**文章编号：**1006-9941(XXXX)XX-0001-16

# 抗爆墙防护效应影响因素研究进展

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**摘 要：** 近年来，意外爆炸事故的频繁发生引发了防护工程学界对抗爆墙结构的深入研究和广泛应用。本研究根据抗爆墙的发展顺序、结构特点和抗爆机理，将抗爆墙分为传统抗爆墙和新型抗爆墙进行评述。传统抗爆墙主要采用传统建筑材料，通过墙体本身的特性来抵抗爆炸冲击波，而新型抗爆墙则通过材料和结构的创新进一步提高其抗爆性能。材料创新主要包括采用高强度材料、纤维增强复合材料等制作墙体、掺入墙体原材料（如混凝土）或贴于墙体表面，以提高墙体的整体强度和稳定性。结构创新则涉及多层墙体结构、夹层填充等设计，旨在通过发挥不同材料各自的性能优势来增强整体抗爆效果。本研究从抗爆性能评估、应用场景、试验和数值模拟方法以及其相关研究结果进行了总结归纳，涵盖了抗爆墙的材料选择、尺寸设计、形状优化和加固方法等关键因素，可为未来的抗爆墙设计提供参考依据。

**关键词：** 抗爆墙；爆炸冲击波；传统抗爆墙；新型抗爆墙

**中图分类号：** TJ55；TU3 **文献标志码：** A **DOI：**10.11943/CJEM2025123

## 0 引言

近年来，诸如巴黎燃气爆炸等意外爆炸事故造成了严重建筑结构损坏和人员伤亡。爆炸作用产生破坏的主要方式有：爆轰产物的直接作用、地面反射冲击波和空气入射冲击波的作用，其中空气入射冲击波起主要作用[1]。为降低爆炸冲击波的破坏程度设置的防爆结构体称为防爆墙[2]或抗爆墙。抗爆墙在爆炸冲击波传播过程中起到障碍物的作用，爆炸冲击波到达抗爆墙后部分能量被反射回来，从而改变了墙后建筑物上的爆炸荷载分布，降低了其峰值超压[3]，部分能量通过墙体变形、破坏以及衍射消耗。

抗爆墙的结构特征如形状、排列方式、数量和表面粗糙度对爆炸波的传播方式具有影响[4-5]。本研究将抗爆墙主要分为传统抗爆墙和新型抗爆墙两类。新型抗爆墙包括墙体原材料的创新和墙体结构的优化加固。针对传统抗爆墙，本研究重点分析了墙体的材料和尺寸对其抗爆性能的影响；针对采用新型材料的抗爆墙，主要总结了其加工方法、抗爆原理及抗爆性能，针对结构优化的新型抗爆墙主要总结分析墙体组成结构、抗爆机理和抗爆性能。

**收稿日期：** 2025-06-09；**修回日期：** 2025-07-01

**网络出版日期：** 2025-07-15

**基金项目：** 国家自然科学基金项目（52278521），中央高校基本科研业务费专项（22120230230）

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## 1 抗爆墙工况下爆炸冲击波传播规律

爆炸发生时，能量在爆心处迅速释放，产生高温高压气体并向外膨胀传播。冲击波前沿压力迅速上升形成压力峰值，其与大气压差值为峰值超压，与持续时间和正相冲量为爆炸冲击波的重要参数。当抗爆墙存在时，影响爆炸冲击波传播规律的因素主要有墙体结构特征[6-7]、炸药形状[8]和炸药当量等[9]。

爆炸冲击波抵达抗爆墙后，其原有的传播路径由于障碍物存在而发生改变。主要涉及的波的现象有反射、绕射和透射，绕射还包括侧面绕射和顶部绕射。已有研究表明，墙后超压峰值比迎爆面反射超压峰值小一个数量级[9-11]，但其作用时间延长2~3倍，在墙后1.5~2.0倍墙高处可能发生马赫反射。徐博明[12]发现防爆墙顶部绕射主要发生在墙后高度1.75 m以上空间。另外，对绕射区超压影响显著的因素依次为装药

**引用本文：**菅冰玉，肖伟芳．抗爆墙防护效应影响因素研究进展[J]. 含能材料，DOI:10.11943/CJEM2025123.

JIAN Bing-yu, XIAO Wei-fang. Research Progress on Influencing Factors of Protective Effect of Blast Walls[J]. *Chinese Journal of Energetic Materials (Hanneng Cailiao)*, DOI:10.11943/CJEM2025123.

量、爆距、防爆墙尺寸和防爆墙倾斜角度。张志刚等[13]开展了602 kg TNT当量的汽车炸弹的爆炸试验。结果显示，汽车炸弹爆炸对墙后目标的破坏作用主要来源于通过顶部绕射的冲击波。此外，墙体高度对抗爆墙体的性能也具有显著影响。当墙体高度超过2 m时，防爆墙对冲击波的衰减效果可高达81%。年鑫哲等[14]研究了爆炸冲击波在柔性抗爆墙上发生的透射与绕射规律。结果表明，随着墙体厚度的增加，透射现象减弱，绕射现象增强。爆炸冲击波可以通过设置抗爆墙可以改变传播路径，从而减小对墙后建筑物的破坏，通过调整墙体结构参数如高度、厚度、角度和形状等，优化抗爆效果。

## 2 传统抗爆墙

传统抗爆墙多采用传统建筑材料，具有结构简单、易于施工的特点。针对传统抗爆墙，按墙体材料和抗爆机理可分为刚性抗爆墙和惯性抗爆墙。刚性抗爆墙主要采用传统建筑材料如钢筋混凝土[15]、钢板、砖块[16]等，将大部分爆炸冲击波通过迎爆面反射方式加以阻挡。采用抗爆墙后，冲击波到达各测点的时间均会较自由场工况延迟[17]。Li等[18]采用干挂石板体系作为抗爆墙，通过爆炸冲击波与石板和破片的相互作用，降低后墙的爆炸荷载，进而减轻墙体的局部损伤和破片产生。常见传统混凝土抗爆墙如图1。

**图1** 混凝土抗爆墙[19]

**Fig.1** Concrete blast wall [19]

惯性抗爆墙具体指大体积和高质量的墙体如沙袋、水体（图2）、砂土抗爆墙等，受爆时可在短时间内发生能量转换，如墙体破碎散耗能量，水体汽化降温。张耀等[20]对比研究了水体抗爆墙和混凝土抗爆墙，发现设置合理的水体抗爆墙也可达到与混凝土抗爆墙相同的抗爆效果。Chen等[20-21]采用方钢管拼装成框架，在框架内置装满水的塑料袋做成水体抗爆墙，研究了比例爆距和墙体高度对抗爆性能的影响。结果表明，


**图2** 水体抗爆墙[22]

**Fig.2** Water blast wall[22]

比例爆距越小、墙体越高，抗爆墙对峰值超压和冲量的衰减率越大。Zhang等[23]在聚苯乙烯容器内部装水制成水体抗爆墙，研究其抗爆性能，结果发现当比例爆距为1.71~3.42 m·kg$^{-1/3}$时峰值超压降幅可高达94.53%。

