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Numerical Assessment of a Sustainable Blast Protection Wall

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ABSTRACT

Terrorist attacks have increased in the past few years in different countries. Explosions are problem that has significant impact on human life, as well as the social and economic situations. Engineers have designed targeted structures to mitigate blast effects. However, design blast-resistant systems is pricey and not suitable choice in most cases. Therefore, install blast barriers to protect occupants and instructed can reduce casualties and losses. Most current studies have investigated the performance of multi-layer composite blast barriers composed of advanced materials, which is not only costly, but require skilled labour to construct. The present study conducts numerical analysis of eco-friendly composite blast protection wall to mitigate blast. The wall structure consists of two face-sheet of adobe brick and core layer of crushed recycled aggregate. The analysis framework includes three different blast wall models using ABAQUS®. The explosive charge of 1-kilogram TNT is placed at different standoff distances from 0.25 to 4.0 meter in front of the wall. The authors conclude sustainable materials to design blast barriers could be effective in reducing the intensity of explosions in certain blast scenarios. The thickness of the core layer and standoff distance have the main contribution to identify the blast response of the blast wall. For instance, the calculated out-of-plane displacement results showed when 1- kg TNT place at 0.5-m from the wall, and thickness of the core increases from 30-cm to 60-cm, the displacement decreases by 38.74%. While the acceleration decreases by 75% for the same range of increase of thickness of the core layer. The present study calls researchers to investigate the performance of low-cost, and environment-friendly materials to attenuate abnormal loads wether are man-made or natural hazards.

1. Introduction

Due to political conflicts and economic crises, terrorism have spread in different regions of the world, especially in the Middle East [1]. Terrorist groups have implemented extensive wave of explosions in the last years causing causalities and massive havoc in infrastructure [2]. Only security and military bases have been designed to resist blast. Civilian-uses structures have not been designed to resist abnormal loads such as blast [3].

Security agencies have taken procedures to prevent explosion attacks inside cities, malls, and airports. For instance, police department restricted traffic flow near city centers and crowded areas [3]. The idea is to maximize distance between the explosion center and targeted area. However, terrorists have adopted undetectable techniques, which made stopping this attack a hard mission [2-5].

The current studies have investigated the performance of blast-resistant systems composed of sophisticated multi-layer components [5]. Generally, those blast resistant-systems are composed of parent structure, front and back face sheets made of high ductile materials, and core structure, usually made of low density, high compressible materials. The role of front face-sheet is to reflect the incident

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wave, while this approach is urgent need to attenuate the blast, but it may not applicable to implement in different countries due to significant cost of construction and lack of advanced materials industry technology.

The present study performed numerical analysis of a blast protection wall system composed of sustainable materials that can provide the required level of protection of explosions in certain explosion scenarios and afford sustainable conditions.

List of Notations:

P: total pressure
R: statndof distance
W: TNT charge weight
Z*:* scaled distance
P_{so}: peak overpressure
t_a: arrival time
t_o: positive phase period
i_s^+: impulse momentum
σ1, σ2, σ3: principal stresses
C: compressive strength
T, is tensile strength

2. Literature review

The most current studies have interested in the behavior of blast walls, also known as barriers under blast loading. These studies have inevistaged the performance of high-sophisticated blast–resistant systems [6]. However, limited studies have been published discussed the air-blast distribution in open-space and blast response of low-cost blast barriers for military purposes [5]. Due to increase in the terrorist activities, the need of designing blast wall that has a capability to mitigate blast effects made of low-cost materials has increased [6]. Several studies have been published to assess the performance of multi-layers.

Tiwari et al. (2016) conducted numerical study to understand how the blast wave propagated and affected the wall. The modelling of the concrete wall was carried out using the AUTDYN. The results of the study showed concrete wall with a metal plate showed a higher efficiency than the other wall when a 100 kg charge was put at a height of 1 and 3 meters from the wall [7].

Li, et al. (2014) conducted numerical and experimental study to study the behaviour of sandwich panels with a corrugated core (see Figure1). The authors presented the resulted of energy absorption and blast response of the sandwich panels. Moreover, the authors conclude that the bending resistance in the length direction of the board is better than the transverse direction, and the board with a corrugated core is less than efficient than the rest of the shapes [8].

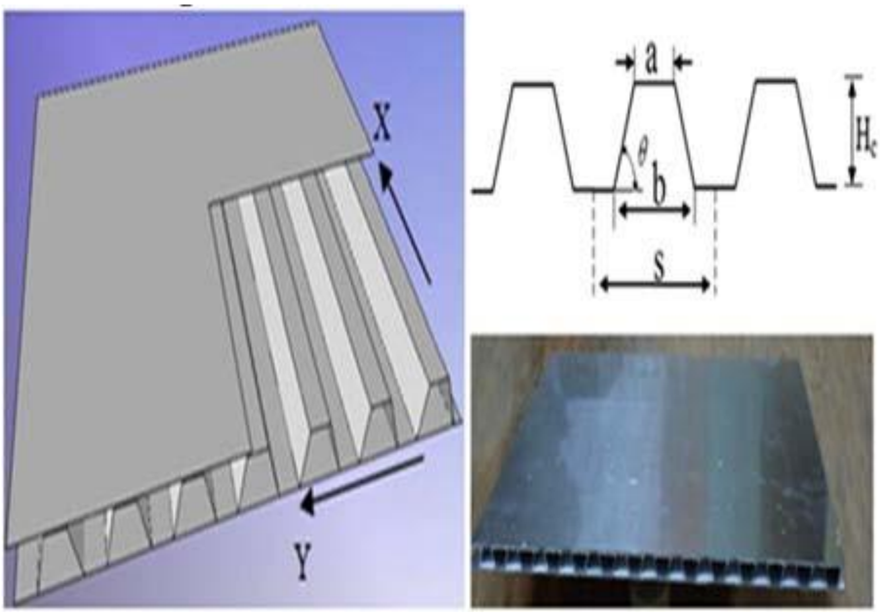

Figure 1. Sandwich panels with a corrugated core [8]

