设计内凹结构构型[30] 削弱水锤载荷

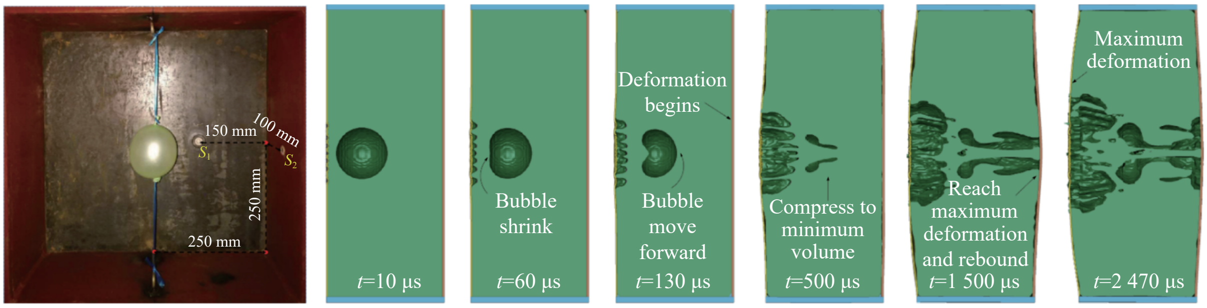
Fig. 22　Weakening hydrodynamic ram loads by presetting free surface[201] and using concave configuration[30]

对结构的不等强度设计问题，Gao 等[30] 创新性地提出了一种内凹胞元蓄液结构（图 22(b)），研究发现内凹胞元结构较常见的方形胞元更易于鼓胀变形，进而更有效地削弱与耗散了空腔挤压载荷。在此基础上，他们进一步定义了“膨胀阻抗”[205]，用于衡量蓄液结构在弹体侵彻下的膨胀难易程度，并探究了膨胀阻抗对水锤载荷的影响规律。可见，通过结构的不等强度设计，提高结构关键壁面的强度，牺牲结构非关键的低强度壁面，并促使结构发生局部大变形，进而弱化空腔发展过程中所受到的结构约束作用，可达到削弱与耗散水锤载荷、保护结构关键壁面的防护目标。

3.3　联合载荷防护

联合载荷同时包含爆炸冲击波与高速破片群两类载荷对象，需根据结构防护目的确定主要的载荷对象，进而有针对性地开展相应的防护技术研究。从防护目的上看，对于舰艇防护液舱等蓄液防护结构，其防护重点在于衰减高速破片群动能，应重视联合载荷中的高速破片群载荷，如 Jin 等[145] 在对液舱结构的实验研究中发现，液舱内的压力载荷主要源于破片所导致的水锤载荷而非爆炸冲击波；对于飞机燃料箱等蓄液结构，其在受到近距离联合载荷作用时结构完整性难以保证，因而通常仅研究其在中、远距离联合载荷作用下的结构动响应，在此距离下爆炸冲击波强度已发生大幅衰减，破片群仍为重点防护对象，如 Wu 等[155] 在对油箱结构的研究中发现，爆炸冲击波先行透射进入结构内部后液体压力仅发生了小幅波动，而后高速破片群侵彻入水引发水锤效应，液体压力迅速上升至峰值；而对于蓄液防爆罐等蓄液防护结构，其需要在小空间范围内完成对爆炸冲击波的削弱与高速破片群的减速，需同时考虑对爆炸冲击波与高速破片群载荷的防护。