传统抗爆墙通过表面加固和材料改性的方式可提高其抗爆性能。表面加固可采用纤维增强聚合物（FRP），FRP由高强纤维与聚合物基体复合而成，具有轻质高强、耐腐蚀等优点，粘贴在抗爆墙表面可提高墙体延性、减小应力集中、吸收部分能量，从而达到增强抗爆性能的目的[24-31]。与采用钢板等刚性材料相比，采用碳纤维聚合物（CFRP）加固可以使墙体吸收更多能量从而提高抗爆性能。增加FRP层数会增加墙体的吸能性能，对墙面位移的影响可以忽略不计[32]。针对进一步优化FRP的层数与厚度设计，优化其抗爆性能，并探索FRP材料在不同环境条件下的适应性，特别是高温、低温和高腐蚀性环境中的性能表现尚需进一步研究。

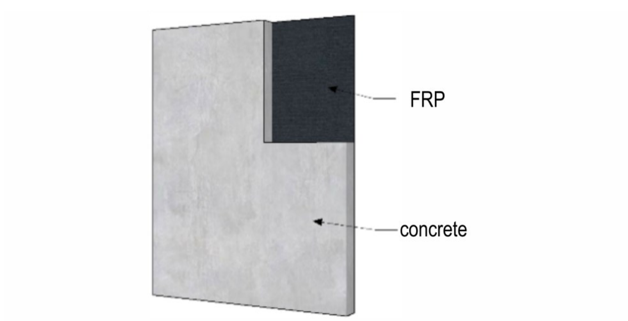



**图3** FRP加固混凝土抗爆墙

**Fig.3** FRP reinforced concrete blast wall

聚脲材料因具有显著的应变率效应，在爆炸荷载作用下会发生从皮革态向玻璃态的相变，故而显著提高其刚度，从而表现出优异的抗爆性能[33-35]。已有研究表明，聚脲涂层可进一步提升抗爆墙提供有效的保护[36]。Zhu等[37]的研究指出，当比例距离 $Z \geq 0.25$ m·kg$^{-1/3}$时，聚脲涂层能够有效保护墙体。聚脲对抗爆墙的加固效果受到多种因素的影响，包括加固位置（迎爆面、背爆面）及加固层数。Song等[38]通过爆炸试验研究发现，

在抗爆墙背爆面喷涂聚脲涂层可显著提升其抗爆性能。Zhu等[39]比较了未喷聚脲、单面(前或后表面)喷涂聚脲以及双面喷涂聚脲的砌体墙的抗爆性能,结果发现背爆面喷涂聚脲的效果优于迎爆面,在同等条件下,双面喷涂聚脲的墙体表现出最佳的抗爆性能。

此外,聚脲加固效果也受加固层厚度的影响,Ji等[40]分析了接触爆炸作用下砌体墙和喷涂聚氨酯增强砖墙的破坏现象,发现当聚脲层厚度增加到8 mm时,砌体墙的损伤面积比未加固时减少55.6%。Zu等[41]通过试验和数值模拟,研究了接触爆炸工况下,370 mm墙体双层涂覆聚脲后的抗爆性能。比较了爆坑的面积、深度和直径,结果表明,当迎爆面聚脲层厚度为6 mm时,背爆面的最佳厚度应为2 mm。Xu等[42]分析了爆炸荷载作用下聚脲加固砖墙的动力响应和破坏模式,结果发现当聚脲层厚度超过6 mm可以有效抑制局部剪切破坏。Santos等[43]进行了四炮次砌体墙的抗爆试验,其中一次未加固,另外3次聚脲层厚度分别为4 mm,6 mm和10 mm,试验结果显示,6 mm厚度的聚脲层综合表现最佳。另外,通过对聚脲材料的改性,还可进一步提升其加固效果。Rivera等[44]研究发现纳米增强聚脲在提高混凝土墙抗爆破性能的同时,还可提高其阻燃性能。Irshidat等[45]用多面体低聚硅氧烷(POSS)增强聚脲,研究结果显示,采用POSS增强后的聚脲显著提升了砌体墙的抗爆性能。

聚脲材料在抗爆墙加固中的应用研究主要集中于加固位置与聚脲层厚度的影响,以及改性技术对性能提升的效果。已有研究表明,聚脲材料在不同条件下表现出差异化的抗爆性能,其加固方法尚需根据结构特点和爆炸荷载类型进行优化设计,包括聚脲涂层厚度和加固位置选择。

除表面加固外,通过对基础材料的改性也可显著提高墙体的抗爆性能。材料改性主要包括在基础材料内掺入增强材料,如纤维,纤维材料因其粒径小,可以填充混凝土当中的空隙,减小孔隙率,在减小体积、提高材料性能的同时增强稳定性。通过在混凝土中掺入钢纤维,可在同等条件下减少墙体厚度,同时提高其力学性能。夏志成等[46]研究发现,同等抗爆性能要求下,与普通钢筋混凝土墙相比,钢纤维混凝土可减少约11%厚度。此外,采用泡沫铝和泡沫混凝土等轻质材料,有利于能量耗散。Shang等[47]通过爆炸实验和数值模拟研究了泡沫混凝土涂层厚度对钢筋混凝土墙抗爆性能的影响,结果发现涂层厚度显著影响泡沫混凝土的碎裂程度。Alsubaei等[48]研究发现,在钢筋混凝土墙顶部加盖顶棚,或采用双层砌体墙填充钢筋聚氨酯泡沫,以及用铝泡沫改造墙壁,可以减少爆炸冲击波对墙后结构的影响。

在混凝土内设置钢筋网可增强其抗爆强度。Shariq等[49]采用FRP和低碳钢筋网对砌体墙进行仅背爆面和迎爆面背爆面双面加固,发现4.5 mm直径的钢筋网双面加固效果和0.5 mm的CFRP背爆面加固效果相当,CFRP双面加固效果较好。Chen等[50]采用FRP、钢丝网和层压钢筋对砌体墙进行加固,对比分析了试验和数值模拟结果的位移响应、破坏模式。结果表明,钢丝网的加固效果最好,CFRP次之并优于层压钢筋。Liu等[51]采用钢丝网和泡沫铝对混凝土墙体进行加固,发现两种加固方式均可提高抗爆性能。此外,钢丝网加固效果更优。