Li et al. (2016) conducted experiments of metallic sandwich panels with honeycomb core [10] (figure2) The results validated with finite element analysis using LS-DYNA software. The outcome of the study explains the relation between the core relative density and graded distribution and the efficiency of the composite panels to resist blast. It is seen that graded panel with higher relative density has better efficiency to mitigate blast load [9].

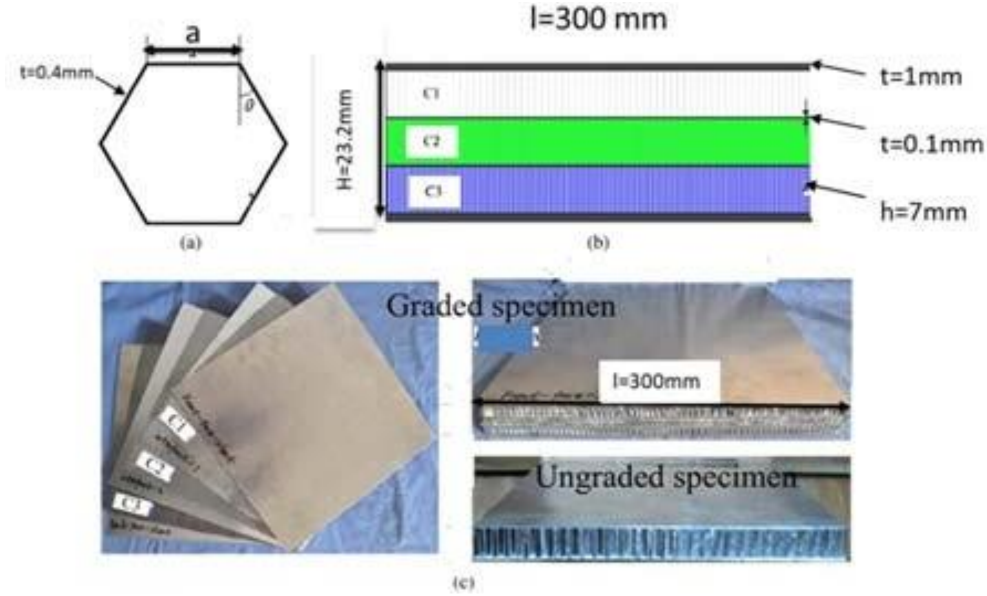

Figure 2. (a) dimensions and geometry of a single cell (b) Gradient cell density on the plate (c) Panel dimensions and geometry [9]

Rose et al. (1998) studied the blast distribution around blast barriers composed of wood, sand, concrete, and foam [10]. The authors considered different heights and dimensions of the blast barriers and measured the blast pressure at specified distances behind these barriers. The authors found that height of the wall and standoff distance are the main key to identify the blast intensity. Furthermore, the blast height is also important to increase the efficiency of blast resistant of the considered blast walls. However, the study did not investigate the response of blast barriers.

In conclusion, there are two approaches to design blast walls: first approach is adopted composite, multi-layers blast-resistant systems. This approach is considered when permanent deformation is not permitted according to design specifications and structural system function. Second method, design blast barriers made of earth-filled, low-cost available materials. This approach is considered when partial failure is allowed and blast wave attenuation is required to mitigate blast shock wave pressure. The present study considered a blast wall made of readily, low-cost materials which can minimize blast intensity.

3. Blast wave characteristic in air

3.1 Blast wave proportion

High energy released due to high explosive burst. This phenomenon is happening at very short period. The blast wave moves from the centre of explosions towards targeted structure at high speed. The blast wave pressure-time parameters depend on the type of explosive and standoff distance. However, the general shape of high explosives is the same [11]. Figure 3 shows a typical pressure-time curve of blast wave in free air. The blast pressure increases significantly from the atmospheric pressure (Po) to peak-overpressure (Pso). The pressure suddenly drops and return to the reference pressure, this part known as positive phase. As the blast wave moves the pressure becomes less than the reference pressure, this point considers starting time of the negative phase. In comparison, negative phases are longer, but larger in pressure magnitude. Therefore, the calculations of the Friedlander equations that are used to describe the blast wave profile, neglected the negative phase as shown in Eq. (1) [12].

$$P(t) = P_{so}\left(1 - \frac{t}{t_0}\right)\exp\left[\frac{A \times (t - ta)}{t_0}\right] \quad (1)$$

