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Review Paper

Blast Mitigation: Review

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ABSTRACT

These days, an increase in terrorist attacks and advanced techniques for creating small explosive devices using powerful, high-explosive materials are causing massive building collapses, economic losses, and death. Protecting and mitigating the effects of explosions on structures and the people in them have become important to scientists. In this article, the effect of different parameters on the target structure, such as standoff distance, charge weight, and the use of protection systems have been reviewed. It is not economical to design the main parts of the structure so that they can withstand different hazards, therefore the use of different protection systems and materials such as walls, fences, sacrificial claddings, sandwich panels, and FRP, to mitigate the blast pressure and diffracted waves, and the results of their analysis have been discussed. The role of these protection systems is to absorb high kinetic energy in the form of strain energy through deformation. It is sometimes possible to replace these systems with a new one after failure at a lower cost than structures without a protection system. This paper presents an overview for beginner researchers to study the effects of the explosion on the structures and investigate solutions to reduce these harmful effects and protect the structures, and their inhabitants.

Keywords:
Energy absorbing system; Blast protection wall; Sacrificial cladding; Sandwich panel; FRP; Polyurea

1. Introduction

Today, military or government facilities and any type of urban building can be attacked. According to Global Terrorism Index, the death toll from terrorist attacks has increased, so there is an urgent need to find solutions to protect the structures and people within them. Explosives are classified according to their physical state (solid, liquid and gas) and divided into light and heavy explosives according to their decomposition rate. When explosive charges detonate in open space, create blast waves, and a very large amount of energy and pressure are released in a very short duration because of the decomposition of explosives into gases as shown in Figure (1).

The shock wave is characterized by an instantaneous increase in pressure from ambient atmospheric pressure (Pa) to the peak overpressure. The gas pressure varies from 10 to 30 GPa and the temperature varies from 3000 to 4000 c. The shock wave is generated in the material connected to the explosive. The blast shock waves occur over a very short period of time. Whereas, if the explosion occurs in the air, a blast wave is generated (Sandhu et al., 2017).

Blast mitigation does not refer to the prevention of explosive events. Instead, it is all about minimizing the damage caused by these explosions. Two approaches among researchers can be used

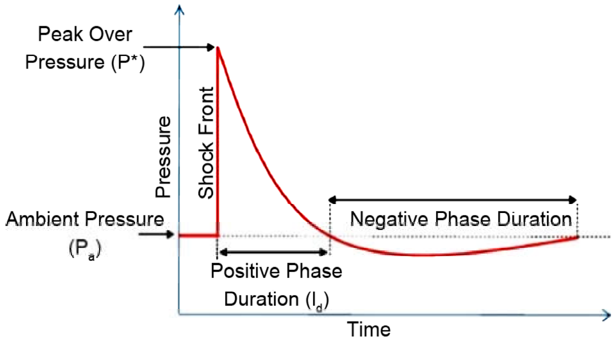


Figure 1. Released energy and pressure (Sandhu et al., 2017).

to protect structures, the first is to focus on the structural dimension of the main parts of the structure that must withstand explosive loads that may not be economical and alternatively, the use of protection systems to attenuate the blast waves, such as the use of specialized materials, blast-resistance walls, sacrificial cladding, and sandwich panels. The first step is to determine the level of risk the building faces.

Depending on the risks you need to protect yourself against, various materials can be used to mitigate the effects of explosions. They can thicken or strengthen the walls of a structure, absorb impact, or help catch flying fragments, or you can use other protection systems to increase the standoff or reduce the pressure felt by the target structure.

Everyone has characteristics and advantages that we will discuss below in each section. Due to the increase in terrorist attacks, in order to maintain the safety of structures and reduce the losses of lives and construction resources, this article aims to provide an overview of the various methods to mitigate the blast waves before reaching the structure and after striking it.

In this article, we cover the barriers and walls of various shapes to diffract and dissipate the blast pressure and reduce the pressure felt by the target structure. On the other hand, we cover methods such as composite sandwich panels, sacrificial cladding, and polymers that can reduce the damage to the structure after being hit by blast waves. This article provides a suitable background for researchers, for getting to know the topics related to the explosion and blast resistance, so that they can take their first steps in their research faster by reading this article (Table 1).

2. Blast Protection Wall

In this section, we want to present an overview of some research about designing a blast protection wall system and barriers. According to the increase in terrorist attack threats, it is important to reduce infrastructure losses. The main objective of pro-tection systems is to increase the distance between the structure and the explosion. Using

Table 1. Summaries of Blast protection systems.

	Blast Protection Systems	
Theory	**System**	**Example**
Creating Suitable Standoff Distance Between the Structure and the Explosive	**Blast Protection Wall** (Alsubaei, 2015; Wei & et al., 2010; Keys & Clubley, 2017; Yusof et al., 2014; Taha et al., 2019; Hussein et al., 2020; Keenan & Wager, 1992; Zhang et al., 2016; Livermore Software Technology Corporation, 2003; Xiao et al., 2019; Hongrui et al., 2021; Adrees & Hussein, 2021; Zong et al., 2017; Esa et al., 2020; Esa et al., 2021; Hadjadj & Sadot, 2013; Chaudhuri et al., 2013; Hao et al., 2017; Hassan et al., 2019; Li et al., 2013; Li et al., 2015; Yuan et al., 2017)	Different Types of Walls and Fences Are Used with Different Shapes, Geometries and Arrangements to Dissipate the Blast Wave and Reduce the Blast Load. For more Details, Refer to the Figures in Section 2.
Absorbing Impact Energy and Reducing the Pressure Felt by the Target Structure	**Sacrificial Cladding and Sandwich Panels** (Guruprasad & Mukherjee, 2000; Palanivelu et al., 2011; Chen & Hao, 2013; Zhou et al., 2013; Abdolzadeh & Izadifard, 2015; Matsagar, 2016; Li et al., 2017; Izadifard & Nazarinejad, 2017; Rolfe et al., 2018; Wang et al., 2019; Gu et al., 2020; Yungwirth et al., 2008; Peyman & Ebrahimzade, 2020; Abada et al., 2021; Blanc et al., 2021; Al-Rifaie et al., 2021; Kostopoulos et al., 2022; Choudhary et al., 2022; Chen et al., 2022; Vo et al., 2022)	Different Types of Sacrificial Cladding and Sandwich Panels are Made from Different Types of Cores and Skin-Layer Bonded to Each Side. For More Details, Refer to the Figures In Section 3.
	Materials (Crawford et al., 1997, 2001; Davidson et al., 2004; Silva & Lu, 2007; Carriere et al., 2009; Elsanadedy et al., 2011; Fazelipour & Tavakoli Zadeh, 2011; Izadifard & Qolipur, 2011; Izadifard & Mehrabi, 2009; Izadifard & Beygi, 2010; Raman et al., 2012; Ji et al., 2022)	Fiber-Reinforced Plastic (FRP) Carbon-Fiber-Reinforced Plastic (CFRP) Steel Fiber Reinforced Polymer (SRP) Polyurea Coating

protection walls and barriers are the most effective ways to ensure a suitable standoff distance between the structure and the source of the explosion. anti-blast walls are one of the ways that you can use to dissipate the blast wave and reduce the blast load that has been felt by the structure. They can absorb the energy and reflect the blast waves. It is not economical to build a structure that is completely resistant to all forms of attack, but this type of protection system can be used to provide the necessary security at a lower cost. The approaches of simple blast walls such as sandbags, timber sheets, and masonry walls refer to the time that people protected themselves from the military or their surrounding hazards. In this article, we want to present high-tech ones that can be installed in urban environments and protect people and structures against terrorist attacks. Figure (2) shows the effect of the blast waves on the barrier wall (Alsubaei, 2015).

Several studies have focused on the performance of masonry walls to dissipate blast energy (Wei & Stewart, 2010; Keys & Clubley, 2017). Wei and Stewart (2010) investigated the performance of unreinforced brick masonry walls under the blast by Numerical simulations based on the dynamic finite element program LS-DYNA, and finally, numerical models were compared with field test data. Damage criteria were taken into account according to maximum deflection and support rotation. In this study, the effects of material strength, boundary conditions, and wall thickness on wall performance were estimated. Four types of boundary conditions were considered, and it was seen that have a great effect on the collapse and response of the wall. Furthermore, it was found that mortar strength and brick strength had different effects under low or high explosive loads. Respectively, their effects are negligible for the response of the structure under high explosive loads and significant for the maximum deflection or the support rotations under low explosive loads. Because of absorbing energy well under high pressures, concrete can be used in anti-blast structures in addition to construction. Concrete reinforced blast wall was investigated to avoid severe damage under explosive loads (Yusof, et al. 2014). Taha et al. (2019) investigated the performance of concrete walls as barriers in the form of the flat (TFBW), convex curve (CCXW), and concave curve (CCVW) and also the effect of the angle of curvature on mitigating the blast waves by a non-linear three-dimensional hydrocode numerical simulation using AUTODYN-3D. This idea was inspired by turtles using their curved geometric shapes as natural armor. The curvature angles considered in this article were 50°, 60°, and 70°. Figure (3) shows the dimensions of these walls with 2 m standoff distance from 10 kg TNT as explosive charge. Different pressure gauges were placed in different positions on the concrete barrier walls and behind them to present the peak pressure recorded for the studied models, and also the internal energy inside the concrete barrier was

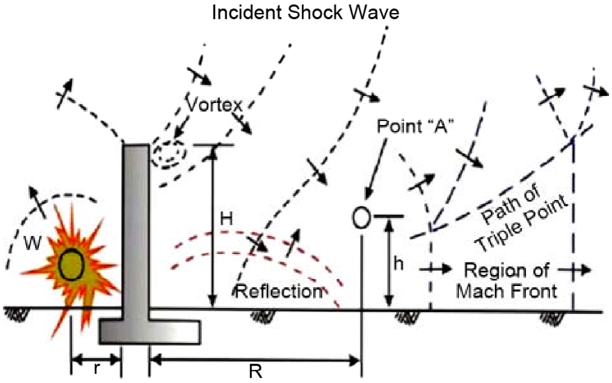
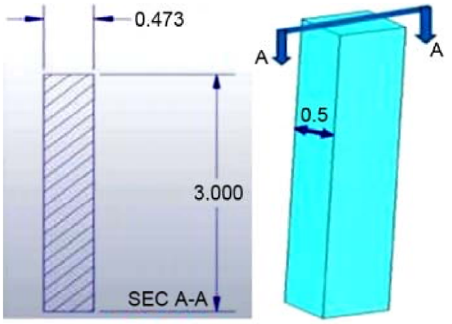
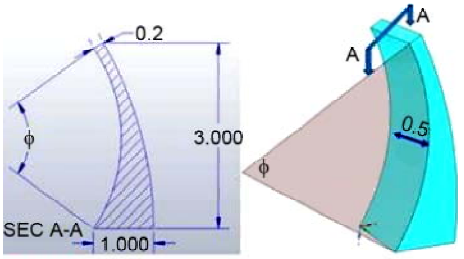


Figure 2. The effect of the blast waves on the barrier wall (Alsubaei, 2015).



(a) TFBW



(b) CCVW and CCXW

Figure 3. Dimension of the walls (Taha et al., 2019).

