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Modeling and Simulation of Honeycomb Steel Sandwich Panels under Blast Loading

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***Abstract*—**Honeycomb sandwich panels have been widely used as protective structural elements against blast loading. The main advantages of these panels include their light weight due to the presence of voids, as well as their energy absorption capability. Terrorist activities have imposed new challenges to structural engineers to design protective measures for vital structures. Since blast loading is not usually considered in the load combinations during the design process of a structure, researchers around the world have been motivated to study the behavior of potential elements capable of resisting sudden loads imposed by the detonation of explosive materials. One of the best candidates for this objective is the honeycomb sandwich panel. Studying the effects of explosive materials on the panels requires costly and time-consuming experiments. Moreover, these type of experiments need permission from defense organizations which can become a hurdle. As a result, modeling and simulation using an appropriate tool can be considered as a good alternative. In this research work, the finite element package ABAQUS® is used to study the behavior of hexagonal and squared honeycomb steel sandwich panels under the explosive effects of different amounts of trinitrotoluene (TNT). The results of finite element modeling of a specific honeycomb configuration are initially validated by comparing them with the experimental results from literature. Afterwards, several configurations including different geometrical properties of the honeycomb wall are investigated and the results are compared with the original model. Finally, the effectiveness of the core shape and wall thickness are discussed, and conclusions are made.

***Keywords*—**Blast loading, finite element modeling, steel honeycomb sandwich panel.

I. INTRODUCTION

TERRORIST attacks such as bombing of the marine barracks in Beirut (1983), the Khobar Towers in Saudi Arabia (1996), the governmental building in Oslo (2011) and bombings of U.S. embassies in Nairobi, Kenya and Dar El-Salaam, Tanzania in the past years show increasing number of bombings worldwide toward important structures. Such incidents alarmed structural engineers to develop methods of design and analysis to protect citizens and properties against blast loads. In this work, honeycomb sandwich panels serve in absorbing energy released by a bomb. Studying explosion effects on the panels require experimental work known to be costly and time consuming. Moreover, these kinds of explosive based experiments are not easy to implement, and permissions from the defense organizations are necessary. The other alternative is to use a simulation program which is preferable as compared to experimental works due to its lower cost and time consumption.

Additionally, reduction of mass while maintaining same level of strength has always been considered a challenging optimization problem. Recently, honeycomb sandwich panels are replacing monolithic structures due to their lightweight, high stiffness and strength, and durability. Now, researchers are focusing on studying the effect of blast loading on sandwich panels that are known for absorbing energy and managing the impulse associated with blast loading. Zhu and Lu [1] studied the characteristics of blast loads and its corresponding structural response and concluded that structures affected by blast wave can undergo large inelastic deformation, tearing, or transverse shear failure at the support. Xue and Hutchinson [2] focused more on studying the effect of a square core sandwich plate in absorbing blast wave. Dynamic effects were studied and identified showing its contribution in strengthening the core using continuum model software. Square-core sandwich panels showed high energy absorption and crushing strength. Fleck and Deshpande [3] analyzed the blast resistance of clamped sandwich beams. Experimental tests were conducted by Dharmasena et al. [4] to study the dynamic mechanical response of square honeycomb core sandwich panels. They have shown that the square honeycomb panels are capable of withstanding air blast loads.

In this paper, the finite element method (FEM) package ABAQUS® is adopted to model steel square and hexagonal honeycomb sandwich panels with different cell wall thicknesses. The dimensions of the sandwich panel are selected to be similar to the work done by Dharmasena et al. [4].

II. THE BLAST LOAD

An explosion by definition is a large-scale, rapid and sudden release of energy. Explosives can be classified on their basis of their sensitivity to ignition. They are classified as either primary or secondary explosives. Among these, primary explosives are the ones that can be easily detonated by a simple ignition from a spark, flame or any form of impact. Mercury fulminate and lead azide are such primary explosive materials. But secondary explosives are the ones that when detonated, create blast (shock waves), causing widespread

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damage to the surroundings. TNT and ammonium nitrate fuel oil (ANFO) are examples of secondary explosives. Condensed high explosives generate hot gases under pressure up to 300 kbar, with temperatures of about 3000-4000 °C. This hot gas then expands, forcing out the volume that it occupies. This blast wave increases to a value of pressure, much above the ambient atmospheric pressure. It is referred to as the side on overpressure which decays as the shock wave goes further away from the explosion center. This pressure behind the front will drop below the ambient pressure within a short time and create a negative phase, which is basically a partial vacuum, as air is sucked in. This effect is accompanied by high suction winds that blow debris far away from the explosion source.