从防护机理上看，以破片群作为主要防护目标载荷时，可参考蓄液结构抗侵彻防护相关研究成果，以降低破片群的穿甲能力、削弱水锤载荷作为主要防护目标。在降低破片群的穿甲能力方面，可通过喷涂聚脲等防护技术提升结构面板的抗侵彻能力和自愈特性。如 Wu 等[155] 开展了联合载荷作用下聚脲涂覆蓄液罐体的动响应特性研究，发现破片群的动能以热能的形式传递给弹孔附近的聚脲涂层，聚脲的软化和熔融过程还可提高弹孔附近的结构自愈能力和剩余强度。Wang[64] 等进一步研究了联合载荷作用下聚脲涂覆的蓄液罐体的损伤响应模式和能量吸收特性，发现聚脲涂层吸收联合载荷能量的理化机理在于其化学键的断裂和部分重组，增加涂覆厚度可显著提高聚脲的吸能占比，进而有效提升蓄液结构对联合载荷的防护性能。在削弱水锤载荷方面，可通过设置阻抗失配层、预留空气等方法削弱水锤载荷：一方面，可设置阻抗失配层以削弱初始激波等水中压力波载荷，如 Kong 等[61] 在液舱结构内壁覆盖橡胶层以抵御联合载荷毁伤；另一方面，可在蓄液结构内预设空间，通过协助液体介质运动和空腔的发展，缓解结构面板受到的压力载荷，如金键等[206] 开展了联合载荷对敞口和闭口蓄液结构的毁伤实验研究（图 23[207]），发现闭口蓄液结构受到的空腔挤压作用显著强于敞口蓄液结构，并进一步提出在蓄液结构内部预制空泡[207]，通过预制空泡的可压缩特性释放稀疏波，为液体介质提供运动空间并改变流场压力环境，有效缓解了蓄液结构在联合载荷作用下的结构损伤。



(a) Liquid filled structure with internal preset bubble

(b) Process of fragments penetrating into the liquid filled structure with internal preset bubble

图 23　在蓄液结构内部预留气泡用以抵御破片群载荷[207]

Fig. 23　Defense fragment cluster loads by reserving air bubbles inside the reservoir structure[207]

爆炸冲击波和高速破片群同时作为防护目标载荷时，需综合蓄液结构抗爆、抗侵彻防护思想，在充分衰减破片群速度的同时，利用液体介质的波阻特性、惯性效应、能量转化等特性，充分耗散水锤载荷、爆炸冲击波载荷。根据 Zhou 等[208] 的研究，由柔性材料制成的结构具有良好的设计性，其在联合载荷作用下易于解体并释放液体介质，且不易产生二次破片危害。可见，柔性蓄液结构可在保证液体介质对破片群减速作用的同时，通过结构自身的破损、液体介质的飞散充分耗散爆炸冲击波载荷与水锤载荷。Zhu 等[40] 使用超高分子量聚乙烯（UHMWPE）制成了一类柔性蓄液结构，用于抵御炸药与预制破片的联合毁伤作用（图 24[40]），该结构通过爆炸冲击波反射波和液体介质层衰减弹体侵彻速度，另外牺牲结构面板使液体介质外泄和飞散，通过液体介质的屏蔽效应阻挡和耗散爆炸冲击波载荷。此外，柔性蓄液结构的破碎过程导致大量液体介质飞散，期间液体介质的破碎、汽化等过程也在一定程度上抑制联合载荷的传播，然而受限于实验测试手段与数值模拟方法，难以定量表征相关的能量传递与转化过程，相应的对于蓄液结构在爆炸冲击波、高速破片群、热效应等复杂多物理场耦合作用下的结构防护机理等问题仍存在研究空间。

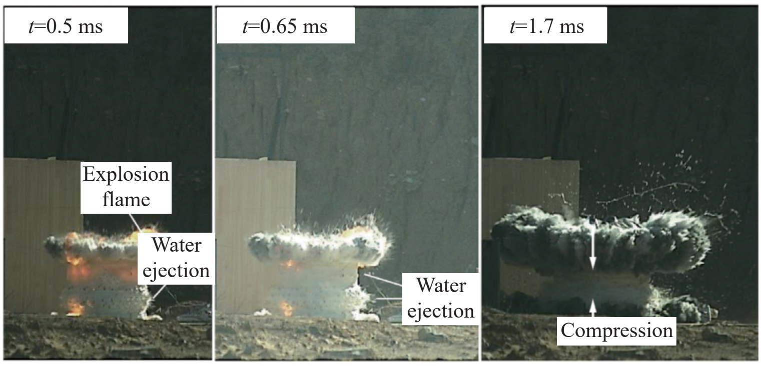


图 24　采用柔性蓄液结构抵御联合载荷[40]

Fig. 24　Defense the combined loads by flexible liquid filled structure[40]

4　总结与展望

蓄液结构的构型、选材与蓄液方式丰富多样，在各类冲击载荷作用下，蓄液结构的动响应特性、防护机理有所不同。对于完全揭示蓄液结构在冲击载荷下的动响应及防护机理，至少还存在以下几个需要认清的问题。