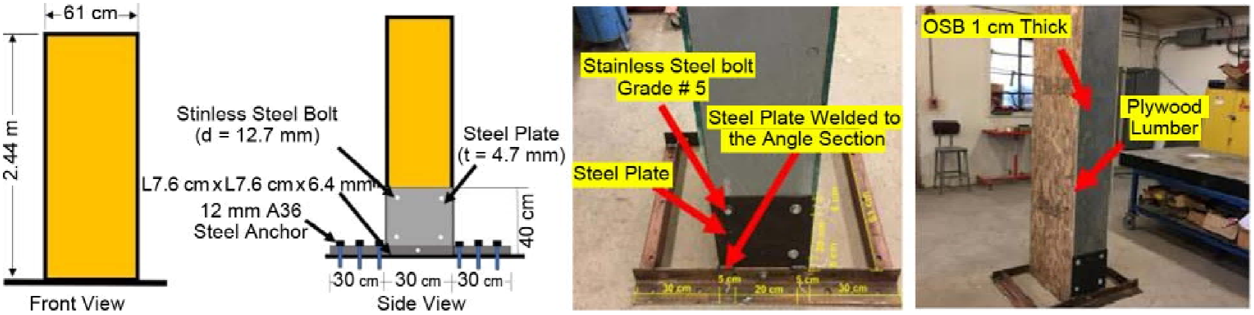


Figure 4. Schematic sketch of the WSaW wall and Connection system details (Hussein et al., 2020).

demonstrated. The results indicated that changing the shape of the wall from a flat to a convex curve has the best effect in mitigating the blast waves. In addition, the curvature angle of 60° is the best shape compared to other types of convex walls.

Hussein et al. (2020) investigated the performance of wood-sand-wood wall (WSAW) as a low-cost wall consisting of readily available materials and low technology. To obtain the blast pressure distribution around/behind the WSAW wall and its response, the wall was tested by an open-space blast test, and after that, the test results were compared with the results of finite element simulations. Two criteria were considered regarding the performance of the WSaW wall: pressure drop behind the wall compared to the pressure at the same distance from the wall without a protection system and the overall response of the wall measured by accelerations at the two discrete locations in the experiments and numerical simulation. The distance between the TNT charge and the wall was 1.22 m, 2.44 m and 3.96 m. It consists of a wooden frame surrounded by OBS sheets and sand as filler. They used a rigid connection system to fix the wall to the ground and used four steel medium carbon bolts to connect the wall to the steel plate from the right and left. The results indicated that this wall can mitigate the blast load significantly and reduce the blast pressure in the areas immediately behind the wall by more than 90 percent. The system of this wall is shown in Figure (4). Water barriers such as water walls are known as passive approaches because the energy of the explosion is reflected or dispersed by them.

At first, water was used in coal mines against dust explosions. Two closed chambers, without water and surrounded by water were affected by the TNT explosion and it was seen that the impulse inside the chamber was reduced by as much as 89% in the case of the chamber being surrounded by water (Keenan & Wager, 1992). The mass of the water, the explosive charge, and the air gap between the charge and water are parameters that influence mitigating the blast waves by water barriers. Zhang et al. (2016) investigated the effect of a water-filled plastic wall as a low-cost barrier on mitigating the blast waves, placed between the target structure and TNT explosion charge without any constraint on the ground using seven in situ tests, Figure (5). Also, parametric studies were carried out.

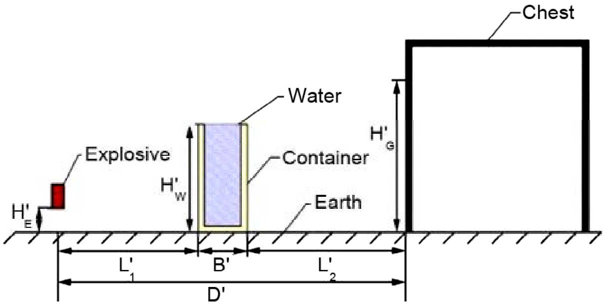


Figure 1. Configuration of the plastic wall filled with water (Zhang et al., 2016).

For estimating the affecting factors carefully, the wall height and the distance between the explosive and the structure were considered varied, and the results were compared with the rigid anti-blast wall defined by the material model 20 in LS-DYNA (MANUAL, 2007). Pressure transducers were installed on the steel chest of the structure to measure the mitigated overpressure by the water wall as well as the maximum reflected overpressures obtained by the pressure transducers. They concluded that although the performance of the rigid anti-blast wall was much better than the plastic wall, the current wall is more efficient and less expensive. Also, the results indicated that whatever the scaled distance between the explosive and the water wall and the scaled distance between the wall and structure decreases and the height of the water wall increases, the attenuation effect on the peak reflected overpressure will be much better. The maximum reduction of the peak reflected overpressure was up to 94.53%, and 36.3% of the minimum peak reflected overpressure reduction in the scaled distance ranging from 1.71 m/kg1/3 to 3.42 m/kg1/3. Numerical and experimental studies were performed to estimate the performance of different gabion blast wall configurations with canopies made of metal plates with different inclination angles under shock waves. Numerical models have been validated based on experimental data. Some gauges were placed to sense the overpressures behind the wall and another to measure the reflected overpressures. The horizontal airflows on either side of the wall have a significant effect on the pressure distribution behind the wall due to the narrow wall width. Three wall configurations with different canopy angles were arranged in a circular pattern around the explosive. Figure (6) shows the configuration of this wall. In the experimental study, three wall shapes were considered as follows, Gabion Wall Canopy back, without canopy, and Gabion Wall Canopy front. The canopies were made of flat steel plates, which were bent on-site and attached to the front face of the wall by two tension belts. The results indicated that the presence of a canopy reduces the overpressure and impulse behind the wall. Among all types of walls, walls with 45° inclined canopies had the best performance in mitigating the blast waves. The optimal angle of inclination was from 115° and 125° (facing the charge) for the impulse reduction and from 105° and 120° (facing the charge) for the overpressure reduction (Xiao et al., 2019).

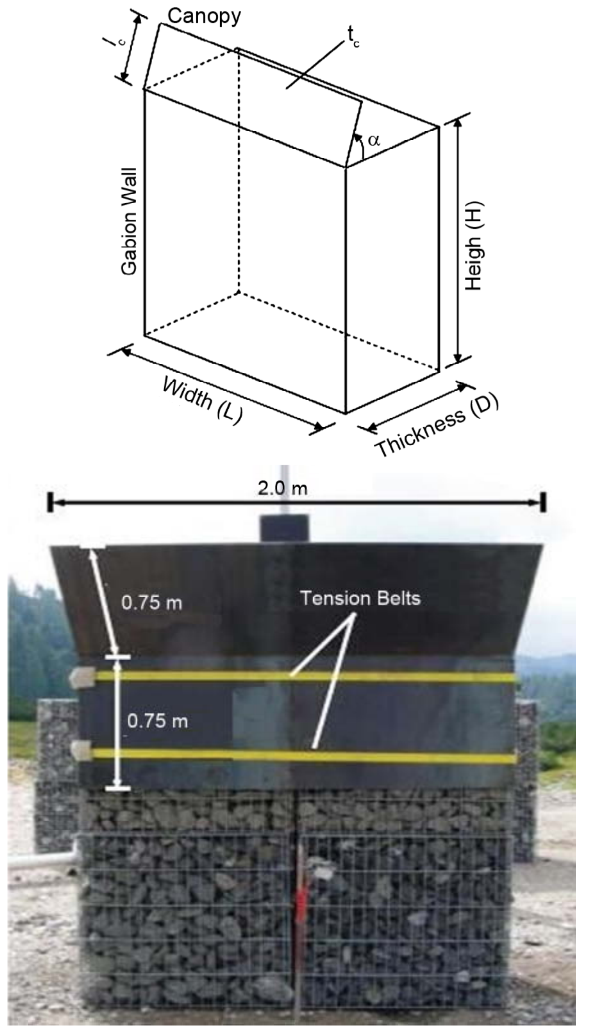


Figure 6. Configuration of blast walls with a canopy on top (Xiao et al., 2019).

Hongrui et al. (2021) introduced the structure and rapid assembly method of an anti-blast wall and analyzed the detonation resistance as well as the stable performance of this wall and its application in the military and civil fields with the latest application cases. The wall was made of reusable low carbon steel wire mesh covered with high quality, high strength geotextile. Wire mesh components were connected by screw hinges and bolts, allowing for free rotation and easy folding for storage and transport. Sand, soil, gravel, or even construction waste are materials that can be used as fillers, as shown in Figure (7). The results indicated that the anti-blast wall had flexible maneuverability during transportation and assembly, high adaptability, and protection.

Depending on its cost and protective performance, it may be suitable for civilian use and this technology should be combined with other protection technologies to provide what is needed in emergencies.

Adrees and Hussein (2021) investigated an environmentally friendly composite blast protection wall using numerical analysis under TNT charge at different standoff distances. As shown in Figure (8), this wall consists of two adobe brick

Figure 7. Rapid assembling anti-blast wall and Mechanical filling (Hongrui et al., 2021).

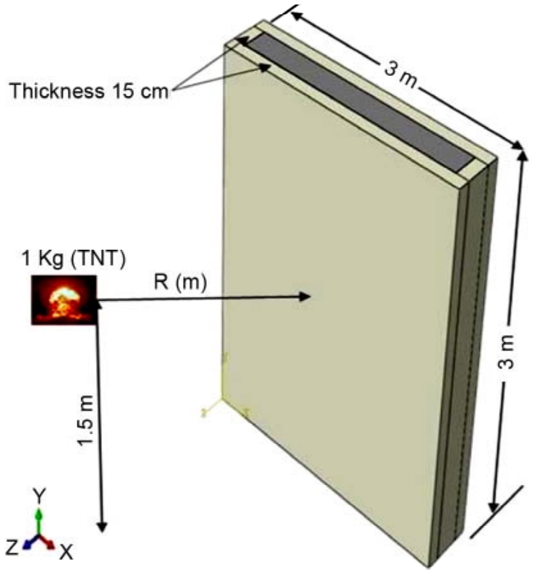


Figure 8. Blast wall geometry details (Adrees & Hussein, 2021).

façade panels and a middle layer of crushed recycled aggregate modeled with ABAQUS. The maximum blast responses of the blast wall, such as out-of-plane displacement, acceleration, and incident surface pressure, were calculated.

The thickness of the core layer and standoff distance had a significant effect on the blast response of the blast wall. The presented durable multi-layer blast wall showed a good capability to mitigate blast, while not targeting partial or total destruction, as the purpose of installing these walls is to reduce losses of target structures. It is worth noting that the effectiveness of the wall depends on the thickness of the core layer and the thickness of the wall. Calculation results of out-of-plane displacement showed that when placing 1 kg of TNT 0.5 m from the wall and the core thickness increased from 30 cm to 60 cm, the displacement decreased by 38.74%. While acceleration is reduced by 75% for the same range of increase in core thickness. The failure of the blast wall was estimated based on the Mohr-Coulomb failure criterion. It was observed that a wall with a 30 cm core layer thickness could remain intact without permanent deformation when an explosive charge (1 kg) was placed at a distance equal to or greater than 4 m. when the thickness of the core layer increased to 60 cm, the failure occurred when the explosive was placed at a distance of 3.75 m or less.

A new fence wall consisting of several columns arranged side by side that can save construction materials and costs has been studied instead of the solid wall for structural protection based on the concept of interference waves. Solid blast walls can be made of concrete masonry units (CMU), reinforced concrete (RC), or steel-concrete-steel (SCS) materials. In this study, the effects of some parameters such as column geometries, column spacing, column dimensions, and fence layer on the reduction of blast loads were evaluated by numerical simulation at AUTODYN2D software. Peak overpressure and impulse were measured using several gauges installed behind the fence wall at various scaled distances. In this new fence wall, the reflected or refracted blast waves could cancel each other out through interactions and cause mitigation of the blast wave energy, as shown in Figure (9). Different geometries of column cross sections such as circle, square, rectangle, rhombus, triangle and hexagon, were considered to evaluate the influence of column geometry. The vertex of the triangular cross-section was placed in two ways, facing the explosive or opposite. Since the deformation of the column was assumed to be very small during the blast load, the column was considered rigid. The results indicated that this new fence wall significantly reduced the peak pressure and impulse of the explosion. Isosceles right triangle columns with vertex facing the explosion and circular shape of the fence wall were the best form for mitigating the blast waves. The use of multiple column layers resulted in further reductions in pressure and impulses but increased construction costs. One of the most effective combinations for this fence wall is the circular columns layer in front and isosceles right triangular columns for the second layer that reduced the pressure and impulse of the blast loads behind the wall by up to 70%. Distances of 0.4 m and 1.0 m between the two column layers resulted in the greatest drop in pressure and momentum (Zong et al., 2017).

