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Bio-Inspired of Pyramidical Concrete Barrier Walls against the Effects of Explosion Waves

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Abstract

Biomimicry is a technique that inspired solutions to engineering problems through the study of natural systems, designs and processes. Recently, the engineering Biomimicry technique has been used to inspire a protection system against the blast waves and that can mitigate, absorb, and reflect the blast waves. Hence, this work studies the effect of different geometrical configurations of concrete wall barriers inspired by nature against blast waves. The non-linear 3d numerical model is used to model the proposed configurations. The finite element modeling is validated with referenced experimental works. The response of the proposed structural configurations of the wall barrier is analyzed. The results showed that the new bio-inspired pyramidical structure configuration (PCBW) has a notable effect on the mitigation of blast hazards which gave the best performance for the protection of the area behind the wall barrier with 19.5% with respect to traditional concrete barrier wall (TCBW). Also, it is concluded that nature inspiration has a great effect on designing new protection systems against the effect of blast waves.

Keywords

Explosions, Barriers Pyramid, Biomimicry Techniques, Numerical Simulation

1. Introduction

Blast accidents are the most terrifying event in all over the world of all the types of the explosions [1]. An example of the deliberate explosion is bomb blasts which is the common method for spreading panic to the tourists, so it takes most of interests to the designers to be studied to secure the government institutions and the infrastructure of any country [2], also accidental explosions in the residential buildings because of the gas leakages cause gas explosions [3] [4] [5].

Abundant researchers have discussed the response of blast waves on many geometric configurations theoretically [6] [7], numerically and experimentally [8] [9] [10] [11] [12], such as Walid Attia, Sherif Elwan and Ismail Kotb [12] Discuss the performance of different types of reinforced concrete barrier walls that were subjected to blast loads and also applied a parametric study for nine RC barrier wall systems with many geometries modeled in the three dimensions with different parameters using ANSYS Autodyn software version 18.2. It has been found that the walls with the steady base of 1.0-meter-thick up to 0.5-meter-high with a confront hunch up to 2.0-meter-high are better than all other considered walls. Ahmet Tuğrul Toy and Barış Sevim [13] studied blasting response on the building of 5-story, considered the columns, shear walls, beams, slabs, raft foundation, masonry walls and windows using finite element software ANSYS Workbench.

TNT is exploded to give a blasting response on the building. The duration of the blast is set to 3 msec. Stresses, displacements, material status, and pressures due to blasting on some gauge points are presented. It is clear that the blast causes local damage to the load-bearing elements. Jian Liu, Chengqing Wu, Chunguang Li, Wenxue Dong, Yu Su, Jun Li, Ning Cui, Fan Zeng, Lan Dai, Qingfei Meng and Jiabao Pang [14] discussed two blast tests that study the blast resistance of high performance geopolymer composite walls reinforced with steel wire mesh (SWM) and aluminum. Conventional reinforced concrete (CRC) walls were also tested as control specimens. The testing conducted that the combined SWM and AF reinforced high performance geopolymer composite walls had a better blast resistance than the CRC walls. Aya El Hozayen and Mohamed hazem Mohamed Awad [15] studied blast loading tests in the air by using ANSYS-AUTODYN program for the simulation. The fourteen simulated models were executed in four phases that were subjected to four different masses of TNT (10, 50, 100, 500) Kg. The main target for this group results is to choose the suitable TNT mass to use in the next phases of the research to make the comparison between models, involving pressure and damage, more obvious.

The engineering Biomimicry technique [9] can be very powerful in conducting a protection barrier walls designs against the blast waves and that combination will distort, absorb, and reflect the blast waves as example of Biomimicry technique protection method is "Turtle shells" [16]-[23] that the curved shapes are found more effective in energy absorption as shown in **Figure 1**. Another example is "Pangolins" [24], protocol have keratinous scales organized in an overlapping fashion similar to fish scales. These sharp and Plate-like scales protect them from the attack of predators are as shown **Figure 2**.