综上所述,传统抗爆墙基于材料特性与抗爆机制,分为刚性抗爆墙和惯性抗爆墙。刚性抗爆墙依托材料本身的力学性质,通过反射实现冲击波衰减;惯性抗爆墙则利用沙袋、水体等大质量材料的动态响应特性,在爆炸瞬间完成机械能向破碎耗能、相变吸热等形式的转换。然而,现有研究需在惯性抗爆墙的参数方面进一步开展,对于惯性抗爆墙的几何尺寸、材料性质与抗爆性能间的量化关系,需开展系统性的参数化试验与数值模拟研究。在性能提升方面,主要包括表面加固与材料改性两种方式。纤维增强聚合物(FRP)与聚脲涂层显提升墙体延性与能量耗散能力,从而提高其抗爆性能。但相关研究仍存在局限性:FRP材料在爆炸荷载与环境条件耦合作用下的性能演变规律需要进一步明确;聚脲材料的应变率效应虽已得到验证,但其加固效果受爆炸当量、加载波形、墙体边界条件等因素的影响机理需要进一步研究。材料改性技术方面,纤维种类和掺量比例优化等策略有效改善了墙体的抗爆性能,但增强效果与基体材料的动态力学性能、多材料协同耗能机制的关系仍需深入探究,在爆炸荷载动态响应特性与材料微观结构演变的关联方面的研究需要进一步开展。

## 3 新型抗爆墙

由于传统抗爆墙结构单一、自重大、抗爆性能提高空间有限等特点,新型抗爆墙被越来越多的研究和应用,主要包括墙体材料和结构的创新。采用新型材料作为墙体如高性能纤维、绿篱植物等,可以利用材料的

柔性特征吸收爆炸冲击波的能量，在减轻质量的同时满足抗爆性能的要求；将高性能纤维掺入混凝土或贴于墙体表面，可提高墙体整体稳定性和爆炸冲击波衰减效果；将刚性材料设计成迎爆面产生能量自消耗的形状，或将其与增强阻尼的材料组合，可在减轻自重的同时提高抗爆要求。

### 3.1 墙体材料创新

针对新型抗爆墙的材料创新，主要包括采用新型材料加工墙体，如柔性纤维材料和树篱等，或对墙体原材料进行适当处理，以提高其力学性能，从而提高墙体的消波效果。常见的方法包括在混凝土中掺入纤维[52]，如长碳纤维[53]、竹纤维、钢纤维[54]、使用超高性能混凝土[55]等，以及在抗爆墙表面粘贴FRP[56]。目前应用最为广泛的原材料加固材料为FRP和聚脲[57-58]。此外，还可采用聚氨酯涂层、附加钢板、泡沫铝、以及工程胶凝复合材料等[59]作为抗爆墙的加固材料。

除了通过迎爆面反射爆炸荷载外，柔性抗爆墙还通过墙体的变形吸收部分能量。Zhang等[60]用超高分子聚乙烯和纤维增强布设计了一种新型柔性复合防爆织物墙体，其对峰值超压的衰减系数接近0.5。绿篱植物作为柔性体，也有学者将其用于吸收爆炸波的能量研究抗爆效果。Gebbeken等[61]采用崖柏、樱桃树、竹子、小檗和紫杉[62]进行抗爆试验。结果表明，与自由场爆炸荷载相比，崖柏抗爆效果最佳，可将峰值超压降低高达61.5%。Tomasz等[63]通过试验研究（图4）测试了沿平行和垂直于金钟柏方向的超压，发现超压峰值分别衰减了14%和22%。Gan等[64]采用激波管对斯巴达杜松的抗爆性能进行测试，发现当TNT当量103 kg，爆心距23.6 m时，该植被可将超压和冲量峰值分别降低23%和11%。已有的柔性抗爆墙研究中，各类材料在爆炸能量吸收方面表现出一定的效果。柔性复合墙体的工程化应用标准（如材料耐久性、连接构造）、植物绿篱抗爆多树种协同布置、排列方式优化及

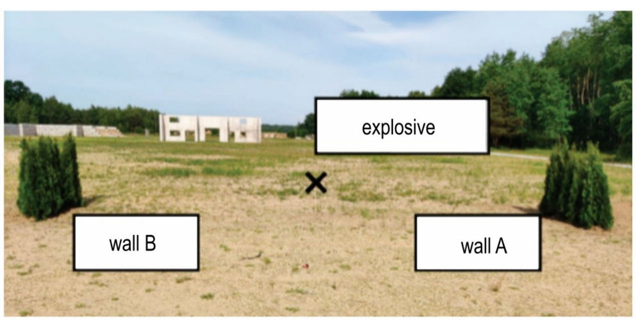



**图4** 金钟柏爆炸试验布置[63]

**Fig.4** Experimental setup of the thuja explosion test [63]

复杂环境适应性的系统分析需要进一步开展。可构建柔性抗爆结构的材料-构造-荷载多参数设计和研究方法，推动该类型的抗爆墙在实际工程防护的应用。

采用纤维增强材料和绿篱植物也可取得较为理想的消波效果，但对于绿篱植物的抗爆性能还需研究更多树种、排列组合以及数值模拟方法的研究。抗爆墙的墙体厚度[65]和高宽比[66]对抗爆性能也有着重要影响。新型材料抗爆墙的抗爆性能如表1所示。通过对比分析可知，针对抗爆性能的量化分析主要通过消波效应系数，即与自由场相比墙后超压和冲量峰值的衰减程度。此外还有诸如破片数量，墙体位移和应变等对抗爆墙破坏模式和动态响应的描述。

### 3.2 墙体结构优化

新型抗爆墙的结构优化主要有两种方式：1）将刚性材料设计成可以延长爆炸冲击波传播路径、增强能量消耗的形状，如波纹板形[70]、角锥形[71]、蜂窝形[72]、栅栏形[73-74]等，通过设置一定的弧度和角度[75-76]利用爆炸冲击波的斜反射和衍射，产生能量自消耗；2）将不同的材料加工组合，发挥各种材料的优势[77]，从而提高其抗爆性能，如将泡沫铝放置于钢板之间，一方面可以利用钢板反射爆炸冲击波，另一方面可以利用泡沫铝耗散能量，且可降低墙体自重。

针对波纹板抗爆墙，赵旭等[78]指出波纹板防爆墙比平板防爆墙具有更优的抗爆性能。Cekerevac等[70]对比了平板和波纹钢板抗爆墙，发现与平板抗爆墙相比，波纹板由于能量自消耗表现出更佳的抗爆性能。王锐等[79]对波纹钢板防爆墙的动力响应特性进行分析，发现高温对结构的响应模式影响显著。Lei等[80]研究了平板、加劲板和波纹板抗爆墙的抗爆性能，发现波纹板抗爆墙比其他类型的抗爆墙具有更好的吸能效果。Hedayati等[81]提出了一个针对不锈钢异形防爆墙的抗爆性能评估框架，给出了基于性能的评估方法在各种爆炸荷载下的最佳动态响应目标值。波纹板因其独特的几何形状能够有效耗散爆炸冲击波的能量，但高温条件对其动力响应影响显著，故需综合考虑不同环境因素的影响。通过在易发生屈曲部位增加加劲肋可使波纹板的抗爆性能得到进一步提升[82]。增加波纹板的凹槽深度和板厚可提高其抗爆性能[83]。波纹板抗爆墙截面形状如图5所示。