Esa et al. (2021) investigated a strategy to attenuate the blast wave through hollow tubes as a barrier. Due to the combination of several aspects of the blast wave such as reflection, interaction, and diffraction, this strategy is such an efficient system. In this article, the researcher compared the effectiveness of the BCMS and CTMS systems under different TNT masses and different standoff distances. The performance of the two systems was calculated by numerical simulation using AUTODYN software. The BCMS system as barriers consists of two rows of staggered reversed triangular prism elements with concave faces facing the blast wave source. The performance of these systems in attenuating blast waves is good and they can withstand blast loads depending on their stiffness (Hadjadj & Sadot, 2013; Chaudhuri et al., 2013; Hao et al., 2017; Hassan et al., 2019). The height of the steel angles with cross-sectional dimensions of the BCMS profile system is shown in Figure (10).

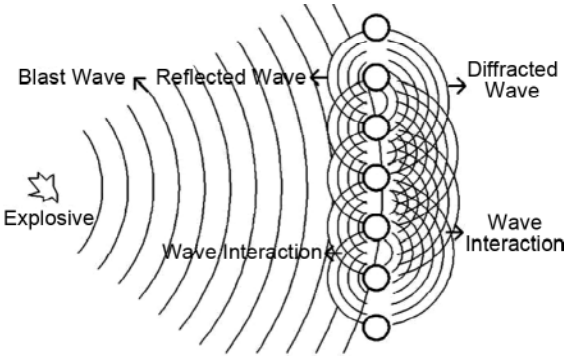


Figure 9. Wave dispersion (Zong et al., 2017).

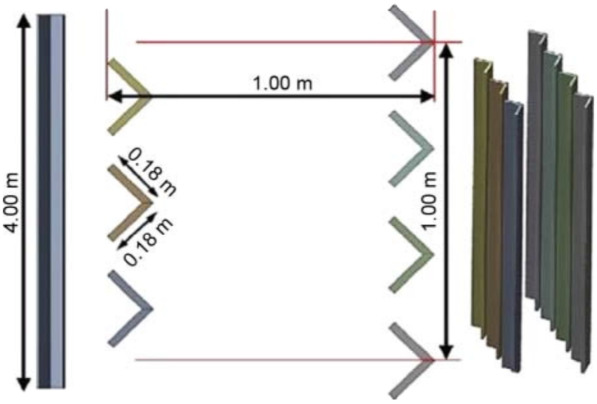


Figure 10. BCMS system configuration (Esa et al., 2021).

The strategy of CTMS systems is similar to the technique of bent tube in shock wave control. It depends on directing the blast waves and absorbing their strain energy (Li et al., 2013, 2015; Yuan et al., 2015).

CTMS consists of a row of steel tubes joined side by side. The top of these tubes is covered with a steel cap. A prismatic trap is used to direct the blast wave inside the tube, and another trap is used at the top of the tube to vent and dissipate the concentration of the trapped wave. Figure (11) shows the CTMS system compared to the BCMS system. Pressure gauges were installed behind the barriers to measure the impulse and overpressure. The results indicated that the performance of CTMS systems is much better than that of BCMS in mitigating the blast waves and

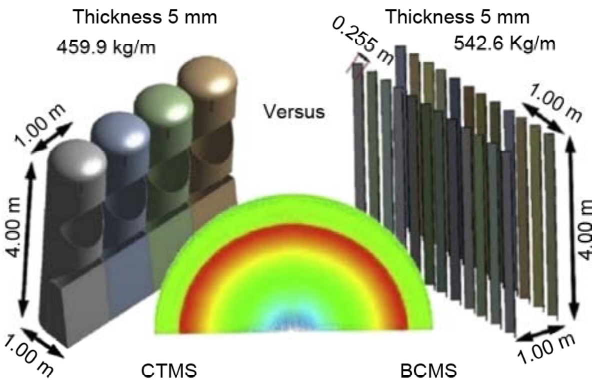


Figure 11. CTMS system in comparison with the BCMS system (Esa et al., 2021).

can provide complete protection for people and the target structure. CTMS can reduce blast waves by at least 94% when the weight of the charges is up to 500 kg TNT at standoff distances (5 and 8 m), which means that only 6% of that blast impulse is applied to the target structure, and for 100 kg TNT at standoff distances (5 m and 8 m) caused 98.7% mitigation. BCMS performance decreased with increasing load weight. It mitigated 16.29% at a 5 m standoff distance and 18.82% at an 8 m standoff distance when the charge weight was 500 kg TNT.

Esa et al. (2020) compared the performance of six side-by-side steel angle arrangements in short/long conditions. Numerical simulations were performed using AUTODYN software. The mitigation percent criteria mathematical method was used to compare the systems' mitigation percentages (Esa et al., 2021). Four pressure gauges were considered behind the barriers to numerically measuring the blast pressure and impulse time histories. To minimize the effect of explosive loads on the target structure, the stiffness of these rows is used as a damping system. The six types that are considered in this article are one row 2 m high and one row 4 m high, two rows short, two rows long, and two rows of different heights such that the short row is in front of the long row. The distance between rows in systems that have two rows was considered 1 m. The general arrangement of the systems under consdieration is in Figure (12). The result indicated that using two rows increases the mitigation and reflection of the blast waves and using two long rows compared to other systems can dissipate loads and decrease the overpressure significantly. using one row short has the worst performance among all systems but adding another short row can improve the performance of the system. Using two rows can protect the target structure better than one row and increase the attenuation percentage.

3. Sacrificial Cladding and Sandwich Panels

Sometimes, transportation or industrial events cause explosions that threaten structures and occupants due to their hazardous combustible materials such as gasoline, propane, etc. The sacrificial claddings have significant capabilities to absorb energy, which is noticed in structural retrofitting. They consist of two layers. Their

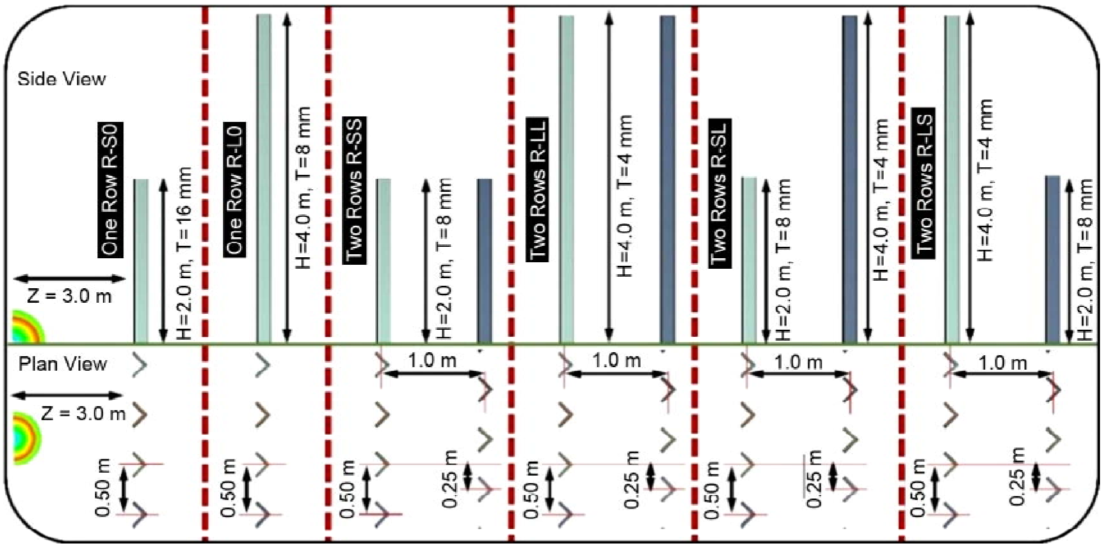


Figure 12. General arranging of the considered systems (Esa et al., 2020).

front layers distribute blast pressure across the breakable core layer and the inner layer, known as the core, deforms and absorbs impact energy, so the pressure felt by the target structure is reduced.

Layered sacrificial cladding fabricated from thin steel sheets, and mounted to the non-sacrificial frame, was investigated through experimental and numerical analyses. But this paper is presented an analytical work. Finite element analysis with step-by-step time marching under large deformation and the large strain was carried out.

The blast load has been modeled as an equivalent triangular blast pulse in this article. Each layer included lots of cells, the components of a unit cell were a base plate, a cover plate, and a web plate as shown in Figure (13), that absorbed very high energy and transmit a small impact to the target structure due to their large plastic deformations. Different cases consisting of 1 or 3 layers for different plate thicknesses have been considered and studied for different durations of equivalent triangular pulses. Several parameters such as reflected overpressure, the force transferred between the sacrificial and the non-sacrificial layers, deformation shape at different times, and the time required for layers to collapse were evaluated and discussed. Using this type of layered configuration allowed us to adjust the number of layers according to the energy level. The performance of these layers was predictable but for better performance, there are a few tips to consider: For plastic deformation to occur there must be enough space between the layers, and they should not rupture during the explosion. These layers collapse in turn, the first layer directly facing the explosion collapsed first. The second layer started to collapse when the previous layer collapsed completely and so on. These layers effectively insulate the target structure and can be designed so that the collapse time of the layers is greater than the blast duration (Guruprasad & Mukherjee, 2000).

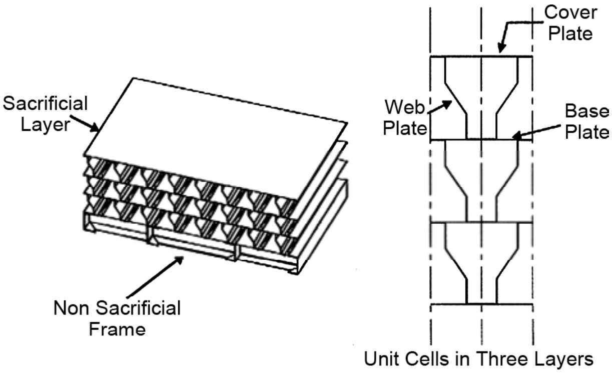


Figure 13. Configuration of sacrificial cladding with non-sacrificial frame (Guruprasad & Mukherjee, 2000).

Empty recyclable metal beverage cans have been investigated as the inner core of sacrificial cladding based on their blast energy absorption properties and the corresponding deformation behavior through experimental and numerical blast studies (Figure 14). Blast parameters such as maximum reflected pressure and the corresponding positive duration were measured. Different skin plates made of aluminum and sandwich composite materials were considered to evaluate the effect of the inertia of the skin plates on energy absorption. It was seen that because of the diffraction and ground-reflected pressure waves, a part of the impulse has been lost. We can be eco-friendly by using these accessible cans made of recyclable material. As shown in Figure (15), two different empty beverage cans assembly configurations (axial and radial) were considered. The result indicated that the peak reflected pressures with aluminum skin plates and sandwich composite skin plates were lower and higher than the ConWep predicted data, respectively. The surface roughness of the reflecting surface had significant effects on

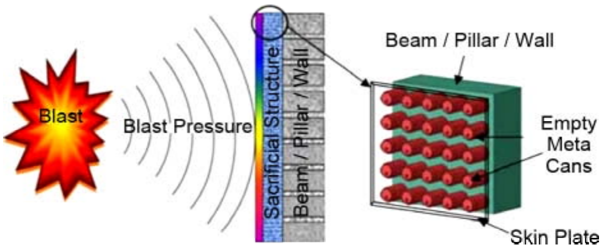
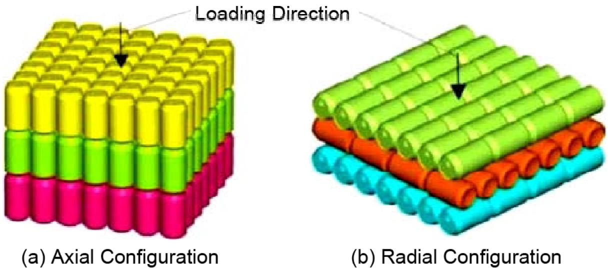


Figure 14. Sacrificial cladding structure with empty recyclable metal beverage cans (Palanivelu et al., 2011).