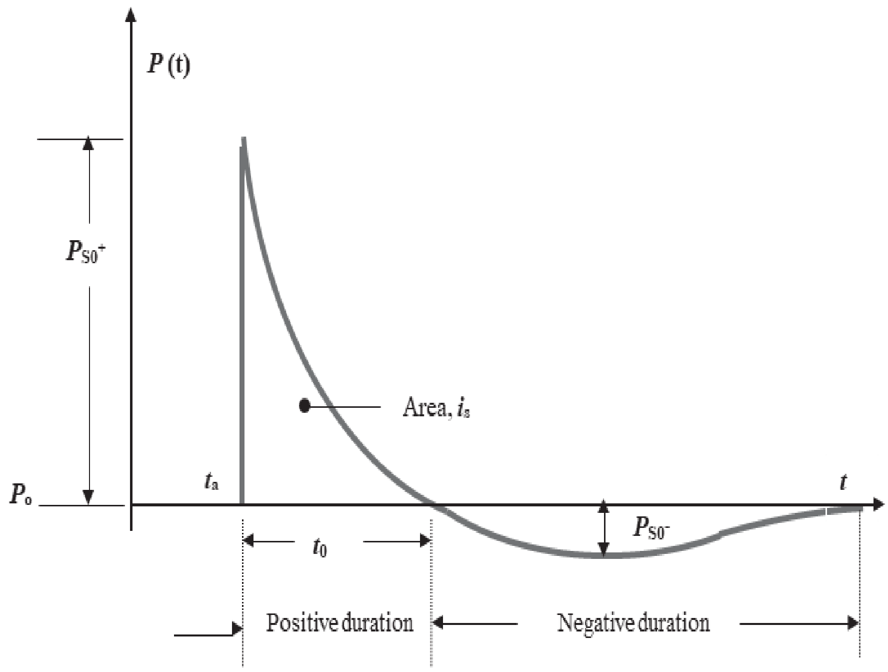

Figure 3. Pressure time history for blast wave (13)

Here, P(t) is the pressure at a certain time, Pso, is the peak overpressure, t_o, time period of the positive phase, (*A*) is the decay factor in the wave, (t_a) is the arrival period.

The other important parameter is theimpulse momentum of the positive phase (i^+),which is equal to the area under the curve. Thisparameter provides assessment of the damage level of targeted structures. The mathematical expression is shown in Eq. (2)

$$i_s^+ = \int_{ta}^{tA+to} P(t).dt \quad (2)$$

3.2 Hopkinson and Cranz scaling law

Hopkinson (1915) and Cranz (1926) formulate cubic root law to calculate blast wave parameters using reference value) s. The Hopkinson and Cranz law are the most common scaling law which can used to determine blast wave parameters when two explosive charges have the same geometry, but different diameters

Blast wave parameters are scaled by a length factor [14, 15]. The expression of the cubic root law is illustrated in Equation (3). Figure 4 shows Hopkinson-Cranz law.

$$Z = \frac{R}{W^{\frac{1}{3}}} \quad (3)$$

where W, the weight of the charge, and R, the standoff distance.

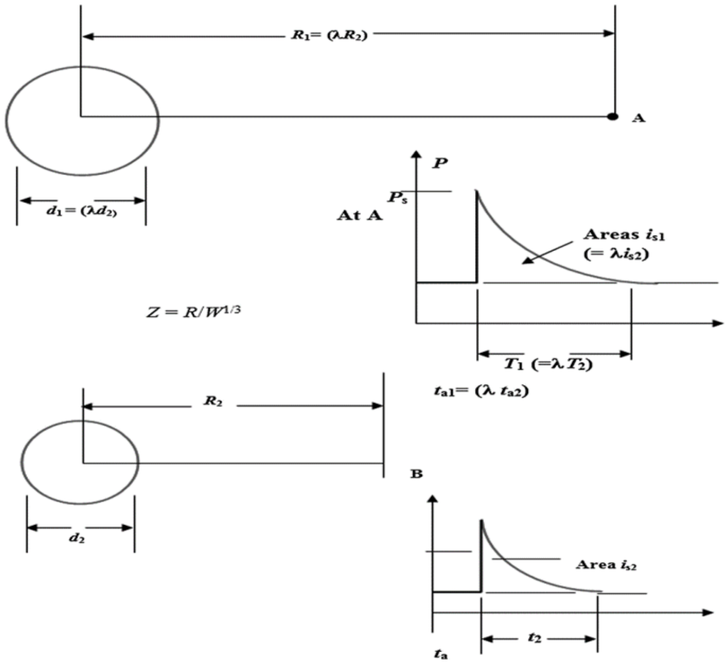

Figure 4. Hopkinson-Cranz scaling laws [12]

4. Mohr – Coulomb failure criteria

The failure theories are applied to predict failure in the material because of applied actions. This paper considered the Mohr-Coulomb theory to determine the failure occurring in the brittle material represented by bricks. Coulomb-Mohr failure criterion is a mathematical model used to illustrate and predict failure of brittle materials. The criterion considered a set of linear equations between maximum and minimum principal stresses (normal and shear stresses) at failure. The Coulomb-Mohr failure criterion uses Mohr-circles to construct failure envelope (see Figure 5) [16]. Equation 4 shows the interaction equation of the Mohr-Coulomb theory [16].