与平板抗爆墙相比，角锥形墙体可以延长爆炸冲击波的传播路径，故能耗散更多的爆炸能量。杨新河[71]通过对比角锥型（图6）、纵向波纹型、横向波纹型和普通直墙刚体防爆墙后的超压峰值，发现角锥型防

**表 1** 新型材料抗爆墙抗爆性能汇总

**Table 1** Summary of protective effects of new material blast walls

| material | size / m | $W$ / kg | $R$ / m | scaled distance | $H$ / m | protective effectiveness | reference |
|---|---|---|---|---|---|---|---|
| High-strength polymer fiber fabric | 5×0.4×2.5 | 5;10;15;20 | 3 | – | 0 | Transmission coefficient: $\Delta p_t/\Delta p$ Diffraction coefficient: $\Delta p_r/\Delta p$ | [14] |
| Ultra-high-molecular-weight polyethylene (UHMWPE), FRP | 2×0.0018×2.5 | 20 | 3 | – | 0.2 | – | [60] |
| Thuja | 2.0×0.55×1.5 | 5 | 6.0;6.5;7.0 | – | 0.5 | – | [63] |
| Thuja | 2×0.55×2 | 5 | 5.5 | – | 0.4 | 61.8% | [61] |
| Cherry-laurel | 1.8×0.55×0.94 | 5 | 5.5 | – | 0.4 | 30.7% | |
| Bamboo | 2.8×1.6×2.7 | 5 | 6 | – | 0.5 | 26.2% | [62] |
| Barberry | 2.9×1.7×2.5 | 5 | 6 | – | 0.5 | 18.3% | |
| Yew tree | 1.7×0.7×2.0 | 5 | 6 | – | 0.5 | 45.2% | |
| Thuja | 2.8×0.85×1.7 | 5 | 6 | – | 0.5 | 39.1% | |
| High-density polyethylene filled with natural loess | 3.0×0.5×(2.0;3.0) | 8.4 | 5 | – | 0.5 | The number of fragments | [67] |
| Sand, earth, stone | – | 3.2;3.5;5.8 | – | 2.78;3.29; 5.57;6.79 | – | Coefficient of wave elimination effect $\mu_p = \frac{\Delta p_{wb}}{\Delta p_{nb}}$ | [68] |
| Bamboo | 2.8×1.6×2.7 | 5 | 6 | – | 0.5 | 24.5% | [69] |
| | | | 7 | – | | 14.7% | |
| Barberry | 2.9×1.7×2.5 | 5 | 6.5 | – | 0.5 | 25.2% | |
| Yew tree | 1.7×0.7×2.0 | 5 | 6 | – | 0.5 | 44.5% | |

Note: $W$, $R$ and $H$ are the explosive equivalent, the distance and height of detonation, $\Delta p$ is the peak overpressure of free-field, $\Delta p_r$ is the peak diffraction pressure behind the wall, $\Delta p_t$ is the peak transmission pressure behind the wall, $\Delta p_b$ it's the shock wave behind the wall overpressures when there's a blast wall, $\Delta p_0$ it's the overpressure of the free field without a blast wall.

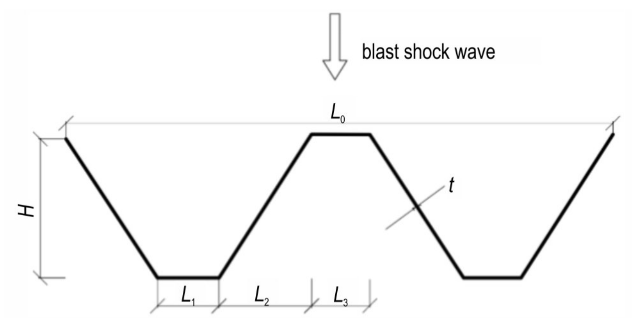



**图 5** 波纹板抗爆墙

**Fig.5** Corrugated plate blast wall

爆墙和纵向波纹型防爆墙抗爆效果更好。Hajek 等[84]采用纤维加固超高性能混凝土材料并对比了相同面积平板和角锥型抗爆墙，发现由于爆炸冲击波在角锥型抗爆墙表面的自相互作用，角锥型抗爆墙表现出更好的抗爆性能。另外，还可对抗爆墙设置角度或弧度以增强其抗爆性能[85-86]。

在两层平板之间设置一定的几何形状可以在发挥材料强度的同时，增大墙体的阻尼和稳定性，同时减小墙体质量，有利于爆炸冲击波能量的耗散[87-89]。Zhao

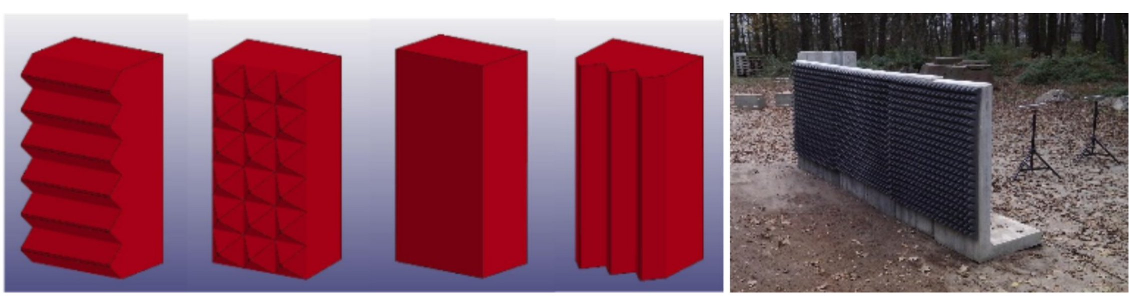
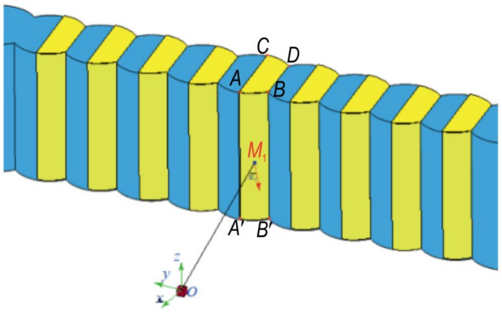


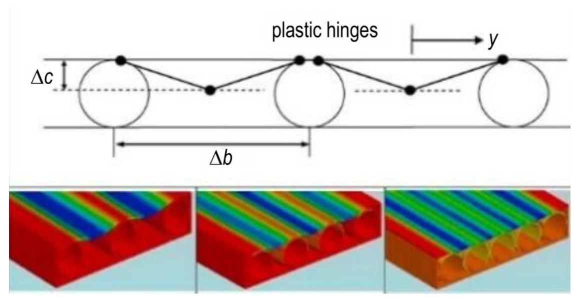
**图 6** 波纹型和角锥型抗爆墙[71,84]