(a) Axial Configuration (b) Radial Configuration

Figure 15. Two configurations of arrangement of empty recyclable metal beverage cans (Palanivelu et al., 2011).

the blast parameters, such as peak reflected pressure and positive duration. The lower mass with sufficient flexural stiffness of the skin plate maximizes the energy absorbed by the inner core structure. Evaluation of the deformation pattern of the empty beverage cans with different skin plate weights showed that the plastic wall was buckling locally along the length of the can, with high inertia and low surface area of the skin plate (Palanivelu et al., 2011).

In addition, the permanent and maximum deformation of the panel was reduced because the spring absorbed part of the kinetic energy (Chen & Hao, 2013).

Sandwich panels absorb high kinetic energy through their irreversible deformation; these are very efficient because of their low weight and high absorption. As shown in Figure (16), sandwich panels with rotational friction dampers which are placed between two pages of the panel were investigated under blast loading. The mechanism of the rotational friction hinge device with spring (RFHD) has been studied by theoretical derivation and numerical simulation by Ls-Dyna to understand its equivalent force-displacement relation and to investigate energy absorption capacity. The maximum displacement, the permanent displacement of the center points of the outer plates, the internal energy dissipation, and the reaction forces were measured. These springs are used to bring the panels back to their original state after absorbing kinetic energy. The results indicated that these plates revert to their original state to some extent, and that they will also be usable after the explosion.

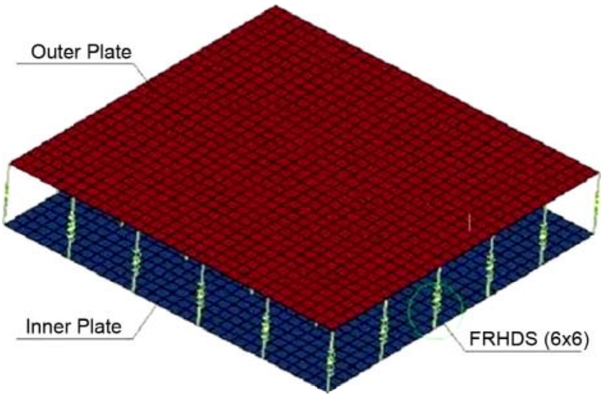


Figure 16. Finite element model of sandwich panels with rotational friction hinge device with spring (Chen & Hao, 2013).

Zhou et al. (2013) investigated the performance of sandwich panel structure by bonding foams of different densities together as a core and creating a three-layer core under Low-velocity impact. The skin plate of the panel out of carbon fiber was bonded to the core. Classified sandwich structures were modeled by finite element analysis and compared with experimental results, and results such as load-displacement response and failure modes were compared. The results indicated that placing a high-density foam core against the top surface skin improved the resistance of the sandwich panel, Figure (17).

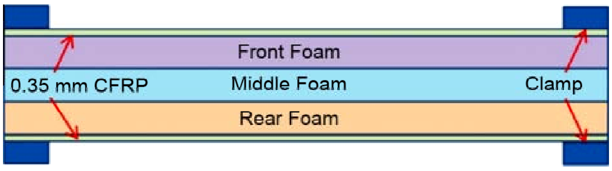
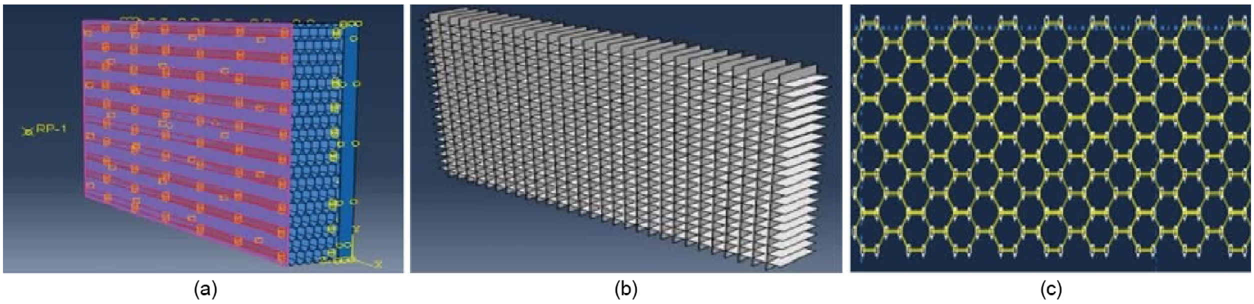


Figure 17. Configuration of a graded foam sandwich panel (Zhou et al., 2013).

Considering that explosive events in recent years have caused the vulnerability and shortened life of many structures, including sensitive and vital structures. The importance of this issue has led to laboratory and numerical research on the use of adsorbent layers as energy dissipators. Abdolzadeh and Izadifard (2015) studied and compared the behavior of ductile and Brittle dissipaters in reducing of explosive loading on Structures using finite element modeling in Abacus software. Absorbent layers are materials that convert kinetic energy into other forms of energy. These layers usually have a sandwich or composite structure consisting of one or more layers with a steel sheet. Steel sheets have a small thickness, only playing the role of covering and distributing pressure on the panels. The core of the sandwich panels is also different and can be made of foam, steel honeycomb, or brittle material. Two types of adsorbent layers, a steel honeycomb sandwich, and a brittle concrete composite as a concrete wall protector, under explosive loading, have been considered and the models, under different explosions, have been investigated in terms of energy dissipation as well as the displacement of the central point of the concrete wall. The results indicated that the functions of these layers are different depending on the type of target and also the amount of explosive samples, so although both types of absorbent layers have a great impact on reducing damage to the main structure, in samples with low blast intensity, the brittle layer performs better by absorbing more energy and reducing the displacement of the center point of the concrete wall than the ductile layer and in severe explosions, due to the plastic behavior, the ductile steel layers perform better (Figure 18).

The performance of the non-composite panels built of steel plates, concrete slabs, and composite sandwich panels with different cores was investigated under blast loading and compared to each other. Three-dimensional finite element analyses were used to investigate the response of steel stiffened and unstiffened plates, plain concrete, reinforced concrete, steel fiber reinforced concrete slabs, stiffened and unstiffened steel-foam-steel, and steel-sand-steel sandwich panels. The performance of the plates, slabs, and panels was measured using peak central point displacement and energy. The total energy is converted to strain energy (S.E.) and kinetic energy (K.E.) in blast loading. The results indicated that steel plates in comparison with concrete slabs Show more deformations and steel stiffened plates in comparison with unstiffened plates Show fewer deformations. Figure (19) shows Stiffened Plates and panels configuration. The circular stiffener has better performance than the rectangular one. Stiffened plates in which the stiffener passes through the central node of the



(a) (b) (c)

Figure 18. (a) An example of models prepared in software, (b) Two-dimensional geometry of the honeycomb, and (c) The three-dimensional geometry of the brittle core (Abdolzadeh & Izadifard, 2015).

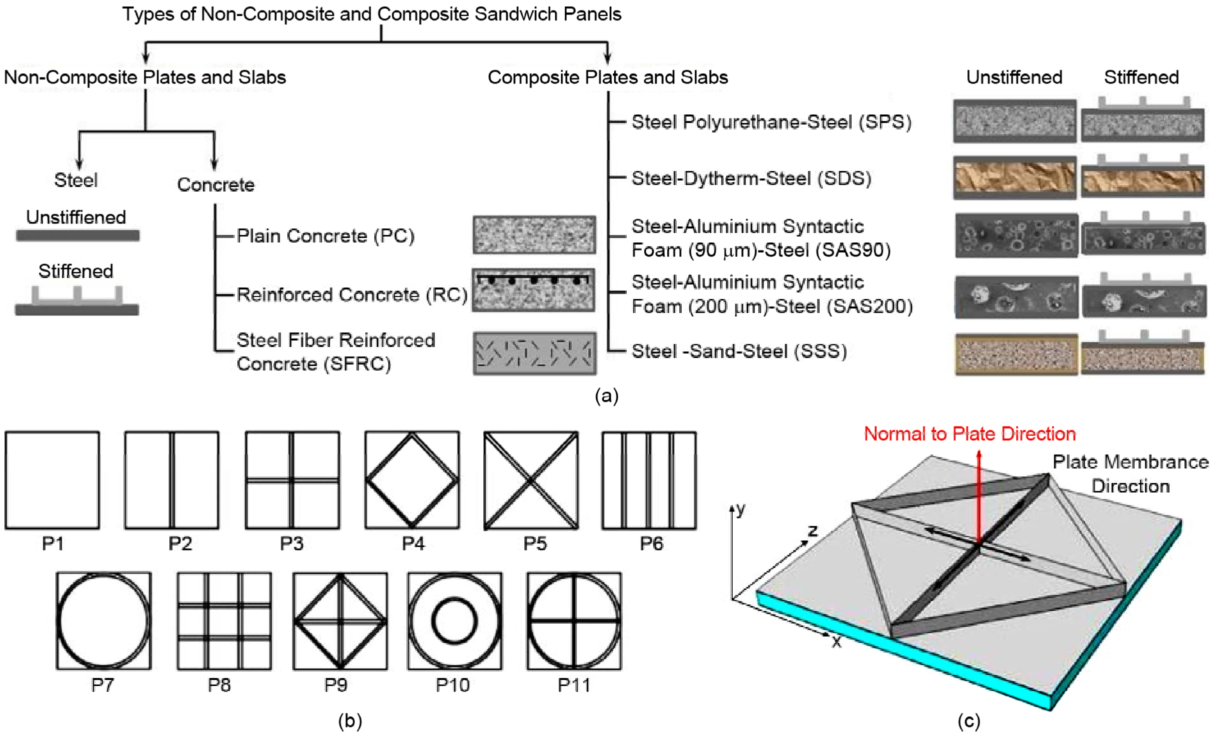


Figure 19. (a) Parameters of studied cases, (b) Configurations of plates respectively weight gain, and (c) Stiffened composite sandwich panel model (P9) (Matsagar, 2016).

plate show more capability in mitigating the response. Since the composite sandwich panel with the aluminum core shows less deformation in comparison to the others, this core material can be used as a suitable material for reducing the blast response. Among those steel stiffened plates that stiffener passes through the central node of the plate, P9 has the most effective performance, and the structure, in this case, has less response. The displacement decreases by increasing the foam/sand core thickness of the composite sandwich panels because of the higher blast energy absorption through the thicker cores and as a result lesser energy transfer to the back sheets (Matsagar, 2016).

The geometry of the core in the honeycomb sandwich panels plays a significant role in the energy absorption capability. The most common honeycomb material that was used was aluminum followed by polymeric. The effects of the density distribution of the core of the honeycomb sandwich panel, constructed with aluminum face sheets with triple-layered graded honeycomb cores on the dynamic behavior, were investigated under blast load using finite element software LS- DYNA and were validated against the experiments. Six core arrangements with identical mass were considered. Some parameters such as impulse on the sandwich panel, permanent deflection of the midpoint of the front and back face sheet, and the core compressions of the layers were measured and deformation/ failure modes of the specimens were observed. it was seen that the Core with a higher density as the first layer increases the absorption capability and resists better because the honeycomb with a high relative density has a super capability in absorbing the energy in comparison to the low relative density one.