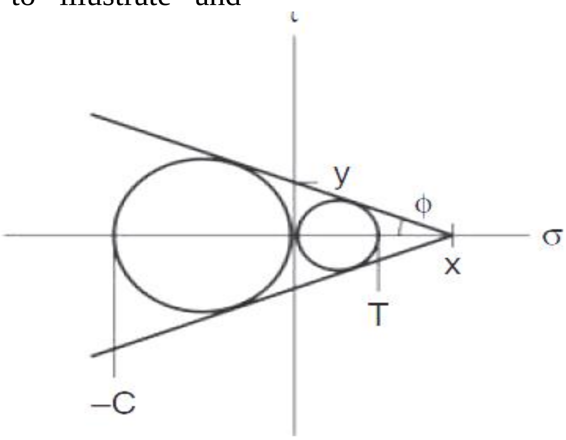

Figure 5. Coulomb–Mohr envelop [15]

$$\frac{1}{2}\left[\frac{1}{T}-\frac{1}{C}\right](\sigma 1+\sigma 3)+\frac{1}{2}\left[\frac{1}{T}+\frac{1}{C}\right](\sigma 1-\sigma 3) \leq 1 \quad (4)$$

where, σ1, σ2 and σ3 are the principal stresses, C, is compressive strength, T, is tensile strength.

The Moh-Coulomb criterion is applied in the present study through calculating the principal stresses of the blast wall and substitute in Eq. (4) to identify the failure.

5. Blast wall geometry and material properties

The present study proposed blast protection wall composed of sustainable materials, which can be easily constructed and does not require skilled workers and meets sustainability requirements. The blast wall consists parent structure and the core layer. The container part made of the adobe brick, while the core made of the crushed recycled aggregate. Figure 6 shows the three different models. Table 1 listed the dimensions of the blast wall.

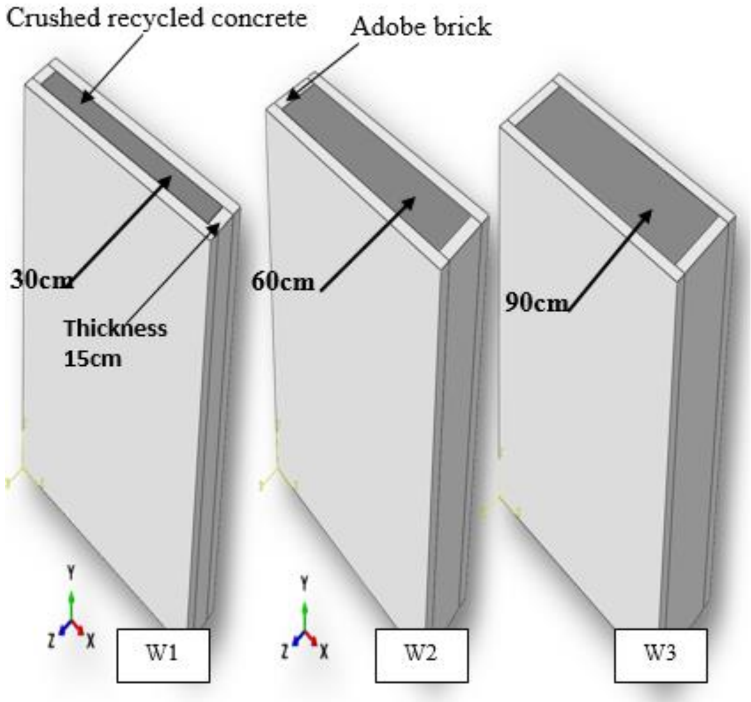

Figure 6. Blast wall geometry details

Table 1: Blast wall dimensions

Model	Height (m)	Width (m)	Thickness (cm)	
			Adobe brick	Concrete powder
W 1	3	3	15	30
W 2	3	3	15	60
W 3	3	3	15	90

To determine the mechanical properties of the crushed recycled aggregate, sieve analysis of was carried out according to ASTM C33. The results of sieve analysis are listed in Table 2.

Table 2: Grading of crushed recycled aggregate

Sieve size	Weight retained (gm)	Cumulative weight retained (gm)	Cumulative % returned
10 mm	0	0	0
4.75 mm	8	8	1.69
2.36 mm	15.3	23.3	4.94
1.18 mm	105.7	129	27.4
600 µ	151.3	280.3	59.53
300 µ	107	387.3	82.26
150 µ	59	446.3	94.79
lower 150 µ	24.5	470.8	100

From the sieve analysis results, recycled aggregate sample classified as poorly graded sand (SP) based on the Unified Soil Classification System standard. The mechanical properties are listed in Table 3.

Table 3: Mechanical properties of recycled aggregate

Properties	Units	Values
Density (ρ_{rc})	(kg/m^3)	1395
Poisson's ratio (v_{rc})	-	0.25
Young's modulus (E_{rc})	(MPa)	10

The mechanical properties of the Adobe bricks, as shown in the Table 4 [17]. The compressive strength of the bricks, it was equal to 1.03 MPa and the tensile strength was equal to 0.22 MPa [18].