**Fig.6** Corrugated and conical blast walls[71,84]

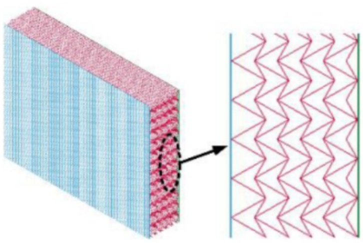
等[90]通过研究在蜂窝状截面抗爆墙工况下爆炸冲击波传播规律（图7a），发现爆炸荷载沿壁长方向呈非单调变化，墙面上的入射角随壁长方向呈周期性变化，反射超压呈锯齿状，且爆源与测点间距离的增加而逐渐减小。Xia等[91]设计了一种管芯夹芯板防爆板，其抗爆墙性能高，且可以通过焊接与面板连接（图7b）。



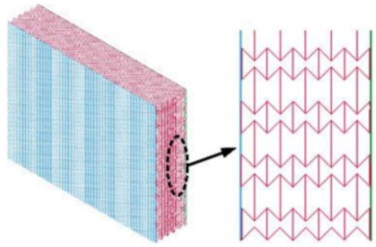

**a.** honeycomb blast wall [90]



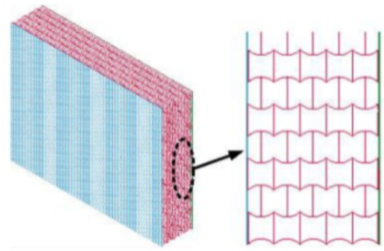

**b.** dice sandwich panel [91]



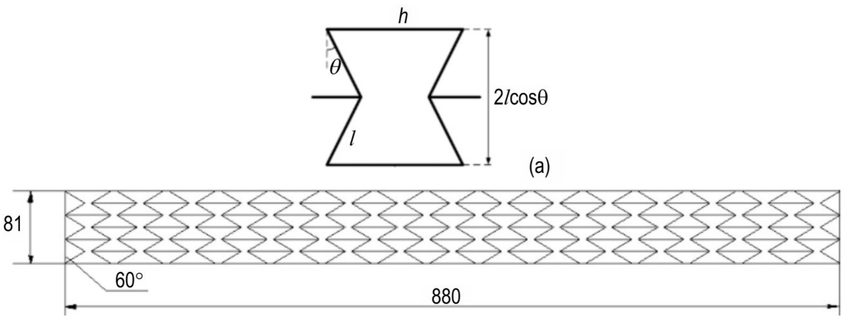
**c.** arrow honeycomb core [72]



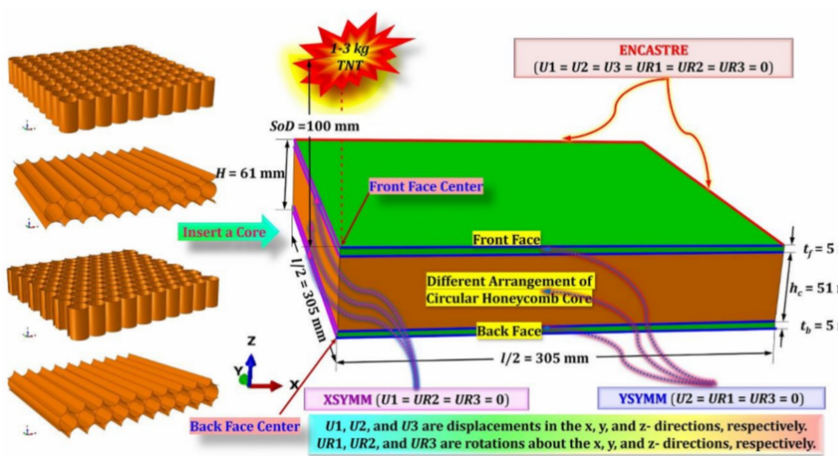
**d.** concave hexagonal honeycomb core[72]



**e.** concave curved honeycomb core[72]




**f.** auxiliary reentry blast wall[92]




**g.** different types of honeycomb explosion-resistant walls [53]

**图7** 不同截面的抗爆墙

**Fig.7** Blast walls with different geometric cross-sections

Lin等[72]发现针对蜂窝状抗爆墙，凹弧形蜂窝芯夹层板的抗爆性能优于箭头蜂窝芯和凹六角形蜂窝芯(图7c~e)。Luo等[92]研究了在冲击荷载作用下，辅助再入式防爆墙(图8f)、钢蜂窝夹层爆炸墙和常规钢波纹防爆墙的破坏机理。结果表明，辅助再入式防爆墙具有良好的防爆性能。图7为不同截面形状的抗爆墙。Bao等[93]研究了波纹夹层防爆墙在爆炸荷载作用下的动态响应，并将其与等质量加筋混凝土抗爆墙的动态响应进行了对比。结果表明，在考虑压力非均匀分布的加载条件下，波纹夹层抗爆墙的残余变形更小。

栅栏式抗爆墙通常由高强钢或复合材料制成，通过将爆炸冲击波分散成小波束，既保证良好的抗爆性能又可节约材料用量。Zong等[94]出了栅栏圆形和等腰三角形抗爆墙设计方案，讨论了栅栏式抗爆墙的排列组合对抗爆性能的影响，结果表明，该研究设计的栅栏式抗爆墙对超压和冲量峰值的衰减程度可达70%[95]，如图8所示。

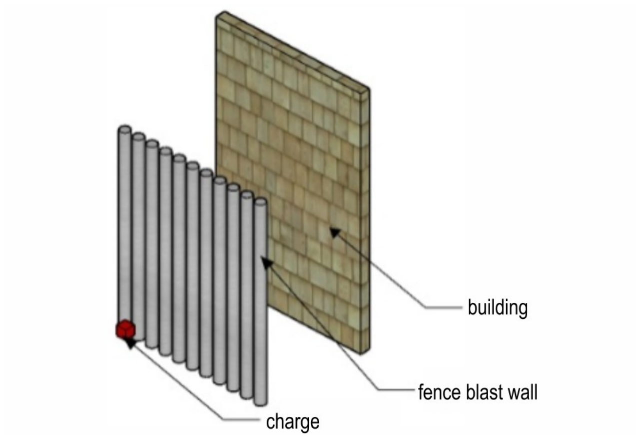



**图8** 栅栏式抗爆墙

**Fig.8** Fence-type blast walls

栅栏的截面形状和排列组合对其抗爆性能具有显著影响[74]。Hao等[96]采用圆形和三角形截面柱来构造栅栏式抗爆墙(图9)，验证了其在衰减爆炸冲击波和结构防护方面的有效性，结果显示，双层栅栏抗爆墙(前排为三角柱，后排为圆形柱)可将超压和冲量峰值分别降低80%和70%。宗瑞卿[97]研究发现，由圆形与等腰直角三角形截面柱组成的栅栏式抗爆墙抗爆性能最佳。Xiao等[98-99]研究了空心截面钢柱组成的栅栏式抗爆墙，讨论了钢柱形状和排列组合方式对抗爆墙抗爆性能的影响，发现其抗爆性能从强到弱依次为：正方形、三角形(顶点背对起爆点)、三角形(顶点面对起爆点)、圆形。