Many recent conclusions have been studied on the methodology which can be conduct from the Biomimicry technique to use it at the defense industries [26] [27] [28]. For example, Armadillo that has overlapping protection layers with dark brown keratin in the outside layer and its inside is arranged with hexagonal bony tiles that connected by collagen as **Figure 2** researchers as example Rivera, *et al.*

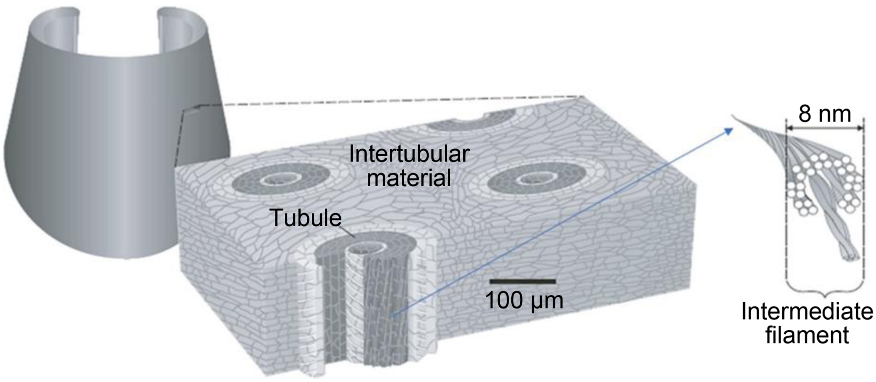


Figure 1. Intratubular material and the arrangements of tubules in the hoof wall [25].

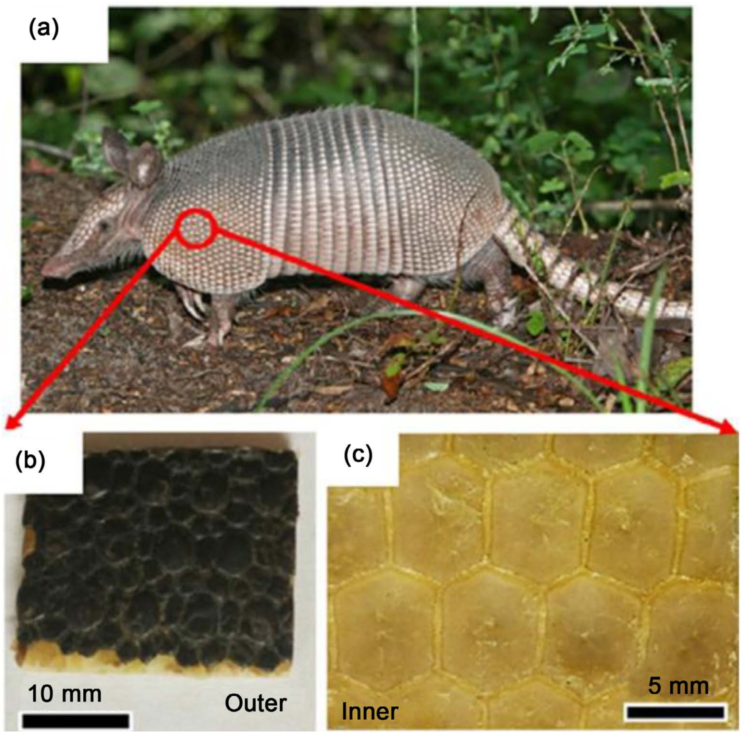


Figure 2. (a) Armadillo (b) outer keratin-based layer of armadillo carapace; (c) inner layer with hexagonal bony segments [26].

[29]. Identified a lightweight compression-resistant exoskeleton in ironclad beetle. GU, *et al*. [30] studied a multilayer additively created biomimetic structure following the complex hierarchical architecture of the conch shell.

This paper discussed the effect of the blast waves on different geometrical shapes which traditional concrete barrier wall (TCBW), and bio-inspired pyramidical concrete panel (PCBW) in order to conclude the best response against the impact blast waves.

2. Numerical Simulations

Numerical studies are very important to simulate the response of explosion and blast effects on different structures as executing experimental investigations is very expensive and requires a lot of machines and precautions during execution.

2.1. Numerical Tool: Hydrocode

A computer program that has the ability of calculating strains, stresses, velocities and spread of blast waves as a function of time and location is known as a hydrocode. In a hydrocode simulation, the effect of a continuous media subjected to dynamic loading is constrained by the conservation of mass, momentum and energy, and also the equation-of-state and constitutive relation of the media. The equation-of-state includes the response of compressibility of the continuous media and is a function of internal energy and density, while the constituent relation represents the media's resistance to shear. In this study the hydrocode simulations on the explosion response on a concrete target are executed using AUTODYN-3D, a fully integrated and interactive hydrocode.

In AUTODYN-3D the basic equations together with the initial and boundary conditions are integrated using a finite difference scheme.