The threat of a bomb can be defined by two elements, both being equally important. The first is the bomb size, or the charge weight W, while the second is the standoff distance R between the blast source and the target. Fig. 1 shows a typical blast pressure profile.

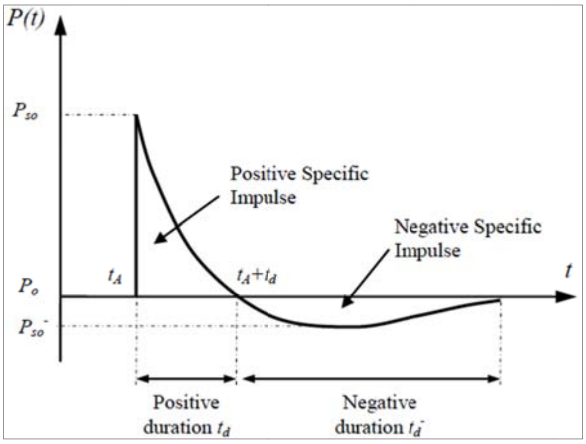


Fig. 1 Time history of blast wave pressure

At the blast arrival time t_A, after the explosion, there is a sudden increase in pressure, leading to the formation of a peak value of overpressure P_{so}, over the ambient pressure P_o. The pressure then decays suddenly to ambient level after duration t_d, then decays further to an underpressure P_{so}^- (creating a partial vacuum) before finally returning to ambient conditions at time $t_A + t_d + t_d^-$.

III. SANDWICH PANEL CONFIGURATIONS AND MODELING

Dharmasena et al. [4] used square honeycomb sandwich panels in their experimental work. All panels were subjected to large bending loads at the centre. Through welding of the core webs and face sheets, large contact area was achieved creating high strength joints. Xue and Hutchinson [2] have shown that sandwich core relative densities in the 3-10% range are of most interest for blast resisting structures. For such attribute, all square honeycomb core panels were designed and fabricated to achieve a core with a relative density of approximately 6%. They had a thickness of 5 mm for the front and back plate and 51 mm for the core. The square core is formed as 0.76 mm thick webs and 5 mm flange width spaced evenly at a distance of 30.5 mm. In their experimental work, TNT explosives were used and set 100 mm away from center of the square sandwich panel with mass charges of 1, 2 and 3 kg.

The material used to create sandwich structure was high ductility stainless steel alloy (AL6XN) composed of 49% Fe, 24% Ni, 21% Cr, and 6% Mo by weight. It was modeled as a rate dependent plastic material, with Johnson-Cook model for strain hardening and rate dependency. The values of the constants were: A = 400 MPa, B = 1500 MPa, C = 0.045, n = 0.4, m = 1.2, $\dot{\varepsilon}_o$ = 0.001 s^{-1}, T_{tr} = 293 K, T_m= 1800 K, and C_p = 452 J/kg-K. The mechanical properties for the AL6XN were obtained from Nahshon et al. [5] with E = 161 GPa, ν = 0.35 and ρ = 7850 kg/m^3. The dimensions of the panel used in their experimental study are 610 mm × 610 mm (see Fig. 2).

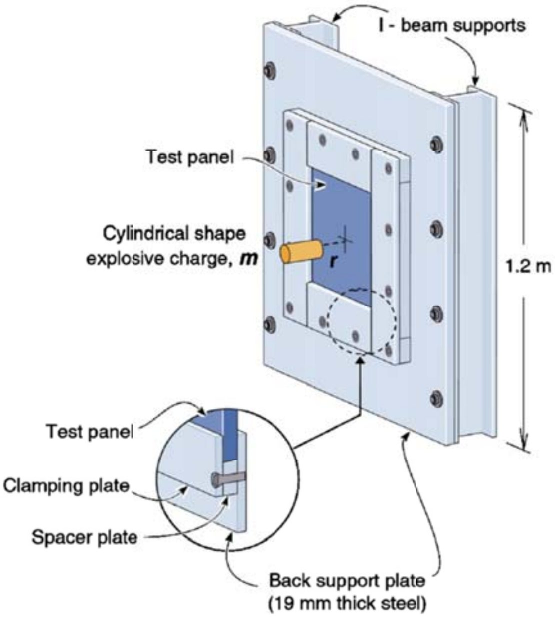


Fig. 2 Schematic arrangement for air blast test [4]