排布组合方式亦对栅栏式抗爆墙的抗爆性能存在影响。Jin等[100]研究了排布组合方式对栅栏式抗爆墙抗爆性能的影响。研究表明：在三排的抗爆墙中，迎爆面为三角形截面，其余两排为圆形截面抗爆效果最好。张晓聪[101]发现网型抗爆墙在衰减超压峰值方面的效果优于栅栏型抗爆墙，但在衰减冲量方面整体效果弱于栅栏型防爆墙，如图10所示。


**图9** 圆形和三角栅栏截面形状[96]

**Fig. 9** Circular and triangular cross-sectional shapes of the fence [96]

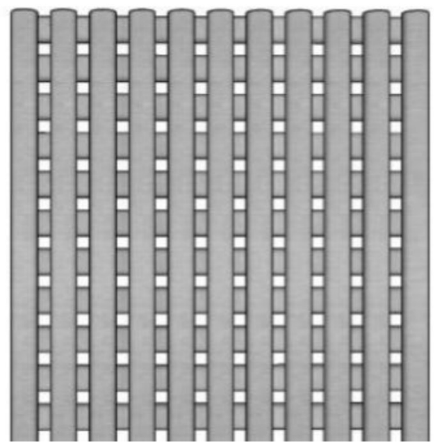


**图10** 网型抗爆墙

**Fig.10** Mesh-type blast wall

此外，抗爆墙还可以通过调整顶板角度影响爆炸冲击波的反射呈现不同的规律。Xiao等[102-103]研究了由石笼墙和薄钢板顶棚组成的抗爆墙，顶棚以不同的倾角安置于石笼墙顶部(图11)。结果表明，当顶棚倾角为135°时，与相同工况下自由场爆炸荷载相比超压峰值减少51.7%~88.0%，冲量峰值减少30.5%~59.2%，并提出了相应的数值模型用于预测其抗爆性能[104]，研究了金属沙网式抗爆墙石笼墙厚度和墙之间跨度的影响[105]，金属沙网使超压和冲量峰值分别降低了1.3%~6.6%和0.2%~4.6%[106]。Sohn等[107]提出了穿孔式抗爆墙(图12)，讨论了不同开孔尺寸、板厚和开孔布置方式与堵塞比的关系。Ram等[108]研究了孔隙率和重叠布置抗爆墙数量对爆炸冲击波衰减程度的

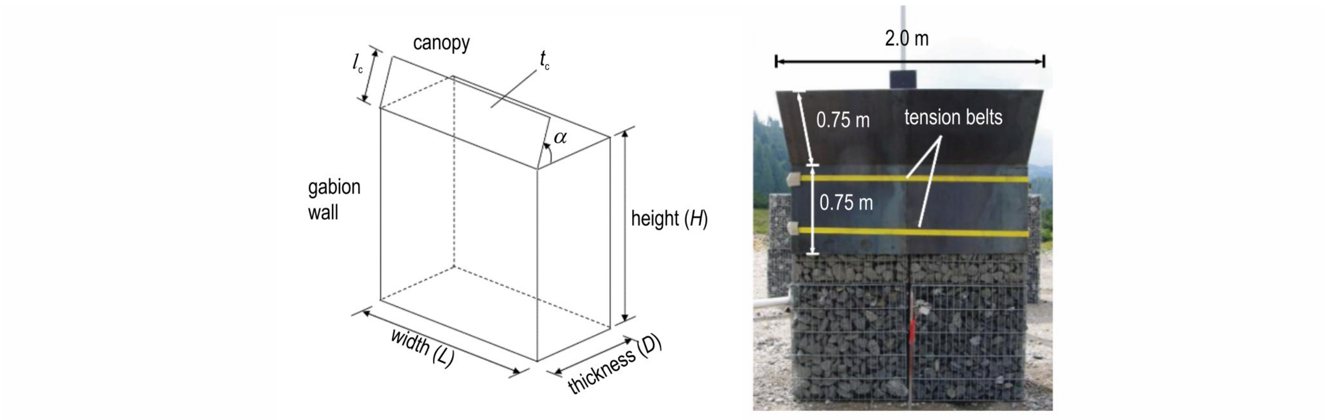



图11 加盖顶棚式抗爆墙[102-103]

Fig.11 Covered ceiling blast wall [102-103]

影响。Esa等[109]设计了CTMS和BCMS抗爆墙（图13），结果发现，当TNT当量为100 kg，爆距为5 m和8 m时，BCMS抗爆墙对冲量峰值的衰减程度为53.78%和28.7%。Fan等[110]提出了一种由悬挂钢板组成的幕墙式抗爆墙，主要通过能量消耗来衰减爆炸冲击波（图14）。研究发现，与自由场爆炸相比，使用幕墙式

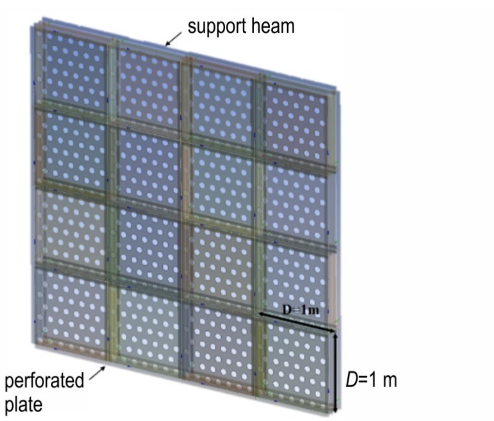



图12 孔洞型抗爆墙[107]

Fig.12 Perforated blast wall[107]

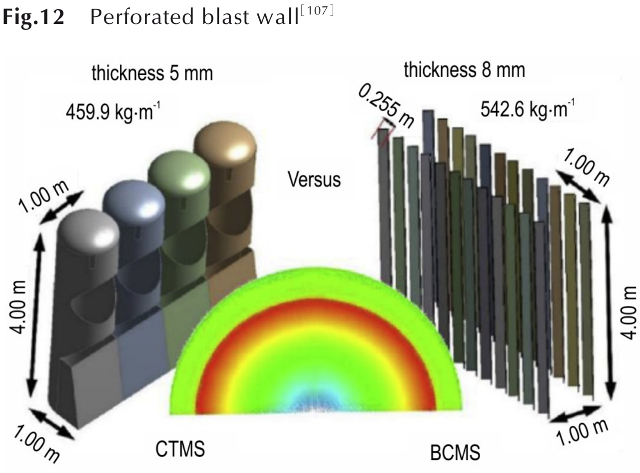



图13 CTMS和BCMS抗爆墙[109]

Fig.13 CTMS and BCMS blast wall [109]