Table 4: Characteristics of the Adobe Brick

Properties	Units	Values
Density (ρb)	(Kg/m^3)	1300
Poisson's ratio (v_b)	-	0.35
Young's modulus (E_b)	(MPa)	135
Tensil stress(σ_t)	MPa	0.22
Compressive strength (σ_c)	MPa	1.03

6. Numerical analysis of blast wall

The brick-recycled aggregate- brick wall has been modeled using ABAQUS ver. 6.14 to simulate the blast wave-wall interaction and determine blast response. The ConWep blast load model was used to simulate a blast in free air and the distribution of the blast load on the wall. The input data of the ConWep are the explosive weight, and the explosive location. The interaction between the brick and the recycled aggregate element performed through general contact algorithm for both normal and tangential behavior. The TNT charge of 1 kg was placed at the central level of the wall at different distances from 0.25 m to 4 m (see Figure 7). The boundary conditions and finite element model is shown in Figure 8.

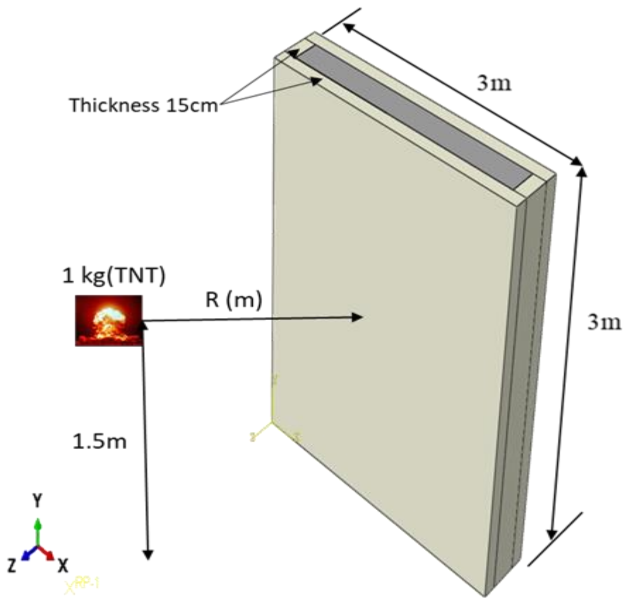

Figure 7. Explosive change setup

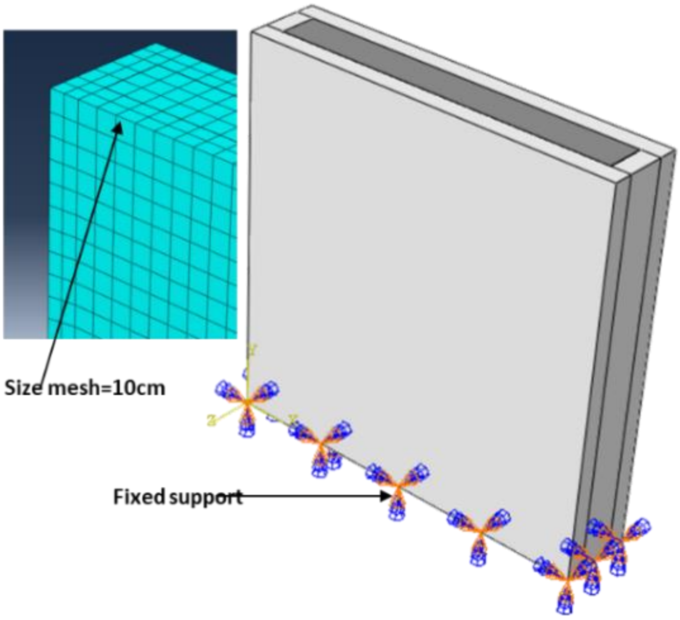

Figure 8. Finite element model and boundary condition

The results of the three–dimensional dynamic finite element method (3-D FEM) show that the performance of the blast wall is improved with the increase of standoff distance (R). This is valid since the explosive weight is fixed (1 kg). Furthermore, the thickness of the core layer has a significant role to dissipate the blast wave energy.

The calculated out-of-plane displacement results showed when 1- kg TNT place at 0.5-m from the wall, and thickness of the core increases from 30-cm to 60-cm, the displacement decreases by 38.74%. While the acceleration decreases by 75% for the same range of increase of thickness of the core layer. The incident surface pressure, which is representing the applied pressure on the front–face of the wall is also calculated. The magnitude of the pressure is 236.194 kPa at distance of 0.5-m for blast wall model W1. The peak calculated out of plane displacement, acceleration, and incident surface pressure of blast wall (W1) is listed in Table 5. The time history of blast wall response presented graphically in Figure 9. Figure 10 a,b,c, shows the contour plots of the displecemnt, acceleration, and pressure, respectively of the wall W1.

Table 5: Peak blast response of blast wall W1

R (m)	Displacement (m)	Acceleration (g)	Pressure (kPa)
0.5	0.0555	3961.62	236.194
1	0.0459	2410.83	189.816
1.5	0.03443	1021.63	154.522
2	0.02311	561.787	135.954
2.5	0.02021	481.896	106.095
3	0.01752	163.487	83.0567
3.5	0.01419	90.8954	78.854
4	0.01235	58.9392	55.9421