The advantage of using graded construction in front of an ungraded one to resist the blast loads, especially for the graded panels with the largest relative density core near the impact face was only in terms of the lower back plate deflections when the same impulse was subjected (Li et., 2017) (Figure 20). Due to the high cost of energy absorbing layers such as honeycombs and aluminum foams, Izadifard and Nazarinejad (2017) provided a low cost and efficient way to mitigate the blast load applied to the slabs. twelve full-scale samples in four groups have been tested under the same weight of the explosive and stand-off (Figure 21). The first group was single RC slabs and the other

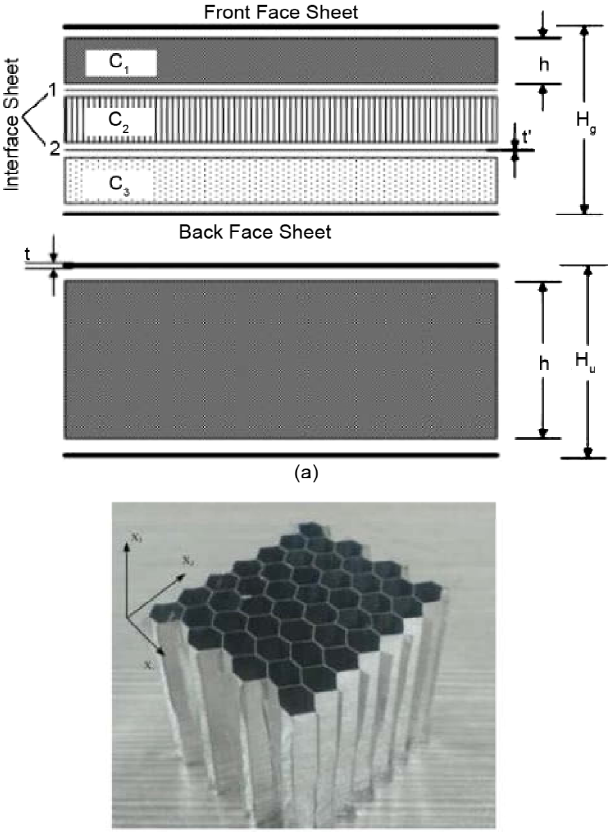


Figure 20. (a) Photograph of a honeycomb and (b) graded and ungraded schematic cross-section of sandwich panel (Li et al., 2017).

(a) Sand (b) Plastofoam

(c) Light Brittle Blocks (Izadifard & Nazarinejad, 2017)

Figure 21. RC slabs with different energy absorbing layers.

three groups were the same RC slabs with an energy absorbing layer: plastofoam, sand, and light brittle blocks. The experimental results of the central displacements of the slabs were compared to each other. the results indicated that using energy-absorbing layers reduces the maximum and permanent displacement at the center of the slab up to 77% and 87% respectively and reduces the number and thickness of cracks, also using the block is more desirable than sand and plastofoam for reducing displacement and mitigating damage.

Two types of hybrid composite sandwich panels out of glass-fiber (GFRP) and carbon-fiber (CFRP) skins and PVC foam core were investigated under blast loading. A finite element model has been used to evaluate the elastic response of a hybrid panel under air blast loading and the results were compared to the experimental data. Some gauges were installed on the front skins to measure the strain, and some others were installed within a concrete pressure block at the same stand-off distance from the charge as the targets for measuring reflected pressure. Deflection of the sandwich panels was recorded using high-speed 3D digital image correlation (DIC) during the blast. The combination of glass-fiber reinforced polymer and carbon-fiber-reinforced polymer (Figure 22) in skins of sandwich panels decreased deflection compared to both GFRP and CFRP panels, but the position of the glass-fiber and carbon-fiber layers didn't have a significant effect on deflection and strain (Rolfe et al., 2018).

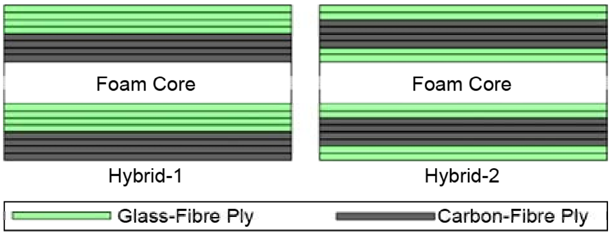


Figure 22. Diagram of hybrid composite panels (Rolfe et al., 2018).

The blast mitigation of cladding sandwich panels with tubular cores was investigated using numerical models, developed in ANSYS AutoDYN (Figure 23). The core including empty thin-walled aluminum circular tube has different configurations. It has different numbers of tubes with different spacing between them made of aluminum and Mild steel. The average deflection of the top plate and the specific energy absorbed by different configurations of cladding panels were evaluated. The tubular cores through the plastic deformation mitigate the impulsive loads effectively that are transferred from the top plate to the backplate. The interaction between tubular cores has an influence on the deflection of the top plate such that increasing the interaction, decreases the deflection. It was observed that parameters like different configurations of the tubular cores and wall thicknesses of the tubular affect the deflection of the top plate and modes of tubular failure, which means that you can design various configurations to have the best performance. As the thickness of the tubular cores increased, the average deflection of the top plate decreased (Wang et al., 2019).

The performance of the sandwich structure with the truss/lattice core (Figure 24) was investigated under dynamic loadings like a blast, analytically and numerically (Gu et al., 2020; Yungwirth et al., 2008).

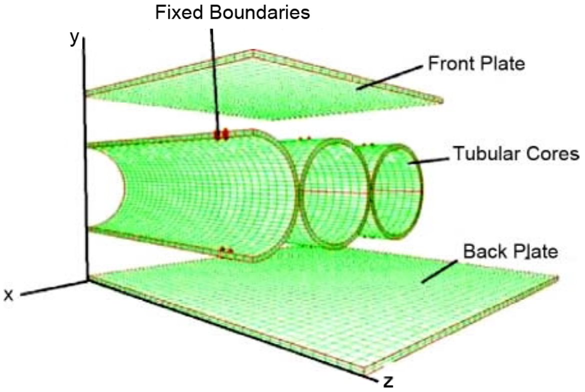


Figure 23. The quarter symmetric model of the cladding panel with tubular core (Wang et al., 2019).

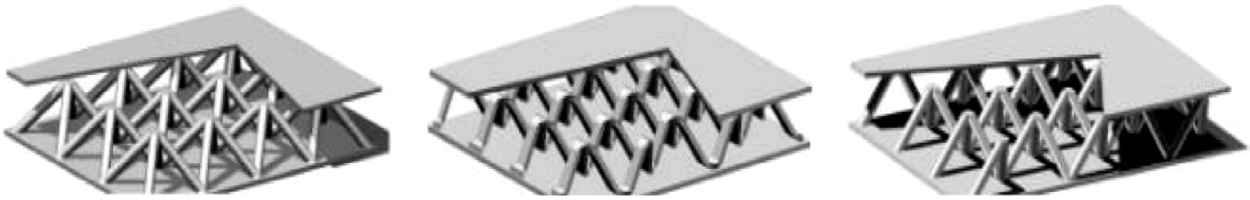


Figure 24. Truss/lattice core sandwich panel (Gu et al., 2020).

Face sheets are typically made out of stainless steel or aluminum or fiber composites and cores are made from metal and polymer. The stress distributions of the sandwich panels with lattice truss core (SPLTC) and the sandwich panels with lattice truss core filled with shear thickening fluid (SPLTC-STF) in the loading direction after compression at the impact velocity were evaluated. The geometry design of the lattice/truss and failure mechanisms of the components have a great effect on the energy absorption ability. The truss/lattice core with filling increases the energy absorption and blast resistance capabilities.

Filling the Sandwich panels with lattice truss core by shear thickening fluid has a significant effect on the energy absorption so that the energy absorption of panels increases with the increase of the fluid viscosity (Gu et al., 2020).

Sandwich panels, which are lightweight and highly resistant, can absorb and dissipate energy. Due to the fact that the geometric shape of the core can affect the amount of energy absorption, Peyman and Ebrahimzadeh (2020) investigated the effect of the geometric shape of the core of the steel sandwich panel on the behavior and amount of energy absorption against the blast wave by numerical methods using Abacus software and then compared the results with experimental data of valid papers. As shown in Figure (25), four different types of regular and easily fabricated cores were modeled and the effect of core geometry on the amount of energy absorption and displacement was investigated. maximizing energy absorption and minimizing maximum displacement were two important criteria in designing these types of sandwich panels. The results indicated that at low pressures Model 4 with a quadrilateral horizontal core has the maximum energy absorption and minimum displacement value. Model 2 with a hexagonal vertical core has the minimum displacement and Model 1 with a quadrilateral vertical has the maximum energy absorption at high pressures.

Hybrid multi-cell tubes were used to equip concrete panels as energy absorbers to protect against blast hazards. This sacrificial cladding was attached to the façade of the concrete panel to absorb the impact of the explosion by progressive plastic deformation. Thin-walled tubes in the form of single, double, and quadruple with CFRP around them make these hybrid multi-cell tubes as shown in Figure (26) Mid-span deflection and damage patterns of the RC panels were investigated by numerical models using the explicit finite element program (Autodyn/ANSYS). The results indicated that using a sacrificial layer improves the performance and causes 62%, 78% and 87% reduction in mid-span deflection for single, double, and quadruple thin-walled tubes respectively, compared to the unprotected concrete panels (Abada et al., 2021).

Sacrificial cladding can be filled with different brittle materials like concrete foam and granular media as shown in Figure (27). All of these materials in terms of friability are the same but they dissipate and mitigate the energy to a different extent. This

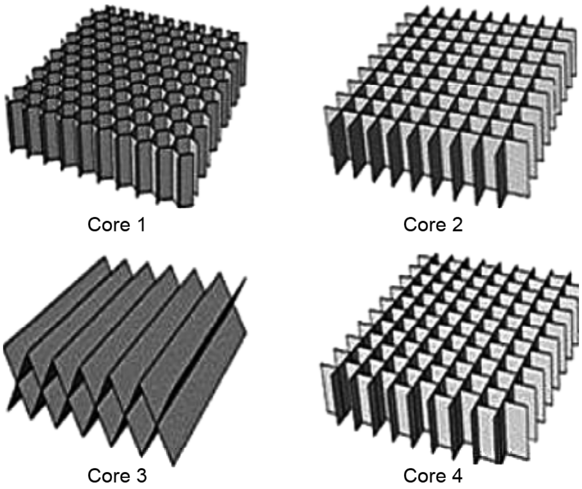


Figure 25. Simulated cores of sandwich panels (Peyman & Ebrahimzadeh, 2020).

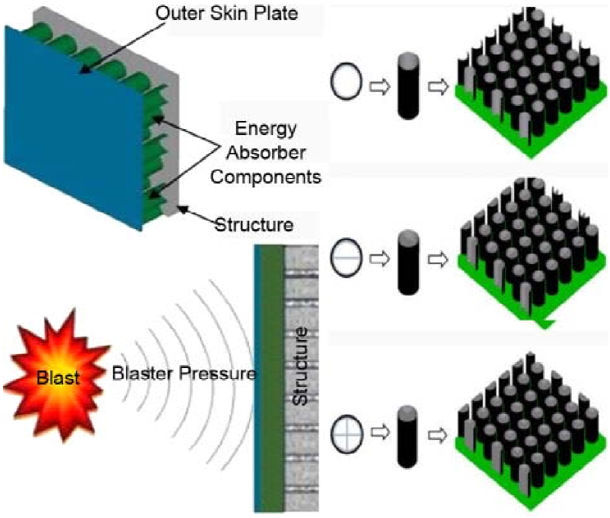


Figure 26. Schematic of sacrificial cladding layers and their inner core (Abada et al., 2021).