2.2. Model Validation

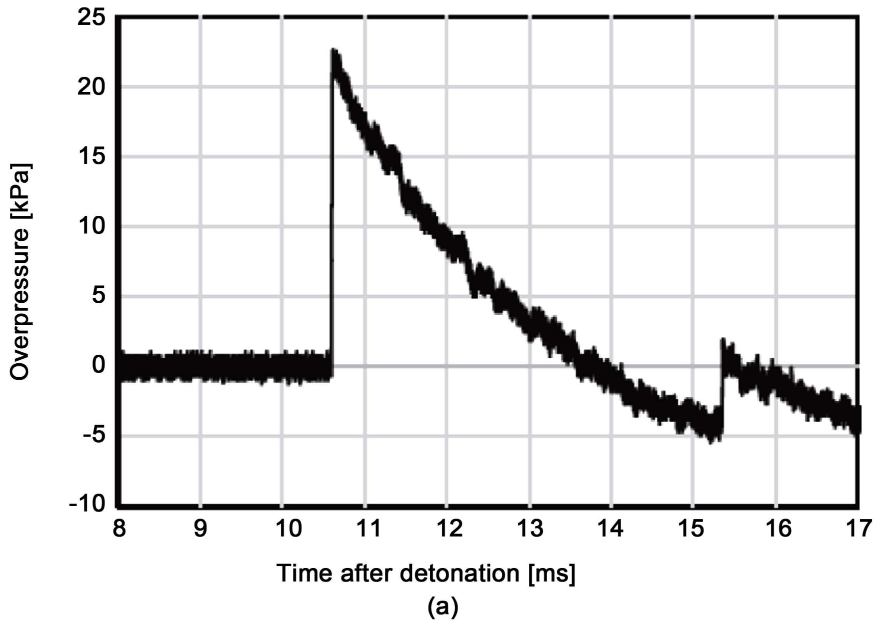
This paper studies a 3D hydrocode simulations using autodyn-3d [11] on the response of explosion on a barrier wall target. The experimental data published by Radek Hajek [10] for two tests executed using a 500 g TNT.

Two experimental tests were applied for verification, in the first experimental test the pressure was measured at a clear distance 6 m from the TNT charge as a typical free field detonation. The comparison between the numerical and the experimental results as shown in **Figure 3** where the pressure recorded in the experimental test is 22 kPa while the pressure measured from the numerical model is 19.16 kPa (after excluding the atmospheric pressure which is measured in the numerical simulation in contrary to the experimental test) with a percentage of error of 12.9%.

In the second test the pressure was measured at the same clear distance 6 m from the charge but with the presence of a concrete barrier at distance 5 m from the detonation point. The height of the barrier is 1.2 m and the compressive strength of concrete used is 156 MPa. The pressure is measured at height 1.2 m from the ground level. The results of the pressure at the gauge point in the numerical test is compared to the results measured in the experimental test as shown in **Figure 4** where the pressure recorded in the experimental test is 9 kPa while the pressure measured from the numerical model is 7.77 kPa (after excluding the atmospheric pressure which is measured in the numerical simulation in contrary to the experimental test) with a percentage of error of 13.6%.

2.3. Proposed Structural Configuration

The new structural configuration has been inspired from nature as shown in **Figure 5**. It is observed from nature that Crocodile has few creatures possess



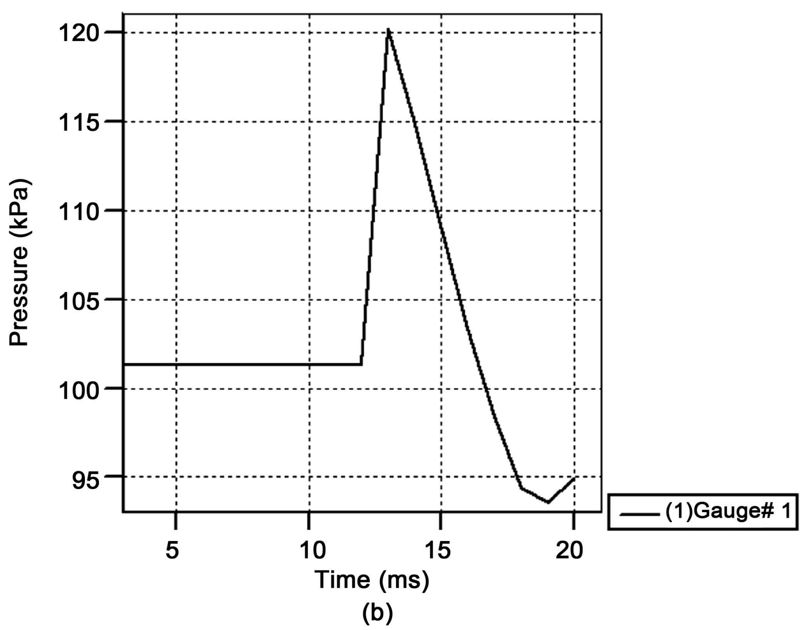


Figure 3. (a) P-T curve of the experimental test. (b) P-T curve of the numerical simulation.

armor that is efficient at dealing with sharp impact loading across the whole body which shaped in pyramidal structure as shown in **Figure 5** as which minimized the plate damage by dispersing the energy created from sharp-edged hitting [8] [31] [32].