抗爆墙可以使超压（冲量）峰值降低70.2%（63.8%）。

综上，空间构型方面，波纹板、角锥形等抗爆墙通过改变冲击波反射路径，相比于平板抗爆墙具有能量耗散优势，但高温工况下材料力学性能与结构动力学响应仍需量化研究。蜂窝状复合夹芯结构通过层间力学性能梯度设计，在维持轻质特性的同时实现阻尼增强，不同芯材几何构型（凹弧形、箭头形等）的能量耗散效率差异揭示了微观与宏观结构响应的关联性。栅栏式抗爆墙截面形状（圆形、三角形）、排列组合及层数是影响其抗爆性能的主要因素[111-112]。网型与栅栏型结构在超压和冲量衰减率上的互补特性，为工程场景的不同防护需求提供了设计依据。135°顶板倾角、悬挂式幕墙等创新设计，通过改变冲击波传播路径或被动耗能，在特定工况下可使超压峰值降低50%~80%。抗爆墙的非开放区域占整体比例较大时，形状和角度对其抗爆性能影响明显。不同的墙体形状和角度对延长爆炸波[113]的传播路径效果不同[84,114-116]。

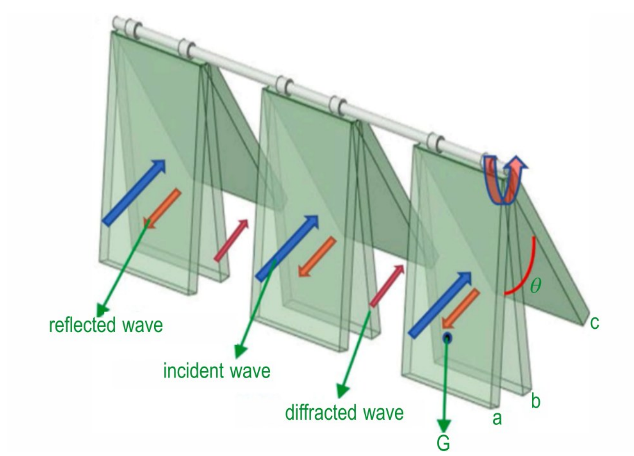



图14 幕墙式抗爆墙[110]

Fig.14 Curtain-type blast wall[110]

抗爆墙通过多种材料组合,采用三明治结构,充分发挥不同材料特性可以提高其整体抗爆性能[117-119]。外层材料通常选用高强度材料(如钢材),中间材料主要用于吸能和阻尼增强(如砂土、泡沫铝)。当爆炸冲击波作用于抗爆墙时,由于外层材料(如钢材)与芯层材料(如泡沫铝、砂土)的力学性能不同,冲击波在材料交界面会发生反射和透射。外层材料能反射大部分冲击波能量,减少进入墙体内部的能量;而吸能芯层材料通过吸收和耗散透射过来的能量,降低冲击波对墙体的破坏作用,从而实现对爆炸能量的梯度耗散,提升抗爆墙整体抗爆性能。

针对外层为钢板的复合抗爆墙,李治中等[120]发现当比例爆距减小、墙高增大时,钢板-砂土-钢板组合防爆墙的抗爆性能增强。夏志成等[121]对比了钢板夹聚氨酯和钢板夹混凝土两种抗爆墙,发现抗爆性能随抗爆墙芯材刚度减小而增大;荷载衰减率随着墙高的增加而增大,随爆距的增大而减小。张建亮等[122]发现钢板夹泡沫铝的抗爆性能最佳,钢板夹混凝土次之,钢板夹聚氨酯最差。Li等[123]设计了一种钢-砂岩-钢组合抗爆墙,通过数值模拟发现,钢-砂岩-钢抗爆墙的防护效果优于混凝土抗爆墙和钢-混凝土-钢抗爆墙。Qu等[124]研究了钢板-沙土抗爆墙表面爆炸荷载,并给出了计算公式。Chen等[125]采用钢制弹簧铰链置于双钢板中间做成组合抗爆墙,研究发现,承受爆炸荷载后,该抗爆墙可以部分恢复原始结构,从而在受爆后保持其原始作用和抗爆性能。

对于抗爆墙结构优化,外层材料的尺寸[126]和自身力学性能对复合抗爆墙的抗爆性能具有重要影响。Taha等[127]研究了墙体厚度以及在双层混凝土内增加空气层或泡沫铝层对墙体抗爆性能的影响。研究结果表明,双层混凝土内增加空气层增大了爆炸波的影响,增加泡沫铝层降低了爆炸波的影响。Yuan等[128]设计了基于钢丝网增强高性能混凝土板和金属管芯的新型夹层抗爆墙(图15),用于减轻多重爆炸荷载的作用,发现夹层墙体爆后能保持完整,具有良好的爆炸性能。Li等[129]研究发现随着墙体高度的增加和爆距减小,复合抗爆墙的抗爆性能增强。Hussein等[130]研究了复合木-砂-木抗爆墙的性能。采用直接蒙特卡罗模拟设计了易损性曲线,用于预测等效单自由度模型的失效概率。将简化模型校准为原型墙的三维有限元分析,用于确定墙后中心的水平位移,如图16。新型抗爆墙结构优化研究汇总如表2所示。

综上,对于抗爆墙的结构优化,主要通过“高强度外层-吸能芯层”的三明治结构,利用材料性能差异,实现爆炸冲击波能量的梯度耗散。结构优化层面,外层材料的几何与力学参数是复合抗爆墙的主要影响因素;墙体高度增加、爆距减小均能提升抗爆性能;夹层结构(空气层或功能材料层)可有效调控爆炸波传播,增强结构抗爆效能。

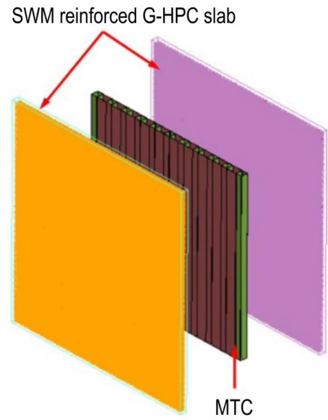



**图15** 新型夹层抗爆墙[128]

**Fig.15** New type of sandwich blast wall [128]

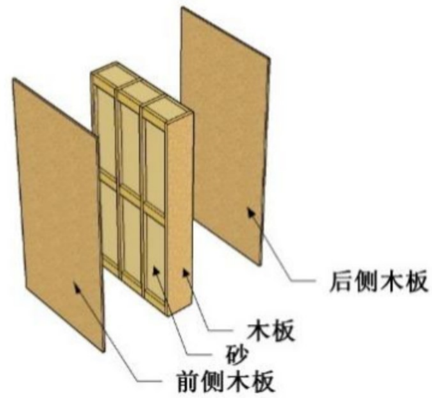



**图16** 木-砂-木复合抗爆墙[130]

**Fig.16** Composite wood-sand-wood blast-resistant wall [130]

## 4 结 论

本文总结了爆炸冲击波的传播规律,将抗爆墙按发展顺序和结构特征分为传统与新型两类。传统抗爆墙依材料性质和抗爆原理分为刚性与惯性抗爆墙,其冲击波衰减效能取决于尺寸规格与材料特性。传统抗爆墙可通过加固的方式提高抗爆性能,外层加固材料的性能、厚度及加固面影响提高效果。新型抗爆墙聚焦材料创新与结构优化,材料和结构层面的多种因素对其抗爆性能影响显著。