In terms of modeling, a square honeycomb sandwich panel, similar to that one used in the experiment, is initially created. Due to symmetry conditions, only one quarter of the geometry (305 mm × 305 mm) is being modeled (see Fig. 3). It contains vertically and horizontally aligned webs of 0.76 mm thickness. Firstly, the model of honeycomb core was created in AutoCAD 3D, then it was imported into ABAQUS®. Later, top plate and bottom plate were produced by this tool. The conventional explosives were detonated at a fixed distance (100 mm) from the front plate of the square honeycomb core panel. The charge mass of TNT detonated was 1 kg, 2 kg and 3 kg.

The top and bottom plates were discretized using 31×31×5 mm continuum-3D eight-noded solid elements with reduced integration (C3D8R). The core was discretized using 30 four-noded bilinear shell elements with reduced integration (S4R), along the height of the core.

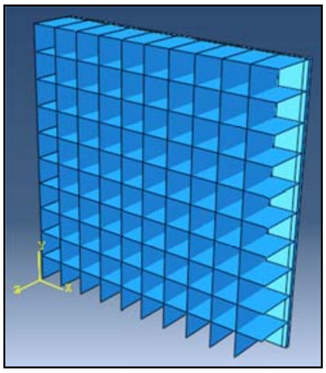
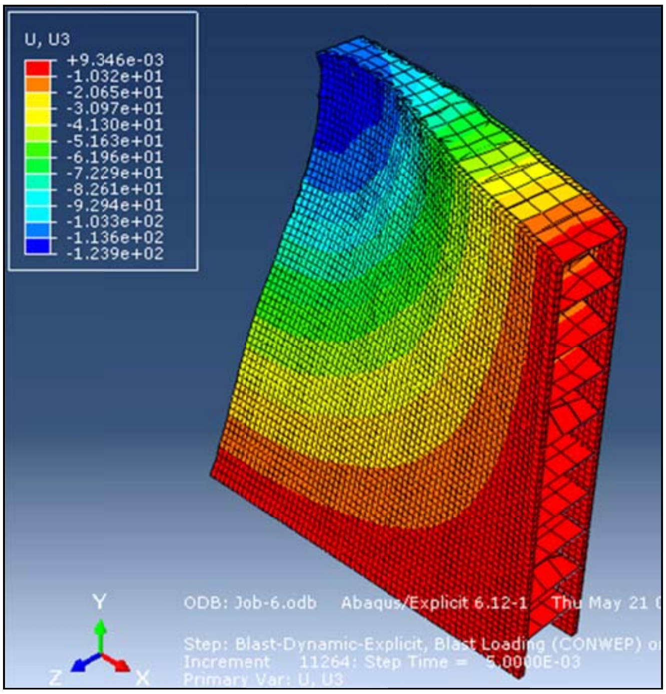


Fig. 3 FEM model of honeycomb panel (front plate not shown)

Overall, the simulations capture the major deformations with buckling and significant folding of the inner webs as displayed by the animation of the deformed plate over the entire time period of 1.5 milliseconds (see Fig. 4). It shows large deformations at the center and the plate stabilizes after a few oscillations.

As for all hexagonal honeycomb core panels, they are considered to be symmetrical homogenous panels with isotropic material as well. All hexagonal honeycomb panels have consistent dimension except for the thickness of the cell walls. The front and back plates are 5 mm thick, and the height of the hexagonal core is 51 mm. In this work, the hexagonal and the square honeycomb sandwich panels have the same overall thickness of 61 mm. The hexagonal core dimension was obtained from Nayak et al. [6]. It is shown in Fig. 5.