The new structural configuration has been proposed as shown in **Figure 6** where two geometrical shapes are proposed: traditional flat barrier wall (TCP), bio-inspired pyramidical concrete panel (PCP) which are subjected to the detonation of a 10 kg comp-B detonated at a distance 2 m from the barrier wall to

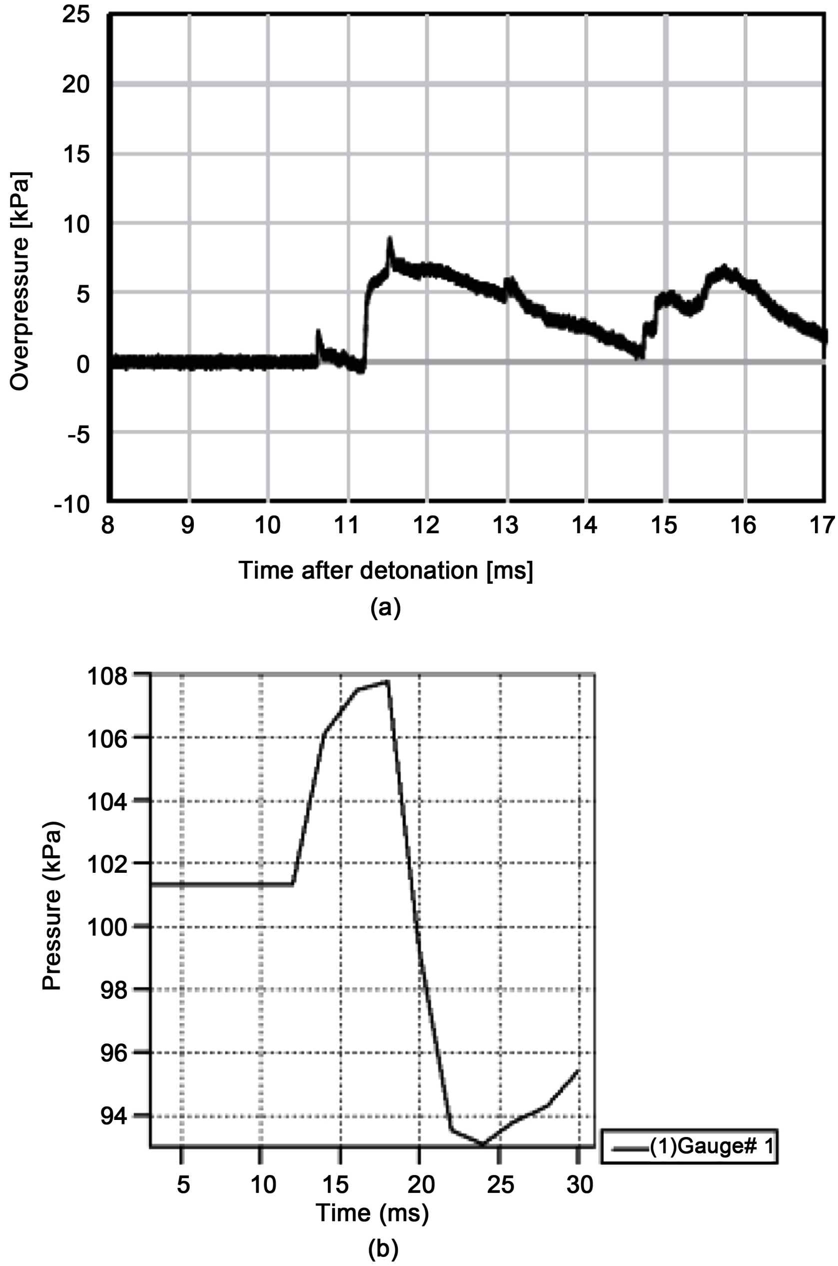


Figure 4. (a) P-T curve of the experimental test. (b) P-T curve of the numerical simulation.

detect the geometrical shape which gives the best performance in the mitigation of the blast wave resulting from the detonation.

Two structural configurations are considered for this study named TCP, and PCP. For the sake of comparison, all the compared configurations have the same weight and height as shown in **Figure 6**.