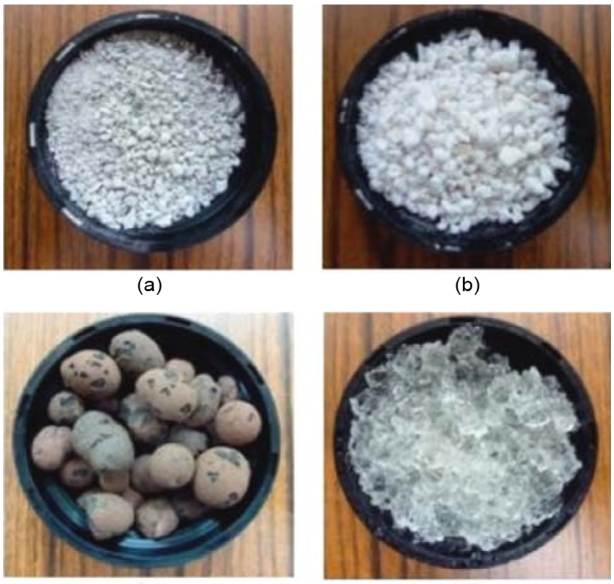


Figure 27. Pictures of core samples: (a) pumice; (b) perlite: (c) clay balls; (d) hydrogel (Blanc et al., 2021).

mitigation occurs through deformation and attrition in the granular environment. One of the differences between granular media and concrete foam is their difference in impulse propagation speed granular media can spread impulse like a fluid due to the movement of grains over a large area. It is impossible to investigate how the energy is dissipated by granular media, but it can be understood that they are efficient energy dissipative materials through a macroscopic approach to their behavior (Blanc et al., 2021).

It becomes very important to defeat attacks, that is why sandwich panels are used in sacrificial structures to absorb the energy of the blast waves. The new low-cost and comfortable model of sandwich panels that are used for a wide range of hazards was introduced. Four different topologies (trapezoidal, triangular, sinusoidal and rectangular) were considered to build unconnected" corrugated layers encased in a steel frame. A numerical study was carried out to investigate their efficiency using Abaqus. Models were subjected to one blast intensity, and parameters such as reaction forces, peak deformations, and plastic dissipation energy were obtained and compared to each other. The result indicated that the trapezoidal topology dissipates the plastic energy more with uniform progressive collapse and lower reaction forces, and has the best performance in comparison to the other (Al-Rifaie et al., 2021) (Figures 28 and 29).

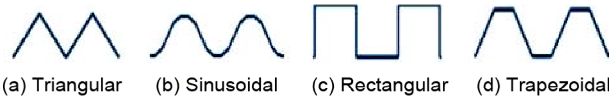


Figure 28. Topology used in sandwich panels (Al-Rifaie et al., 2021).

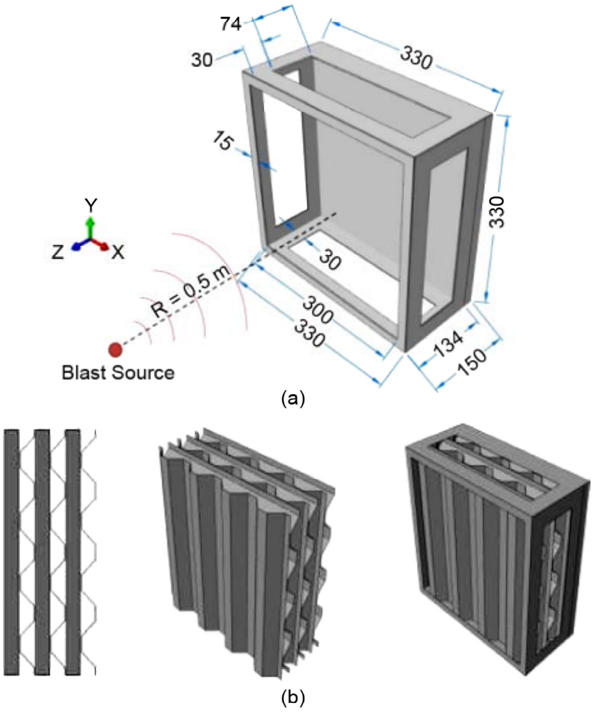


Figure 29. (a) The 3D views of the steel frame and (b) Side and 3D views of layers composing the aluminum cores with Trapezoidal topology (Al-Rifaie et al., 2021).

The front panel of sacrificial cladding structures tries to distribute the generated pressure to the core which deforms and absorbs a significant amount of the blast energy and converts it to internal energy, as a result, the pressure transferred by the sacrificial cladding and the pressure that the main structure feels are significantly reduced. Since the impulse duration is shorter than the natural period of Civil Engineering structures, it can cause destructive damage. Sacrificial claddings change this immediate load to one with a longer duration and smaller extent (Figure 30).

The composite foam-core sacrificial cladding was investigated as a protection system for steel Reinforced Concrete (RC) structures using explicit finite element analysis in LS-DYNA. First, the response of an unprotected RC column to blast loading was examined extensively for variable explosive mass and stand-off distance through numerical simulations. Subsequently, the same column was studied with the addition of the composite foam-core sacrificial cladding. The concrete column had a rectangular cross- section and was fixed-ended. The compressive strength of the concrete was kept equal to 25 MPa and the reinforcement steel bars (both transverse and longitudinal) had a yield stress of 500 MPa. The sacrificial cladding was considered to consist of a PVC foam core with a thickness of 100 mm. In this study, a TNT type of explosive was used in quantities of 1 and 2 kg having a spherical shape. The maximum mid-span displacement and the total internal energy of the column and the contact force between the column and sacrificial cladding were examined. To study how effective the core configuration was, as shown in Figure (31), the four different core geometries tested were considered (Figure 32), and the energy absorption and the peak force transmitted to the main structure were evaluated for every core. It was seen that the conical-array core geometry was the most effective in reducing the peak force transmitted to the main structure, and it was the most lightweight of the four.

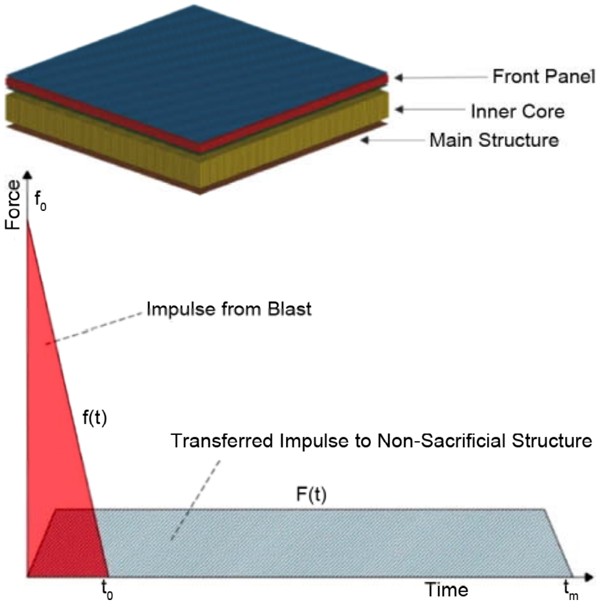


Figure 30. Sacrificial cladding structure and its working principle (Kostopoulos et al., 2022).

Also, a comparison between two sacrificial claddings with the conical array core and a uniform foam sheet made of the same material and thickness was done. It was seen that the conical-array core was more beneficial than the other one because of distributing the blast load over time and keeping the peak force at lower levels, Figure (33). The conical array core was 71% lighter than the

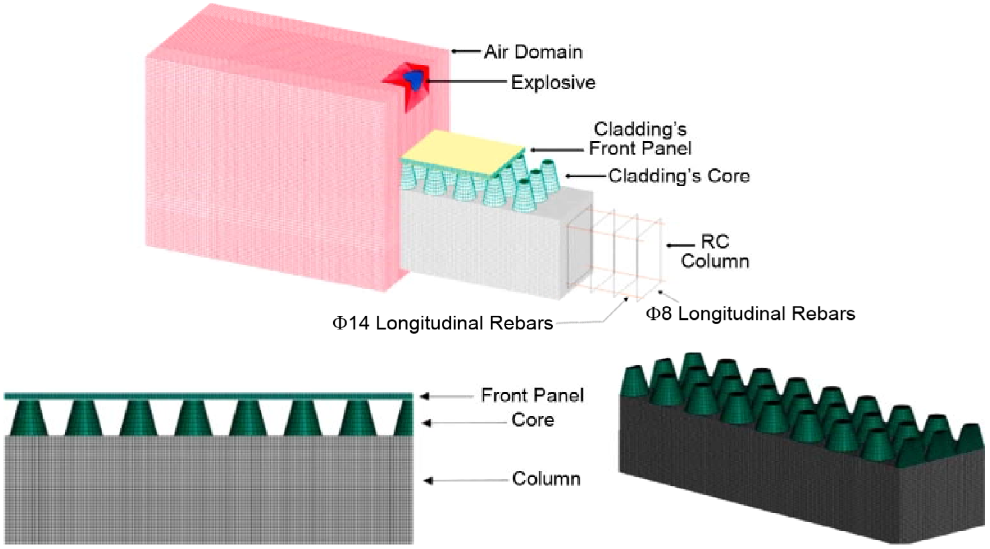


Figure 31. Configuration of conical-array core (Kostopoulos et al., 2022).

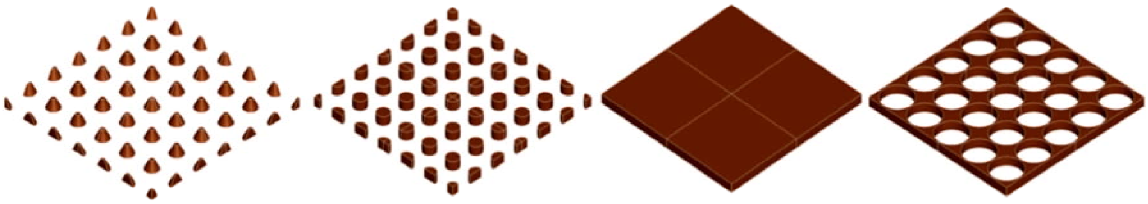

(a) (b) (c) (c)

Figure 32. Core geometries (Kostopoulos et al., 2022).

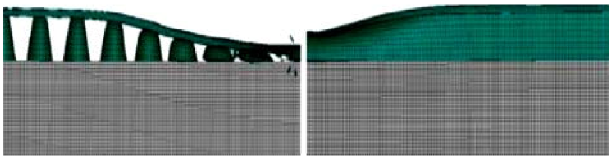


Figure 33. Deformation of conical-array core and uniform foam sheet (Kostopoulos et al., 2022).

cladding with the uniform foamed core, and it can reduce transferred load up to 50% more.

The validation analysis showed that this type of core was valid for close-in explosions (up to 1000 mm stand-off distance) and the mid-span displacement was reduced by 48% for 250 mm stand-off distance and 2 kg TNT mass, whereas the total internal energy of the RC column decreases by 72% for the same blast condition with respect to the unprotected RC column (Kostopoulos et al., 2022). A square RC panel equipped with an innovative sacrificial system, comprising hollow tubes consisting of hollow mild steel tubes used with a steel sheet, was investigated under blast load using the three-dimensional (3D) nonlinear finite-element software ABAQUS/Explicit.

For this parametric study, different lengths (L), outer diameter (D), and thickness (t) of hollow mild steel tubes under different blast loads were considered. The efficiency of this innovative sacrificial system was measured by the percentage deformation of hollow mild steel tubes during blast loading, whatever the tubes deformed more, caused lesser deflection in the main structure. A Three-dimensional (3D) view of the sacrificial system on a reinforced-concrete (RC) panel with the hollow mild steel tube connected to a circular steel plate and embedded reinforcement bars are shown in Figure (34). The spacing of tubes from each other and the distance between the center of corner tubes and the edge of the RC panel were 250 mm c/c and 125 mm respectively. The fixed boundary condition was provided in the X and Z direction of the RC panel. The hollow mild steel tubes were connected to the RC panel using 4-mm-thick circular plates.

The ConWep program was used to apply the blast load on the steel sheet or the top surface of the RC panel. Optimization was done for finding the safe scale distances for every steel sheet thickness before punching failure. Figure (35) shows an example of the punching failure of steel sheets by hollow mild steel tubes after small and large increments in the scaled distance above the safe scaled distance.