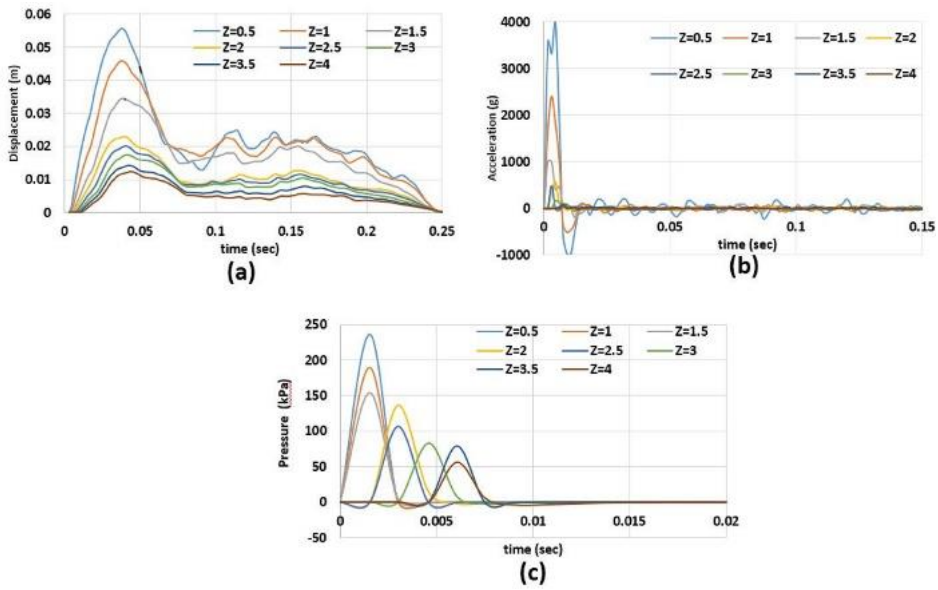

Figure 9. Blast response of Blast wall (W1), (a) Displacement (b) Acceleration (c) Pressure

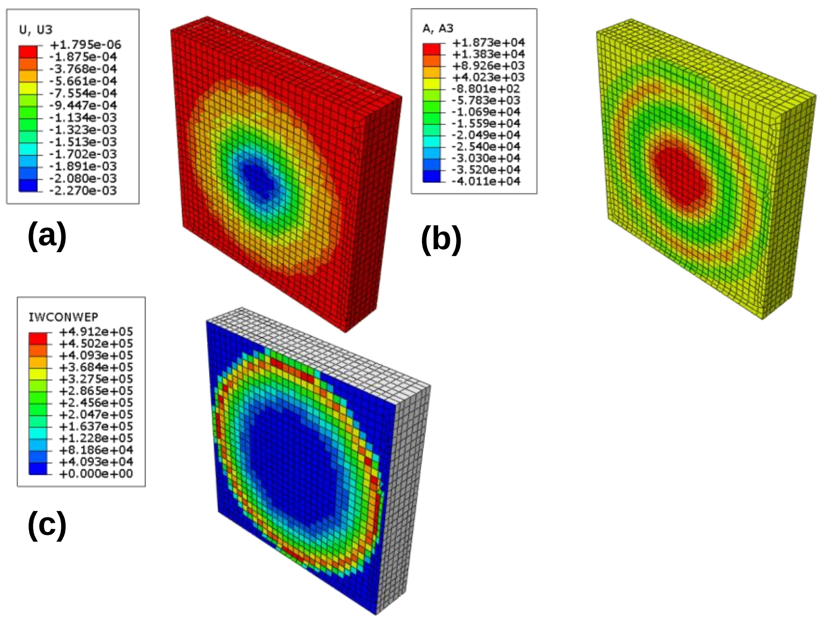

Figure 10. Contour plots of blast wall (W1) (a) Displacement (b) Acceleration (c) Incident surface pressure

It is clear that the performance of the blast wall is function of the mass of the wall. For instance, based on the results of the analysis of blast wall W1 and W2, it is noticed the reduction in the out-of-plane displacement when 1-kg TNT of charge is placed at a distance of 0.5-m is 16%, while the reduction in the acceleration is 6.68%. Moreover, the reduction of the pressure is higher and it was 46.61%. This reduction is noticed when thickness of the core layer increased by 50%. The peak blast response of the blast wall models W1 and W2 are listed in Table 6 and Table 7, respectively. Figure 11 and 12 present the time –history of the blast wall W1 and W2, respectively. Figure 13, and 14, show the contour plots of the displacement, acceleration, and pressure of blast wall W2 and W3, respectively.

Table 6: Peak blast response of blast wall W2

R (m)	Displacement (m)	Acceleration (g)	Pressure (kPa)
0.5	0.0425	3696.66	230.488
1	0.0386515	2179.61	179.951
1.5	0.0285354	1123.22	144.073
2	0.01806	543.827	107.134
2.5	0.01736	308.088	97.117
3	0.01443	122.4	78.854
3.5	0.0122596	97.6079	55.9421
4	0.0103929	54.145	38.687

Table 7: Peak blast response of blast wall W3

R (m)	Displacement (m)	Acceleration (g)	Pressure (KPa)
0.5	0.035774	920.144	123.037
1	0.020048	534.593	100.532
1.5	0.014447	304.943	98.365
2	0.012943	225.934	81.1121
2.5	0.0108	200.404	74.4476
3	0.0107	127.437	50.9504
3.5	0.008765	63.8844	43.706
4	0.007361	40.1554	30.563