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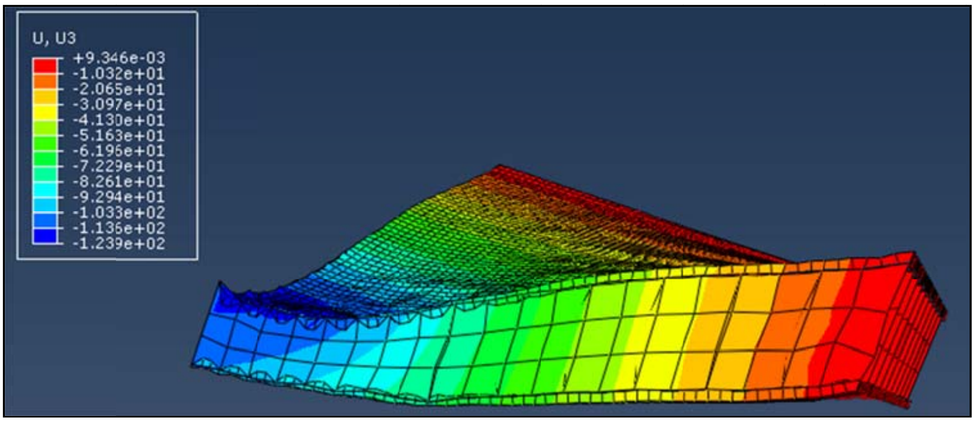

(b)

Fig. 4 Deflection of honeycomb panel (3kg TNT): (a) front view; (b) side view

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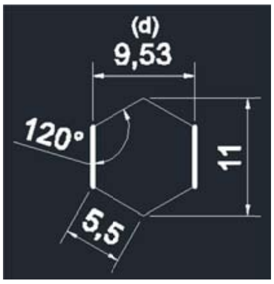


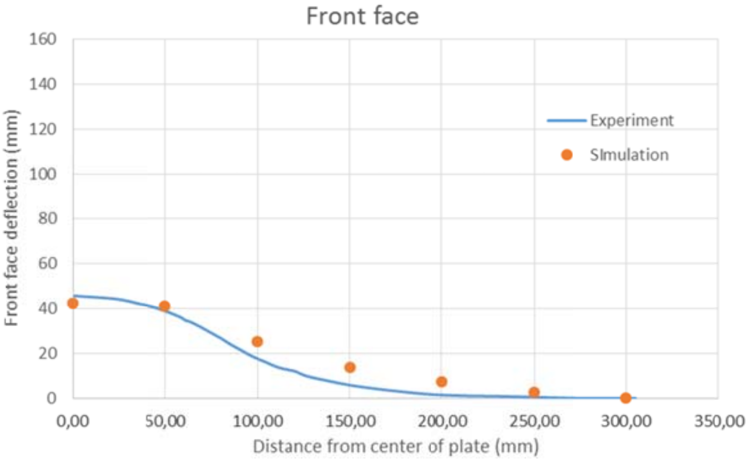
Fig. 5 Hexagon cell dimensions [6]

During simulation, the cell wall thickness has been changed to study its effect on the energy absorption capacity and the deflection of the sandwich panels. The thicker sides shown in Fig. 5 represent cell walls with double thickness (2*t*) to simulate the honeycomb manufacturing. Different cell wall thicknesses of 0.1, 0.25, 0.5 and 0.76 mm have been used.

IV. Results and Discussions

The results of square honeycomb simulations are shown in Figs. 6-8 and are compared with the experimental results from literature [4].

It is clear that the deformations recorded in the experiment and the simulation are in good agreement for the front plate of the panel for 1 kg and 2 kg of TNT explosions. In all other cases, simulations showed slightly different values for front and back plate deflections. This could be because the equipment and tools that were used in the experiment, not being properly defined in the reference research paper. Another reason can be the fact that the reported displacement is the final permanent displacement in experimental setup, whereas the maximum displacement during the blast was reported in simulations. Comparing simulation work to the experimental work verifies the efficiency of the FEM model.