(1) 多胞蓄液结构的冲击动响应与防护特性。伴随力学学科的飞速发展，蓄液结构的结构形式已逐步从单胞元结构发展至多胞元结构，结构构型逐步从传统的箱体构型发展至蜂窝、波纹、点阵、夹芯等复杂构型。目前，针对各类多胞结构的力学特性研究十分广泛，但在对各类多胞结构蓄入液体后，各类冲击载荷在结构内部的传递与耗散过程复杂多样；冲击载荷作用下结构的动态力学行为、动响应特性、防护机理可能发生显著改变；在等质量或等体积情况下，液体介质布置方式与结构基材、构型、规格尺寸的改变可能导致结构防护性能出现巨大差异。通过开展多胞蓄液结构的冲击动响应与防护特性研究，有望进一步将增材增编工艺、仿生结构设计、纳米与超材料设计等新兴技术融入蓄液结构的抗冲击防护技术中，助力实现蓄液结构的轻质化、经济化、智能化抗冲击防护设计目标。

(2) 联合载荷对蓄液结构的毁伤机理。联合载荷作用下蓄液结构的动响应过程复杂，涉及冲击波载荷与高速破片群载荷在时间维度和空间维度上的多重叠加与联合作用。目前，对于联合载荷在空气中的载荷传播机理、联合载荷下未蓄液结构的动响应机理已有诸多研究，而对于联合载荷在液体介质内的传播与耗散机理、联合载荷作用下蓄液结构的动响应机理研究，由于涉及气、液、固多相介质的相互作用以及多方向的流固耦合问题，受实验测试手段与技术不足、数值模拟难度高、理论分析模型复杂等诸多因素的影响，相关研究仍具有相当高的难度。围绕联合载荷作用下蓄液结构的冲击动响应与防护机

理这一科学问题，需针对多破片以不同姿态入水后的水锤效应、爆炸冲击波透射入水后与水锤载荷的相互作用、蓄液结构所受联合载荷的时空分布特性与载荷解耦方法、蓄液结构在联合载荷作用下的结构动响应理论等诸多问题开展进一步的研究。

(3) 蓄液结构冲击动响应高效数值计算方法。随着结构形式、载荷特性、蓄液方法等趋于复杂化，蓄液结构冲击动响应问题的数值计算难度显著提升，尤其是联合载荷等复杂载荷作用下的蓄液结构动响应问题。一方面，需同时考虑破片群在炸药驱动下的飞散、破片群对结构的密集穿甲、破片群进入结构后所引发的水锤效应与空腔运动、结构在水锤载荷作用下的变形与破损等多个流固耦合问题，相应的有限元网格划分难度大，计算结果呈现出高度非线性，不易于收敛。另一方面，需考虑爆轰过程、穿甲过程、流固耦合过程的精确模拟，流体介质网格尺寸不宜过大，结构网格尺寸受到破片网格尺寸制约、流体固体网格之间的尺寸需相互匹配，相关的模型网格数量庞大，相应的计算时间较常规问题呈现指数增长，亟需创新相关的理论和数值模拟方法，并结合大数据、人工智能等开展算法技术革新。

(4) 新材料蓄液结构的冲击动响应与防护机理。已有蓄液结构的冲击动响应理论大都针对均质、各向同性材料所制成的蓄液结构，对于纤维增强复合材料等各相异性材料制成的蓄液结构，其在冲击载荷下可能经历分层、纤维断裂、融化等复杂的变形与破坏过程，相应的流固耦合、结构动响应过程、结构失效机理也较均质结构更为复杂，值得进一步的探索。此外，随着液体材料的不断发展，蓄液结构内的液体介质已由常规的水介质发展为剪切增稠液体、磁流变液体、甲基纤维素水溶液、纳米材料功能液体等性质各异、可设计性强的液体材料体系，在不同种类液体介质的填充下，各类蓄液结构的动态力学性能、能量吸收特性、结构防护机理势必发生改变，通过对结构形式、液体介质种类、蓄液方式的合理配置，有望进一步改善结构的变形吸能模式与载荷耗散特性。

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