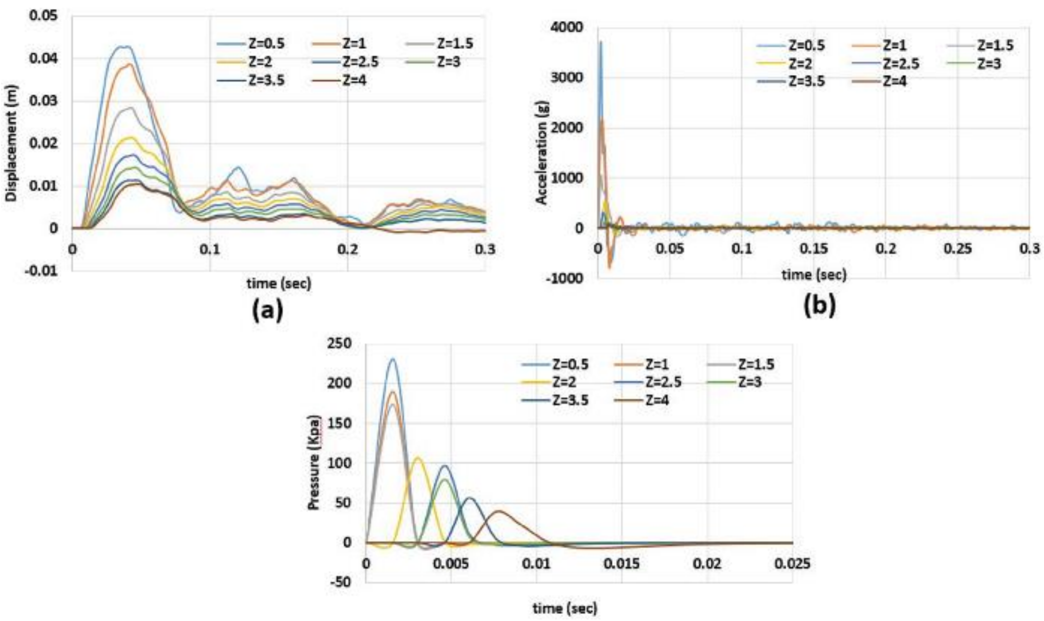

Figure 11. Blast response of Blast wall (W2), (a) Displacement (b) Acceleration (c) Pressure

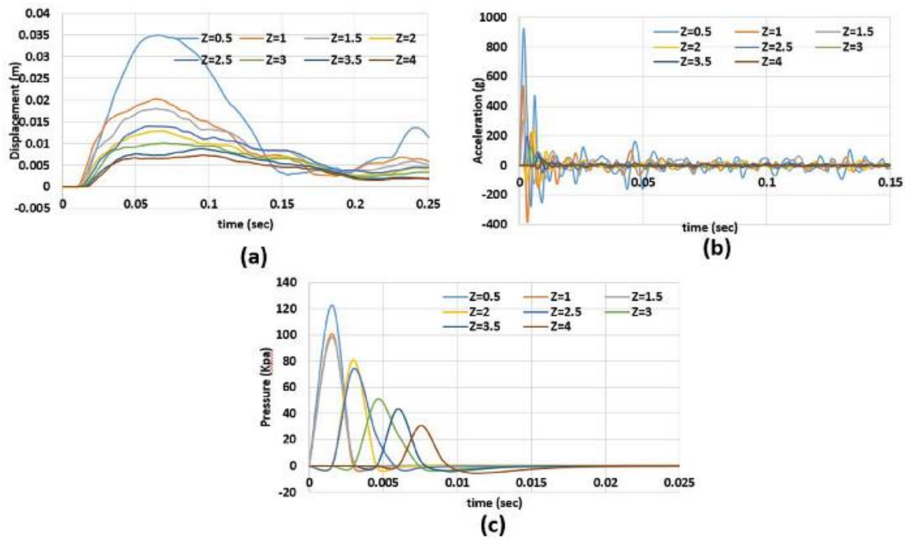

Figure 12. Blast response of blast wall (W3), (a) Displacement (b) Acceleration (c) Incident surface pressure

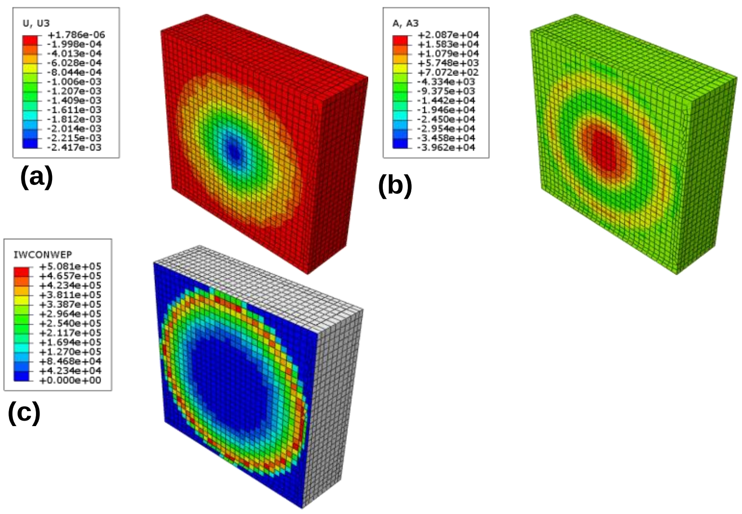

Figure 13. Contour plots of blast wall (W2) (a) Displacement (b) Acceleration (c) Pressure