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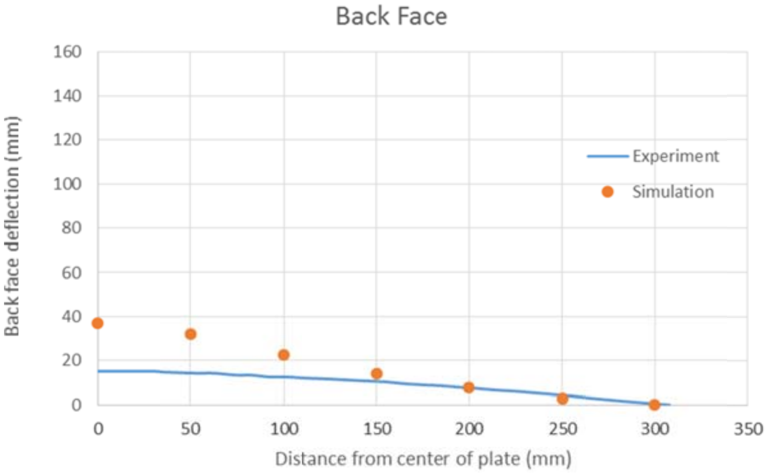

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Fig. 6 Deflection vs. Distance from the center of plate (1 kg TNT): (a) front plate; (b) back plate

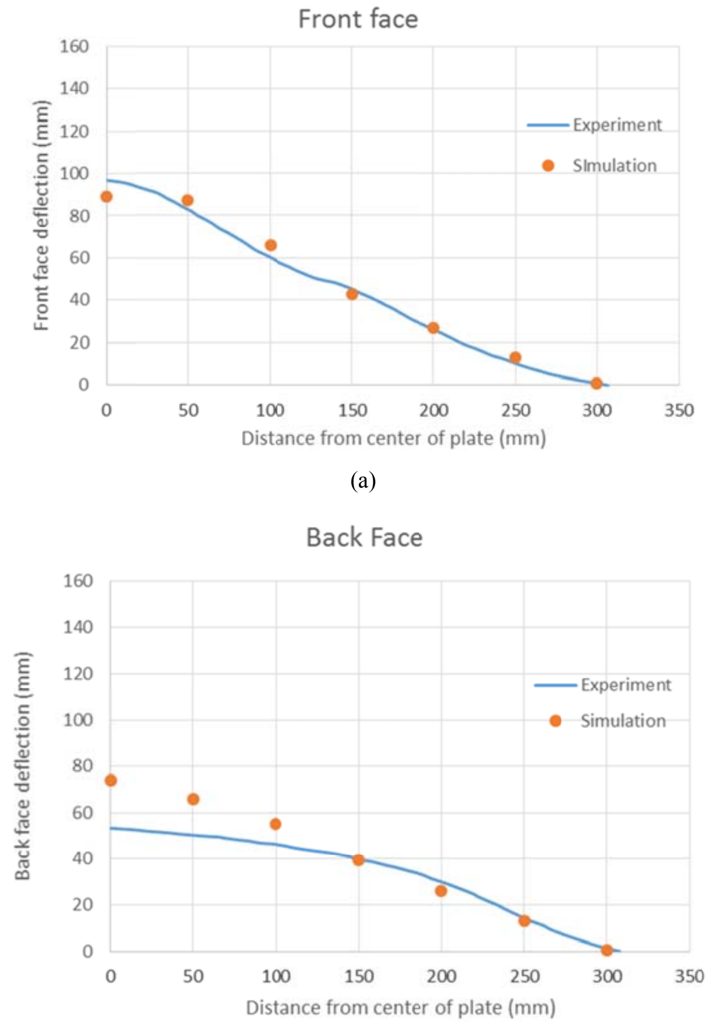

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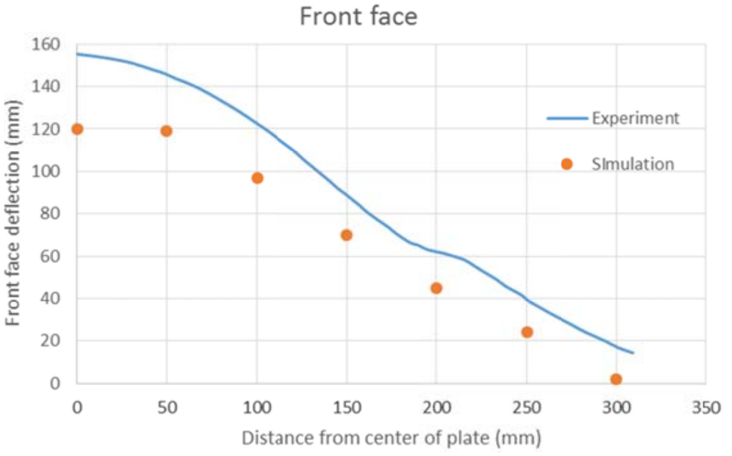
Fig. 7 Deflection vs. Distance from the center of plate (2 kg TNT): (a) front plate; (b) back plate