2.4. Finite Element Model

In this model, the traditional flat barrier wall target is modeled with 1960 element

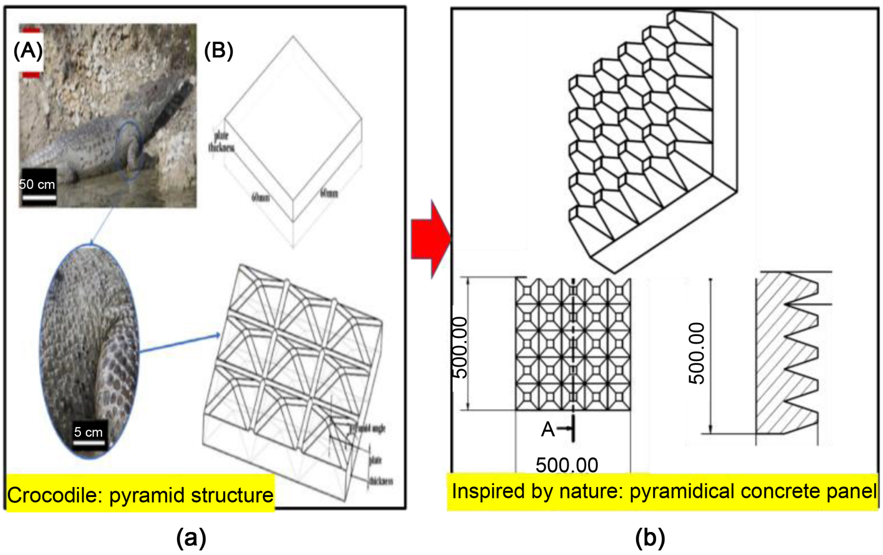


Figure 5. (a) Crocodile: pyramid structure [8], (b) new bio-inspired proposed structure configuration.

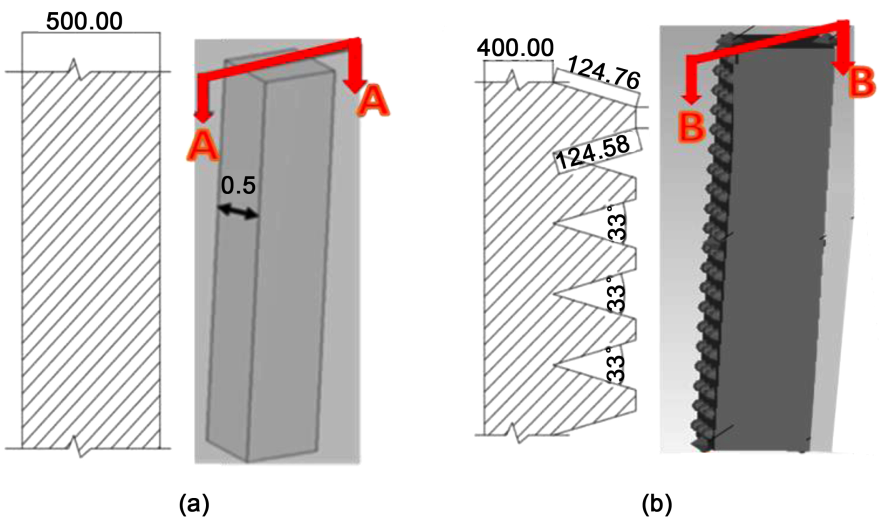


Figure 6. Structural configuration of the proposed model. (a) TCBW. (b) PCBW.

while for the bio-inspired pyramidical concrete panel target, it is modeled with 1400 element and the air domain is modeled with 1,215,555 elements and 1,254,400 nodes as shown in **Figure 7**. The concrete used in the barrier wall has a compressive strength of 35 Mpa.

The properties of the used materials are shown in **Table 1**.

The technique that used in the numerical simulation was Remap. The initial detonation and blast wave expansion of the explosive in free air were first calculated in a 2D domain, the result was then recalculated into a 3D space. This leads to save time and make the model more accurate.

Flow-out boundary conditions that was utilized on the outer surfaces of the air domain to enable the pressure of the blast to be wasted outside the air domain

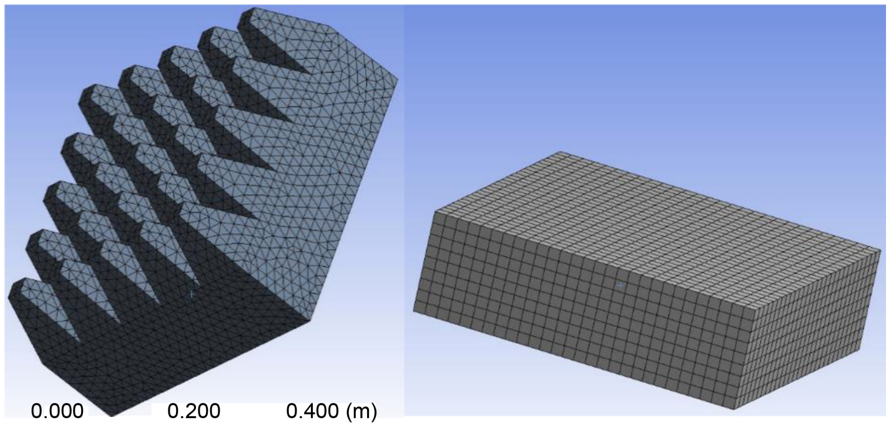


Figure 7. Meshing of the proposed TCP, and PCP models.