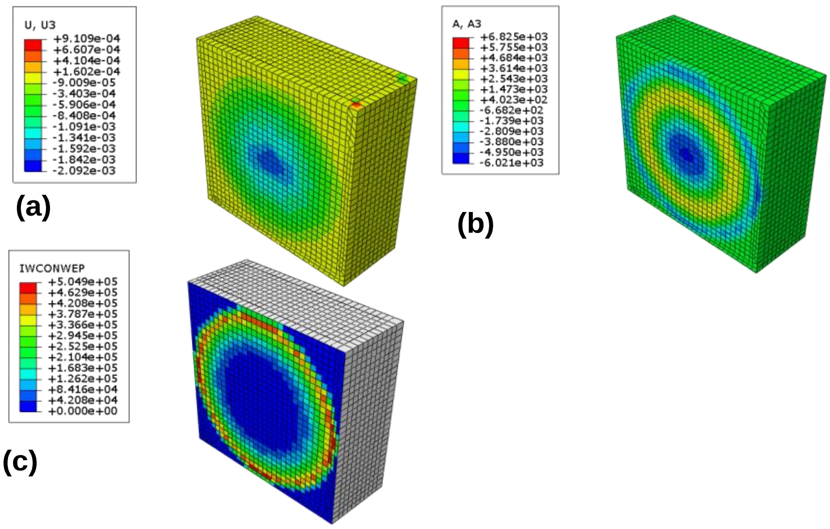

Figure 14. Contour plots of blast wall (W3) (a) Displacement (b) Acceleration (c) Incident surface pressure

7. Failure prediction of blast wall

The failure of the blast wall is estimated based on the Mohr-Coulum failure criterion. Figure 15 shows the failure index of the wall as function of standoff distance (R). The authors observed that the wall whose core layer thickness is equal to 30-cm can stay intact without permanent deformation when the explosive charge (1-kg) is placed at a distance equal or larger of 4-m. However, when the thickness of the core layer increased to 60-cm the failure occure when the charge is placed at a distance of 3.75-m or smaller. The blast wall W3 can mitigate blast without failure if the standoff distance is equal to or larger than 1.25-m. In conclusion, even simple blast wall composed of sustainable components can provide a reliable safety in certain explosion scenarios.

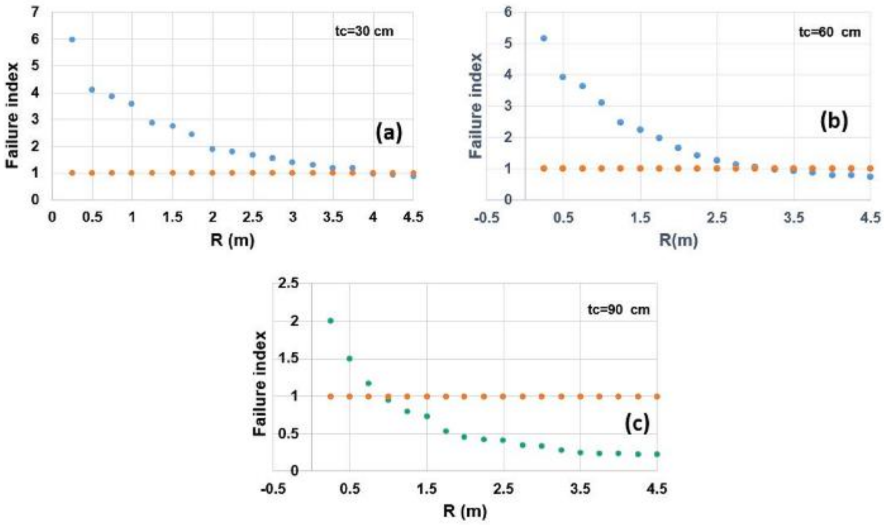

Figure 15. Results of failure indicator wall a) W1, b) W2, c) W3

7. Conclusions

The current study proposed multi-layer sustainable blast wall to attenuate blast pressure. The feature of the suggested blast wall is the applicability to use in most countries. Partial or full failure is probable of this type of blast wall systems, but it is not an issue since the purpose of installing these walls is to reduce casualties and losses. The structural system uncomplicated is uncomplicated, and easy and cheap to rebuild and maintain. The outcomes of the study highlighted the important of readily reachable materials to design blast protection wall systems. However, the integrity conditions of blast-resistant systems may not apply for such types of blast barriers since it is not part or connected to other structural components which are no allowed to deform due to design specifications. The response of the considered blast wall showed a good capability to mitigate in certain blast scenarios. The thickness of the wall had a great effect in resisting the impact of the blast load on the wall. The calculated out-of-plane displacement results showed when 1- kg TNT place at 0.5-m from the wall, and thickness of the core increases from 30-cm to 60-cm, the displacement decreases by 38.74%. While the acceleration decreases by 75% for the same range of increase of thickness of the core layer.

The failure index also showed the efficiency of the wall depends on the core layer thickness. For instance, the blast wall W1 fails when standoff distance is less than 4-m, while blast wall W3 fails if Standoff distance is less than 1.25m. In conclusion, the present study tried to highlight the efficiency of low-cost materials to mitigate blast through evaluate the performance of brick-recycled aggregate-brick blast wall.

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