It was concluded that thinner sections of hollow mild steel tubes can protect better than the thicker sections. The mid displacement of the panel increased with an increase in the thickness of hollow mild steel tubes because of the complete deformation of the thinner tube by absorbing energy.

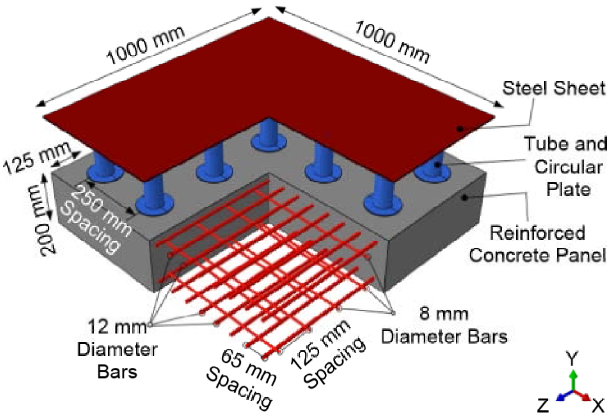


Figure 34. The geometries of the model (Choudhary et al., 2022).

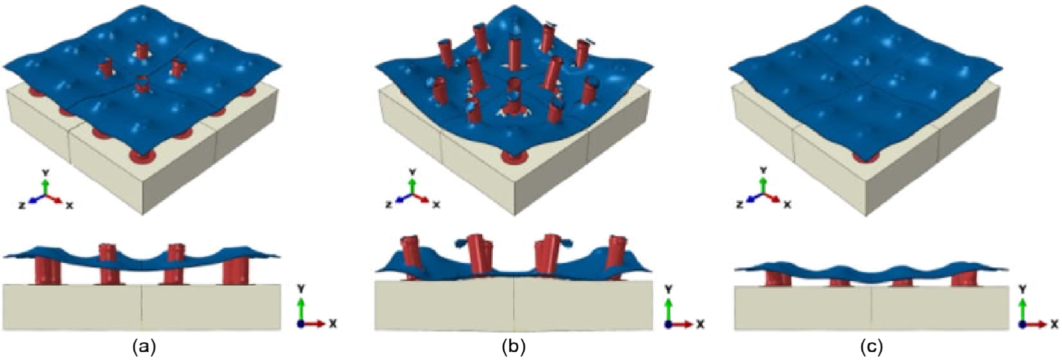


Figure 35. Punching failure, (a) small increment, (b) large increment t in the scaled distance above safe scaled distance and (c) scaled distance below the safe scaled distance (Choudhary et al., 2022).

It was observed that increasing the thickness of the steel sheet increases its capacity to withstand higher blast loads without failure.

Tubes with a lesser outer diameter and the same thickness caused lower deflection of the RC panel (Choudhary et al., 2022). Auxetic honeycomb structures have superior indentation resistance and energy absorption capability under blast and impact. the dynamic behaviors of metallic sandwich panels with auxetic re-entrant and regular hexagonal honeycomb cores were investigated experimentally. The back-face maximum permanent deflections of these panels were evaluated. Specimens were made from 304 stainless steel out of two identical face sheets jointed to an anisotropic honeycomb core (Figure 36). Two types of honeycomb cores were considered, re-entrant honeycomb (RH) with a negative Poisson's ratio and hexagonal honeycomb (HH) with a positive Poisson's ratio. Also, double arrowhead honeycomb sandwich panels (DAHSPs), which include tendon and stuffer walls with different inclined angles, with the same weights as those of RHSPs and HHSPs were considered to compare the results.

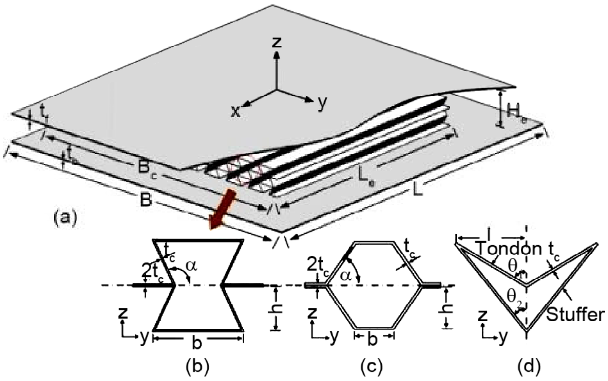


Figure 36. (a) The sandwich panel with (b) RH core, (c) HH core and (d) DAH core unit cells (Chen et al., 2022).

Figure (37) shows a schematic of the set-up for the blast tests in open testing ground. The experimental results were classified into the recognition of the panel deformation and failure modes, and the quantity of maximum permanent deflections of the panel front and back face sheets.

The blast resistance of the target panels can be evaluated by the examination of the deformation/failure modes of the sandwich components which have a close relationship with the energy absorption mechanisms.

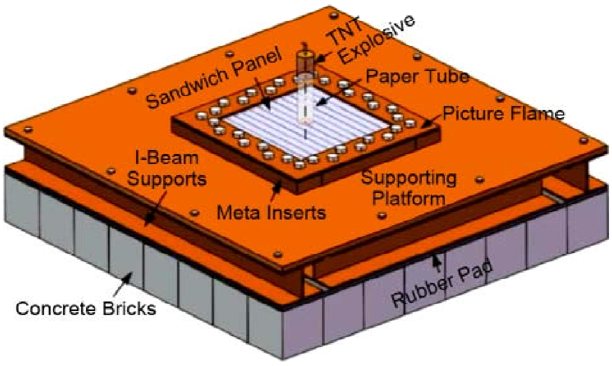


Figure 37. Schematic of the set-up for the blast tests (Chen et al., 2022).

The results of the face sheets of the tested specimens showed four failure modes: large plastic deformation, large plastic deformation with central thinning, partial tearing in the central area, and complete petal-like tearing in the central area. Predominated failure modes of front faces of RHSPs with negative Poisson's ratio changed from the complete petal-like tearing to a local inner dome by decreasing the blast impulse. The DAHSPs reduced better the back face maximum permanent deflections regardless of core relative densities than RHSPs (Chen et al., 2022). Blast resistance and energy absorption capacity of a new design of the meta-panel consisting of three components, including two thin face sheets bonded to meta-truss cores, were investigated numerically and analytically in LS-DYNA (Figure 38). As shown in Figure (39), the meta-truss bar with resonators included 6 modules in which each module had three components consisting of the outer tube, soft coating and resonators, that the tube and resonators were made of aluminum, polyurethane (PU).

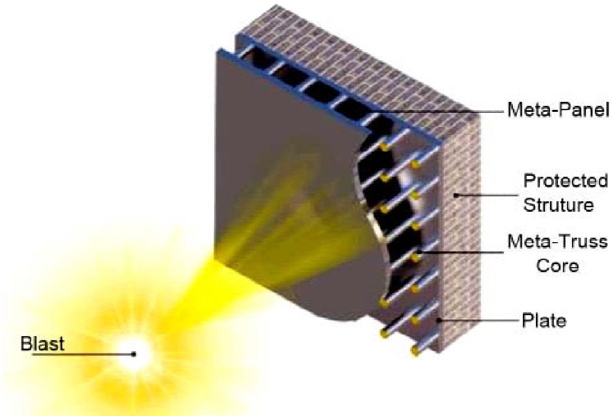


Figure 38. Schematic view of meta-panel as a sacrificial cladding (Vo et al., 2022).

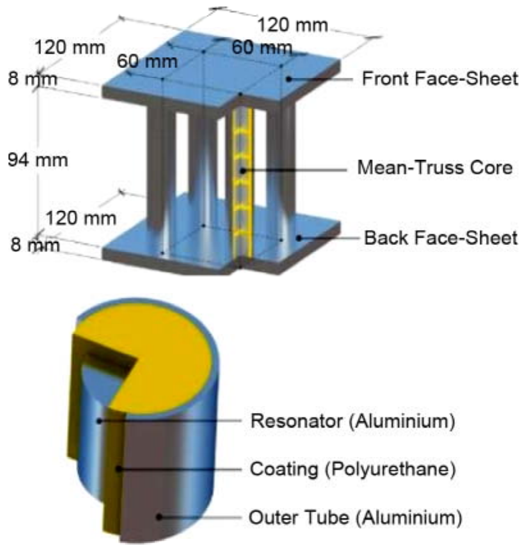


Figure 39. A view cut of meta-panel (Vo et al., 2022).

Different parameters such as inclusion arrangements and inclusion shapes were selected to investigate the better wave attenuation of the proposed system. the peak force transmitted to the main structure, energy absorption, and the central displacement of the back face sheet were evaluated.

Multiple types of resonators were considered. As shown in Figure (40), the meta-truss bar included two zones represented by Zone 1 and Zone 2, each zone has uniform unit cells with the same geometry, but different resonators made of tungsten (W) and aluminum (Al), and meta-panels with uniform resonators were considered. It was concluded that the panel with the meta-truss bar consisting of two types of resonators absorbed and mitigated the energy better than the uniform-resonator panels. Therefore, it is important for the better blast protection of structures, to choose a proper combination of the meta-cores.

Beside material properties, the dimension and geometry of the core and its influences on the frequency bandgaps were investigated and other parameters such as the material properties, the diameter, and the thickness of the outer tube didn't change in this section. The meta-truss bars with uniform aluminum resonators and different radii were considered (Figure 41).

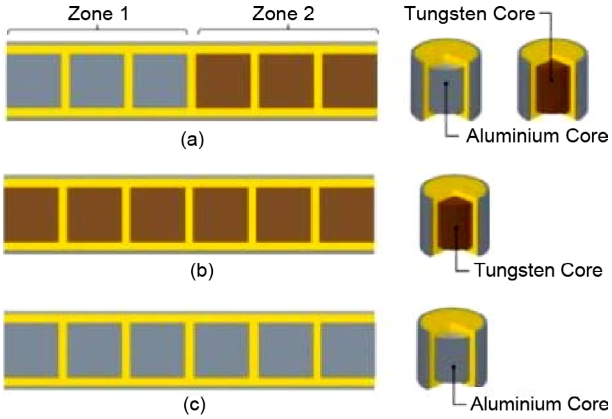


Figure 40. The meta-truss bars with different arrangements of resonators (Vo et al., 2022).

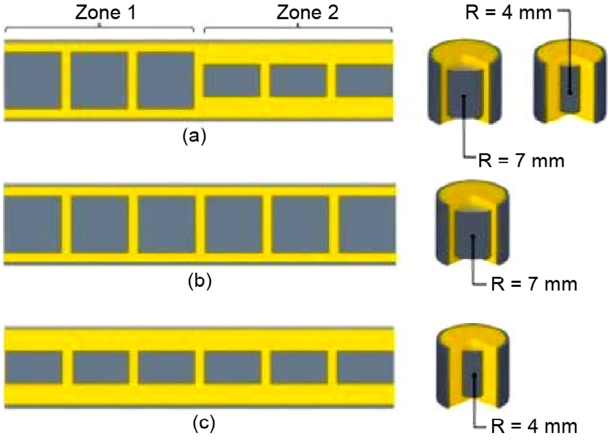


Figure 41. Schematic diagram of meta-truss bars with different sizes of resonators (Vo et al., 2022).

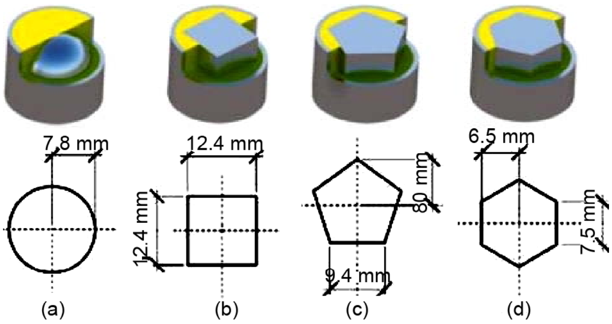


Figure 42. Schematic and dimensions of meta-unit cells with various inclusion shapes including (Vo et al., 2022).