Table 1. Properties of used materials.

Material	Equation of state	Strength model	Reference density	Shear modulus
Concrete	P-alpha	RHT	2.75	1.67e7
Comp. B	JWL	-	1.71	-
Air	Ideal gas	-	1.225×10^{-3}	-

without reflecting and making any effect on the concrete target.

The concrete target is qualified with the Lagrange solver. Comp B is modeled using Jones-Wilkins-Lee equation of state which simulates the pressure generated by chemical energy in an explosion. Air was modeled by an ideal gas equation of state, which is considered as the simplest forms of equation of state.

3. Numerical Results and Discussions

This section presents and discusses the results of different pressure gauges placed in different locations on the concrete wall barrier and behind it as shown in Figure 8 to show the response of different shapes of the barrier walls.

Table 2 discussed the peak pressure reached for each gauge for the proposal models. The pressures vs. time histories are discussed at each gauge to make the comparison of the peak pressure at the proposed models. Also, the response of the wall barrier on the pressure behind the wall is also investigated by evaluating the pressure at gauge 7.

Gauge 1 is in the middle lower part of the concrete barrier. As shown in Figure 9, the results of pressure measured on this gauge shows different values of different barrier shapes and configurations on the pressure obtained in this location as we see that when comparing the pressure measured at gauge 1 for TCBW and for PCBW, the pressure measured at PCBW was 200 kpa which is slightly lower than that measured at TCBW (232 kPa). Also, Gauge 2 is in the middle part of the concrete barrier. As shown in Figure 10 the results of pressure

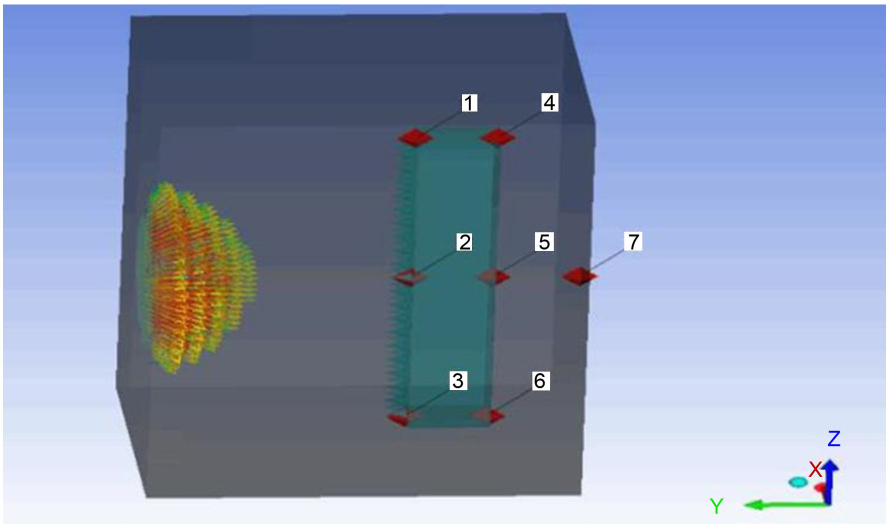


Figure 8. Locations of added gauges.

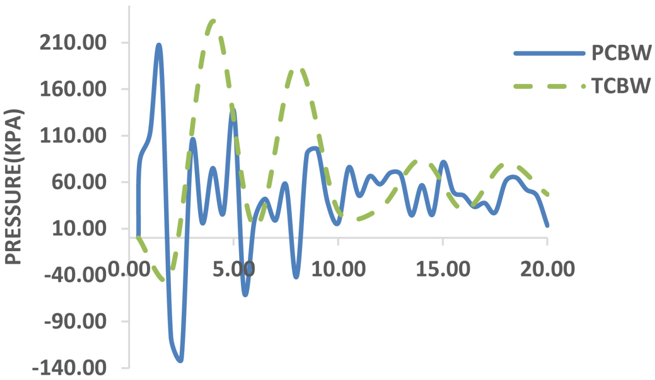


Figure 9. Pressure-time history for gauge 1.