对于混凝土等传统材料改性方法、柔性材料等新型材料的消波机制与设计方法需要进一步完善。未来

**表 2** 新型抗爆墙结构优化研究汇总

**Table 2** Summary of research on structural optimization of new blast walls

| structural form | size / m | $W$ / kg | $R$ / m | $H$ / m | Scald distance / m·kg$^{-1/3}$ | protective effectiveness | reference |
|---|---|---|---|---|---|---|---|
| Steel Plate-Sand-Steel Plate | 1×0.5×(2.0；2.5；3.0) | 20 | 2.0；3.0；4.0 | 0.6 | – | Protective Effectiveness Coefficient：$\mu_P=\frac{\Delta p_{wb}}{\Delta p_{nb}}$ | [120] |
| Steel Plate-Sandwiched Polyurethane；Steel Plate-Sandwiched Concrete | 6×0.52×(2.0；2.5；3.0) | 20 | 4.0；5.0；6.0 | 0 | – | Protection Rate：$\alpha=1-\frac{p}{\Delta p_m}=1-\beta$ | [121] |
| Steel Plate-Foam Aluminum-Steel Plate | 4.0×0.24×3 | 5 | – | – | – | Protection Rate：$\alpha=1-\frac{p}{\Delta p_m}=1-\beta$ | [122] |
| Steel Plate-Polyurethane-Steel Plate | 4.0×0.24×3 | 5 | – | – | – | | |
| Steel Plate-Concrete-Steel Plate | 4.0×0.24×3 | 5 | – | – | – | | |
| Steel WireMeshReinforcedHigh-PerformanceConcrete-MetalPipeCore | 1.5×0.15(0.12)×1.5 | 0.2 | 0.4 | – | – | – | [128] |
| Wood-Sand-Wood | 1 | – | – | – | – | – | [130] |
| Steel Plate-Fiber Reinforced Concrete-Steel Plate | 1.2 | 1 | – | – | 0.4 | – | [131] |
| | | 6 | – | – | 0.22 | Penetration Damage Area: Reduced from 510 mm×577 mm to 187 mm×165 mm | |
| Steel Plate-Fiber Reinforced Concrete-Steel Plate | 1.2×0.09×1.5 | – | – | – | – | – | [132] |
| Wood-Sand-Wood | 0.61×0.3×2.44 | – | – | – | – | – | [133] |
| Wood-Sand-Wood | 0.61×0.3×2.44 | – | – | – | – | – | [134] |

Note：$W$，$R$ and $H$ are the explosive equivalent，the distance and height of detonation，$\Delta p_{wb}$ represents the overpressure at the back wave front of the combined structure；$\Delta P_{nb}$ is the overpressure of free field；$\beta$ is the overpressure ratio；$p$ is the simulated peak value of overpressure with explosion-proof wall；$\Delta P_m$ is the simulated peak value of free field overpressure.

需探究惯性抗爆墙墙体几何构型对能量耗散的影响机制，通过材料改性提升其耗能效率。针对新型抗爆墙，栅栏式、波纹板等构型的截面形态、组合设计，以及复合抗爆墙的形状参数与层间连接方式，需开展更深入的研究以优化整体抗爆性能。此外，还可进一步探索爆炸冲击波传播规律与抗爆墙设计参数的关联，为抗爆墙的设计提供更精准的理论依据。

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## Research Progress on Influencing Factors of Protective Effect of Blast Walls

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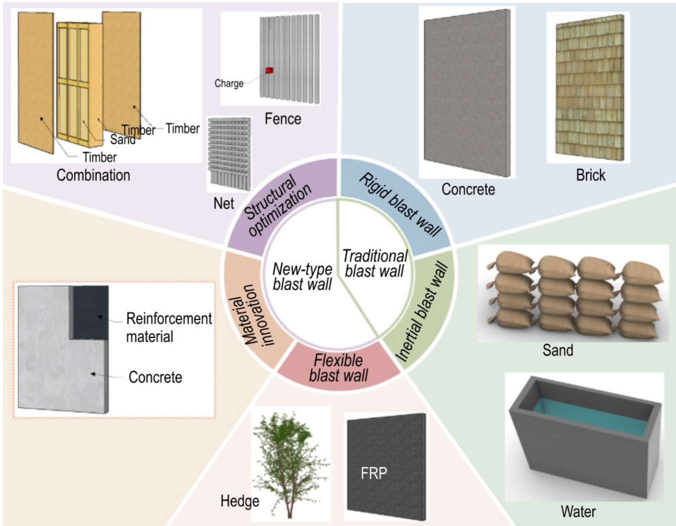
**Abstract:** In recent years, the frequent occurrence of terrorist attacks and industrial accidental explosions has triggered in-depth research and extensive application of blast wall structures in the field of protective engineering. According to the development sequence, structural characteristics, and explosion-resistant mechanisms of blast walls, this paper classifies and reviews blast walls into traditional blast walls and new-type blast walls. Traditional blast walls mainly use conventional building materials to resist explosive shockwaves through the inherent properties of the walls themselves. In contrast, new-type blast walls further enhance their explosion resistance through material and structural innovations. Material innovations mainly involve the use of high-strength materials, fiber-reinforced composites, etc., which are used to construct the walls, incorporated into the raw materials (such as concrete) of the walls, or attached to the wall surfaces to improve the overall strength and stability of the walls. Structural innovations involve designs such as multi-layer wall structures and sandwich fillings, aiming to enhance the overall explosion-resistant effect by leveraging the performance advantages of different materials. This paper summarizes and generalizes the explosion-resistant performance evaluation, application scenarios, experimental and numerical simulation methods, as well as related research results, covering key factors such as material selection, dimension design, shape optimization, and reinforcement methods of blast walls, providing a reference basis for future blast wall designs.

**Key words:** blast walls; explosive shockwaves; traditional blast walls; new-type blast walls
**CLC number:** TJ55; TU3 **Document code:** A **DOI:** 10.11943/CJEM2025123
**Grant support:** National Natural Science Foundation of China (No. 52278521), Fundamental Research Funds for the Central Universities (No. 22120230230)

(责编: 高 毅)

图文摘要：




In this paper, Blast walls are categorized into traditional and new types based on development sequence, structural features, and blast-resistant mechanisms. Traditional blast walls are classified into inertial blast walls and rigid blast walls according to materials, while new-type blast walls focus on material innovation and structural optimization. Performance evaluation, applications, experimental/numerical methods, and key factors (material selection, dimension design, reinforcement) are summarized, with references provided for future designs.