The results indicated that the meta-panel consisting of two resonator zones had the best performance in all criteria, with the smallest displacement of the back face-sheet, the lowest reaction force, and the highest energy absorption. The peak displacements at the center point of the back face-sheet were 3.7 mm and 3.9 mm and 2.7 mm for the panel with uniform resonator (i.e., R7 and R4) and meta-truss bar consisting of two sizes of cores respectively. Also, four regular shapes including cylinder, cuboid, pentagonal prism and hexagonal prism were considered while other parameters of the meta-panel were kept the same (Figure 42).

The results showed that the highest and the smallest energy absorption were for the meta-panel with cuboid inclusion and cylindrical cores respectively (Vo et al., 2022).

4. Materials

There are several solutions to prevent the destruction or maximum damage to structures in explosive environments. In this part, another way of retrofitting methods and energy absorbing systems is presented that can mitigate the blast pressure after being applied and reaching the structure. CFRP has a higher Elasticity coefficient than FRP, which is used in retrofitting structures. Crawford et al. (1997, 2001) investigated the effect of using CFRP composites on the performance of the structure in blast attacks. The performance of the circular RC column retrofitted with CFRP was studied against TNT charge. The results showed that CFRP composites can prevent progressive collapse and reduce lateral displacement significantly (Crawford et al., 1997). Polyurea fiber has a good link with concrete and steel, also it has good blast resistance because of its stiffness and ductility that usually sprays on the structure for retrofitting against blast hazards. Masonry wall was retrofitted with a polymer coating once inside and once again on both the inside and outside the walls, and walls were tested experimentally. Pressures, accelerations and deflections experienced by the walls were measured using pressure gauges. The results indicated that using this fiber inside the wall increases the resistance of the structure, but if the masonry wall is equipped on both the inside and outside, in addition to increasing the strength, the wall was not fragmented (Davidson et al., 2004).

An RC slab equipped with carbon fiber polymer (CFRP) and steel fiber (SRP), once on one side of the slab and once on both sides, was investigated under the blast of RDX. Five slabs were tested under real blast loads experimentally and the load-deformation response of these slabs was investigated. Also, the way to predict the explosive charges weight and standoff distances required to impose a given damage level were discussed through the analytical steps with the relevant experimental results. To evaluate the influence of negative moments which are developed under dynamic loads, the slab was strengthened on both sides, not for evaluating the influence on resistance capacity. The results showed that the retrofitted slab on both sides has a better performance than the other because in this condition the slab has a better resistance against the negative flexural moment and using this composite on both sides of the slab increases the stiffness of the slab under this negative bending. Slabs retrofitted with SRP performed the same as the slabs retrofitted with CFRP composite, but SRP technology, because of its cost-effectiveness has shown great potential for improving the blast resistance capacity of concrete structures (Silva & Lu, 2007). Steel is a material that is widely used in the field of construction such as reinforced concrete, therefore steel fibers were considered to make structures resistant to explosions. Deficiencies of concrete, including its weakness in tensile strength and fragility, can be solved by adding these fibers to concrete, and we can increase the shear, flexural and tensile properties of concrete through this. Steel fiber reinforced polymers (SRP) were used and all around RC beams and beam-columns were completely wrapped with them, their performance was investigated experimentally and numerically in AUTODYN, and detailed observations were validated against numerical models. The blast pressures applied to the specimens were estimated; also the crushing and spalling of the cover concrete and the flexural crack widths at mid-span and supports, and the damage sustained were checked and observed. This polymer increases the strength of concrete by allowing it to achieve high strains.

These wraps enhanced member capacity in failure modes and the ductility of the concrete through enhanced confinement. It seems that the spalling of concrete in an explosion can be preventable by the use of SRP wraps. It was also observed that SRP materials can withstand 50 kg explosives at a distance of 2 m without peeling from the surface of the concrete (Carriere et al., 2009), Figure (43).

The RC circular column of 600 mm diameter reinforced with longitudinal bars and tie with and without retrofitting, was studied under blast loads to analyze the effect of CFRP on the progressive

Figure 43. Square of steel reinforced polymer strip and the wire wraps used to apply steel reinforced polymer (Carriere et al., 2009).

collapse and collapse behavior through the nonlinear finite element analysis using LS-DYNA software. Also, in this study, other parameters like stand-off distance and charge weight were investigated. Some critical cases such as lateral displacement and the damage that occurred for longitudinal and Shear reinforcement and their maximum Tensile Stress, Peak, and Permanent displacement were evaluated and discussed. The results indicated that the retrofitted column reduced the initial natural time period of vibration of the column by About 11.7% and increasing the used layer of CFRP caused the column to resist better in intense blasts because even a light retrofitting improved the resistance and also reduced the peak lateral displacement considerably, the amount of which varies for different stand-off distances and charge weights. Since the exponential relation between increased peak lateral displacement and decreased stand-off distance, the stand-off distance played a big role in mitigating the blast load. Retrofitting columns with CFRP reduce the peak lateral displacement considerably, which varies from 8% for 100 kg charge weight at a stand-off distance of 4 m to 79% for 500 kg charge weight at a stand-off distance of 4 m. The example of damage and deformation for the numerical model is shown in Figure (44) (Elsanadedy et al., 2011).

Fazelipour and Tavakolizadeh (2011) investigated the nonlinear behavior of retrofitted concrete walls with CFRP (carbon fiber reinforced polymers) against the blast waves using Abaqus finite element software (Figure 45). In this study, the explosive load, support conditions, wall dimensions, fiber material, and properties of the materials used, were considered the same, and the effect of arrangement and thickness of CFRP sheets in different modes was investigated. First, the

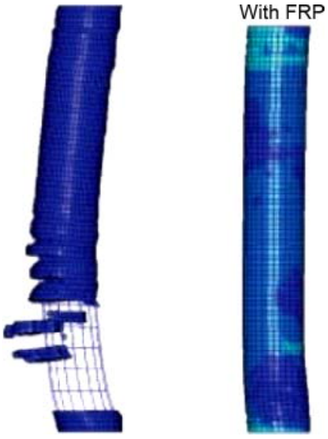


Figure 44. Damage of column with and without FRP due to 100 kg charge weight at 1 m stand-off distance (Elsanadedy et al., 2011).

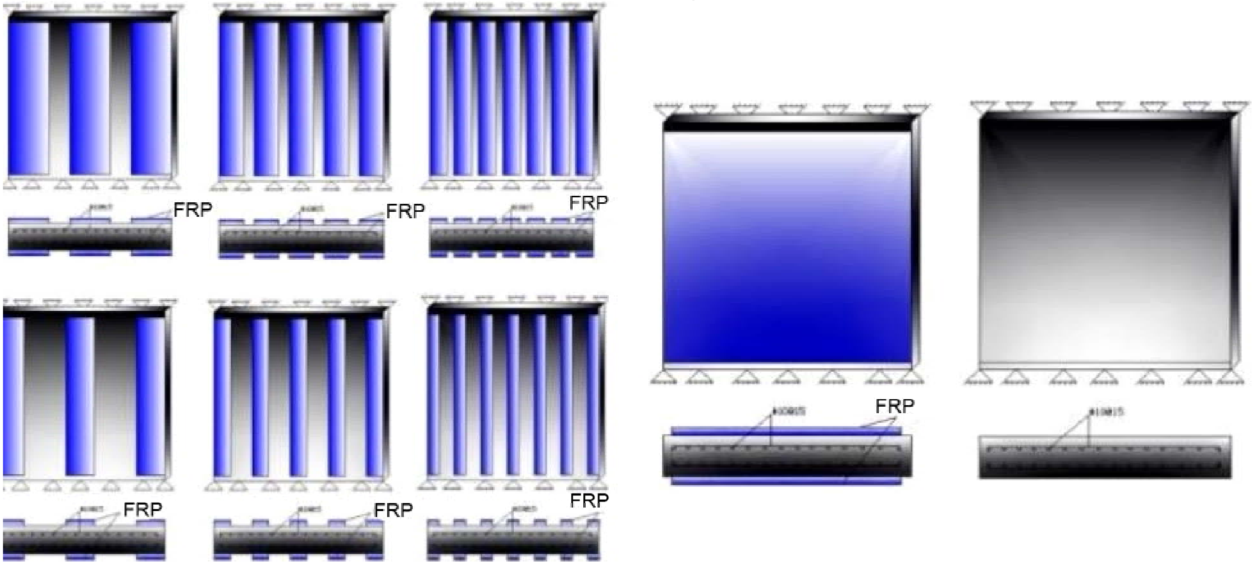


Figure 45. Details of reinforced concrete wall sections and how the fibers (CFRP) are arranged (Fazelipour & Tavakolizadeh, 2011).

amount of displacement and the distribution of stress and signs of destruction in the walls were calculated, and critical areas were identified. The responses of retrofitted walls were compared to the performance of reinforced concrete walls, and the effect of using this method of retrofitting walls against explosive loading was determined. According to the results, Strip layouts have been found to be more suitable for retrofitting walls than full wall coverings. Also, retrofitting of reinforced concrete beams using FRP layers and GFRP and CFRP and Steel Mesh has been done (Izadifard & Qolipur, 2011; Izadifard & Mehrabi, 2009; Izadifard & Beygi, 2010) polymer coatings are used as an alternative way to retrofit the structures against blast loads. The performance of the unretrofitted reinforced concrete panel was compared to the performance of several polymer-coated panels using an explicit nonlinear finite element (FE) code. The energy dissipated during a blast is converted into strain and kinetic energies. Two parameters, Maximum and Permanent displacements in the panels due to the blast load and peak kinetic energy in concrete was evaluated. The polyurea coating can absorb the high kinetic energy dissipated during the blast, which consequently results in reduced displacement. The results indicated that these polymer coatings can act as a protective layer in improving the durability of the structure and reducing its damage. One of the problems of composites like FRP is the low breakdown strain which plays a significant role in the high impulsive loading that has a high strain rate. As a solution, elastomeric polymers like polyurea and polyurethane are used for retrofitting the elements and structures that are subjected to blast effects (Raman et al., 2012), Figure (46).

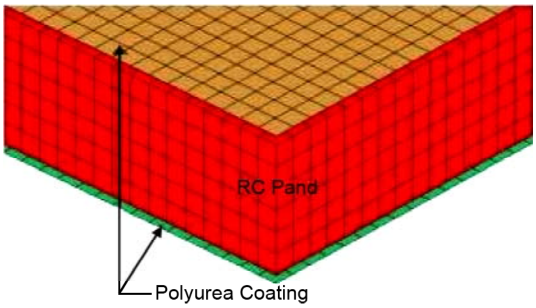


Figure 46. A section of the panel (Raman et al., 2012).

The response of the sprayed polyurea reinforced brick wall was investigated under explosion to enhance the resistance of the building walls. Numerical simulation and experimental verification were carried out to analyze the failure phenomenon. The results showed that when the thickness of the polyurea layer increases, the damaged area of the masonry wall decreases. Spraying polyurea on both surfaces of the masonry wall improves the resistance of the wall significantly. It was found that by increasing the thickness of the polyurea layer on the back blasting surface, the range of the crack area on the back blasting surface gradually decreases (Ji et al., 2022).

5. Conclusion

Because of the increase in terrorist attacks, reliable blast protection systems are required to attenuate and mitigate the blast loads and protect the structures and their occupants from every damage due to the explosions.

The results of different research that were done experimentally and numerically showed that using protection systems can lead to a decrease in damage and the pressure felt by the target structure. Using anti-blast walls and fences can increase the standoff distance between the charges and target structures, and they can mitigate the blast pressure before reaching the structures. Sometimes protection systems reduce the pressure after the blast loads strike the structure, in these states, the structures can be equipped with sacrificial claddings or sandwich panels or be covered by materials such as polyurea or FRP. The result showed that using these materials reduces the displacement and increases the blast resistance capacity of the structures.

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