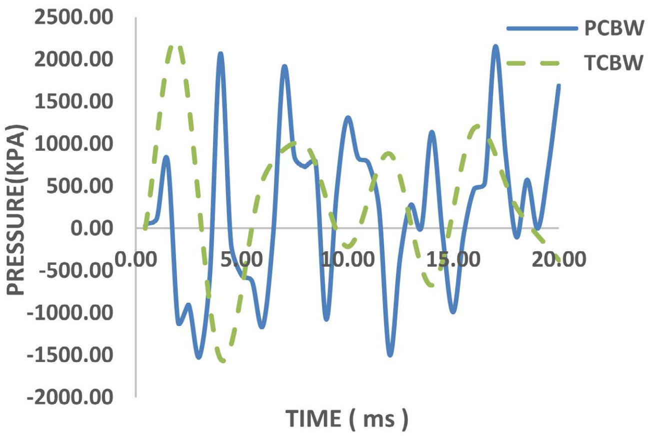


Figure 10. Pressure-time history for gauge 2.

founded on this gauge shows different values of different barrier shapes and configurations on the pressure measured in this location as the pressure obtained in the model TCBW is the highest When model PCBW pressure decreased to 2151 kPa.

Gauge 3 is in the upper middle part of the concrete barrier. As shown in Figure 11, the values of pressure obtained on this gauge shows different responses of different barrier shapes and configurations on the pressure obtained in this location as the pressure obtained on the TCBW is lower (313 kPa) than the pressure obtained on the model PCBW (319 kPa). Gauge 4 is in the lower middle part of the concrete barrier in the back face. As shown in Figure 12, the values of pressure obtained on this gauge shows different responses of different barrier shapes and configurations on the pressure obtained in this location as the pressure obtained in the model TCBW is higher (470 kPa) than the pressure obtained in the model PCBW 358 kPa.

Gauge 5 is in the middle part of the concrete barrier in the back face. As shown in Figure 13, the values of pressure obtained on this gauge shows different responses of different barrier shapes and configurations on the pressure obtained in this location as the pressure obtained in the model TCP is 2845 kPa which is lower than the pressure obtained on the model PCP (3355 kPa). But

Table 2. Peak pressure for gauges.

Barrier walls Shapes	TCBW	PCBW
Gauge no.	Peak pressure (kPa)	
1	233	200
2	2203	2151
3	313	319
4	470	358
5	2845	3355
6	870	683
7	282	239

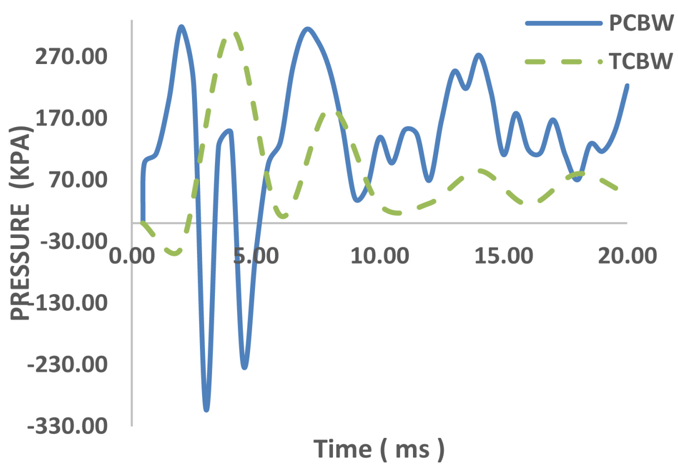


Figure 11. Pressure-time history for gauge 3.

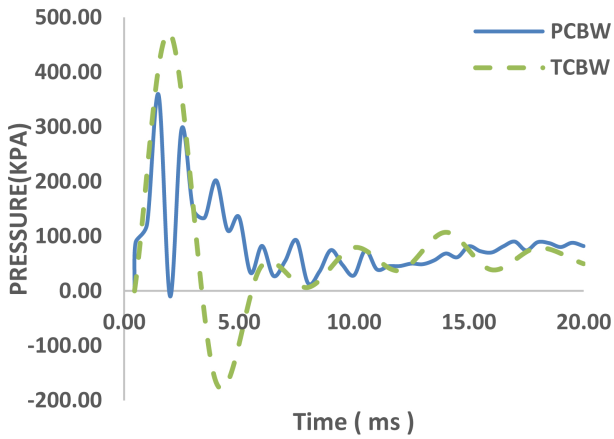


Figure 12. Pressure-time history for gauge 4.

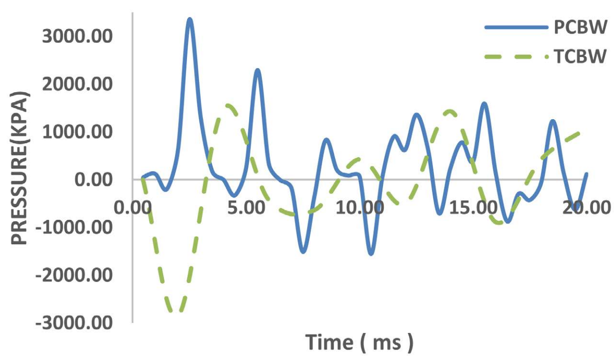


Figure 13. Pressure-time history for gauge 5.

when the model CCP pressure decreased to 1591 kPa. Gauge 6 is in the upper part of the concrete barrier in the back face. As shown in Figure 14, the values of pressure obtained on this gauge shows different responses of different barrier shapes and configurations on the pressure obtained in this location as the pressure obtained on the flat wall in the model TCP is 870 which is higher than the pressure obtained in the model PCP (870 kPa) but when model CCP pressure decreased to 550 kPa and then it increased once again to 683 kPa when at the model PCP.

Gauge 7 is at a distance 1.5 m behind the concrete barrier and this gauge shows the variation of the response of the explosion on any object or any living organisms behind the barrier. As shown in Figure 15, the pressure obtained on the flat wall in the model TCP has a high value (282 kPa) then the pressure changed in the model PCBW to 227 Kp.

As we can see here from Table 1 and Figure 15 that the max pressure at gauge 7 (located at 1.5 m behind the wall barrier) has its maximum value (282 kPa) for the model TCBW where the figure shows the least area of the barrier wall affected by the blast wave and then as the area of the barrier wall affected by the blast wave increases the pressure recorded at gauge 7 decreases as it reaches 239 kPa in the model PCBW with a percentage of decrease of 19.5%.

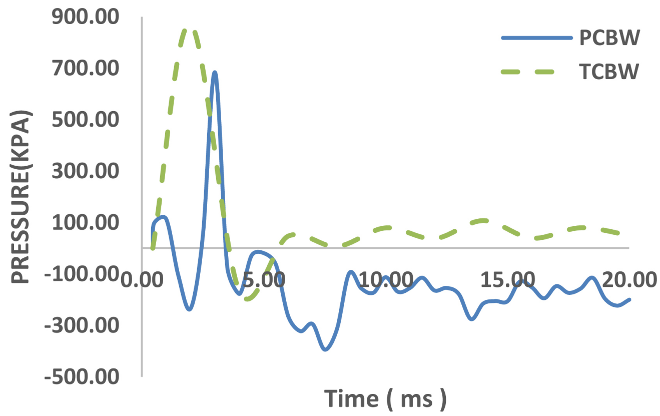


Figure 14. Pressure-time history for gauge 6.

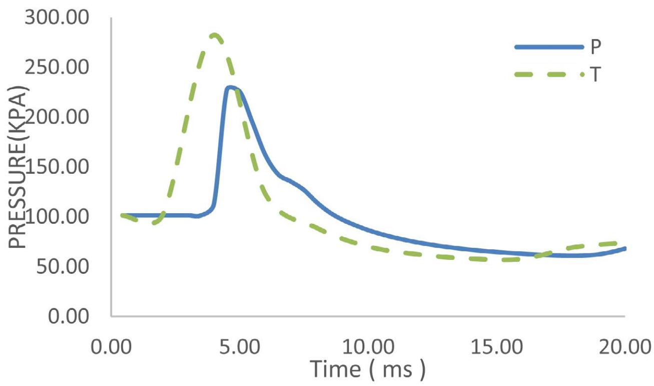


Figure 15. Pressure-time history for gauge 7.

4. Conclusion

The engineering Biomimicry technique can be very powerful in conducting a protection barrier walls designs against the blast waves and that combination will distort, absorb, and reflect the blast waves, therefore the current study studies the effect of different geometrical configurations of concrete wall barrier inspired from nature against blast waves. The non-linear 3d numerical model is used to model the proposed configuration. The response of the proposed structural configurations of the wall barrier is analyzed. The numerical model presented has a good verification with the experimental work in the validation. After making the comparison of the different structural configurations proposed in our study, the new bio-inspired pyramidical structure configuration (PCBW) has a notable effect on the mitigation of blast hazards which gave the best performance for the protection of the area behind the wall barrier with 19.5% with respect to traditional concrete barrier wall (TCBW). Moreover, it is concluded that the nature inspiration has a great effect on designing new protection systems against different types of loads.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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