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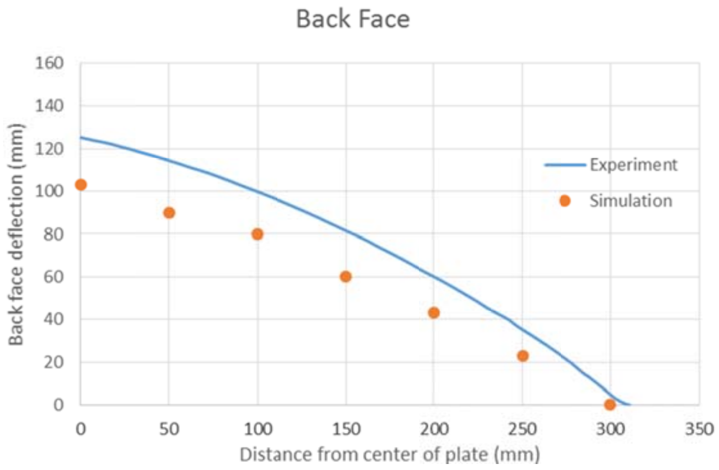

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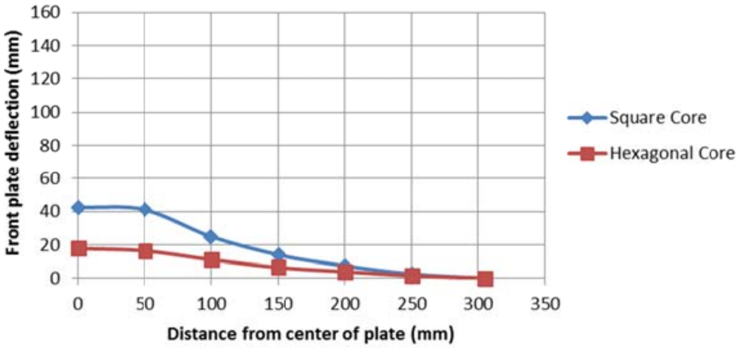
Fig. 8 Deflection vs. Distance from the center of plate (3 kg TNT): (a) front plate; (b) back plate

The same procedures were followed in modeling the hexagonal sandwich panels described earlier. Deflections of the hexagonal honeycomb core panels were compared to those of the square panels with similar wall thickness (i.e. 0.76 mm) and shown in Figs. 9-11. Simulation of hexagonal and square core sandwich panels show that the core shape has a great influence on the deflection of the front and back plates. By comparing all panels subjected to 1 kg, 2 kg and 3 kg of TNT, the deflection has decreased almost by 40% to 60%.

Hexagonal core sandwich panels are able to withstand higher blast loads due to the increased number of cell walls (six sides instead of four) and increase of structural and flexural rigidity.



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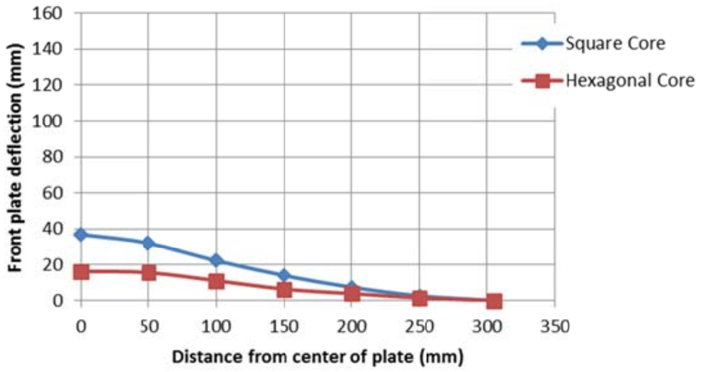

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Fig. 9 Comparison of deflections in square and hexagonal core panels (1 kg TNT): (a) front plate; (b) back plate

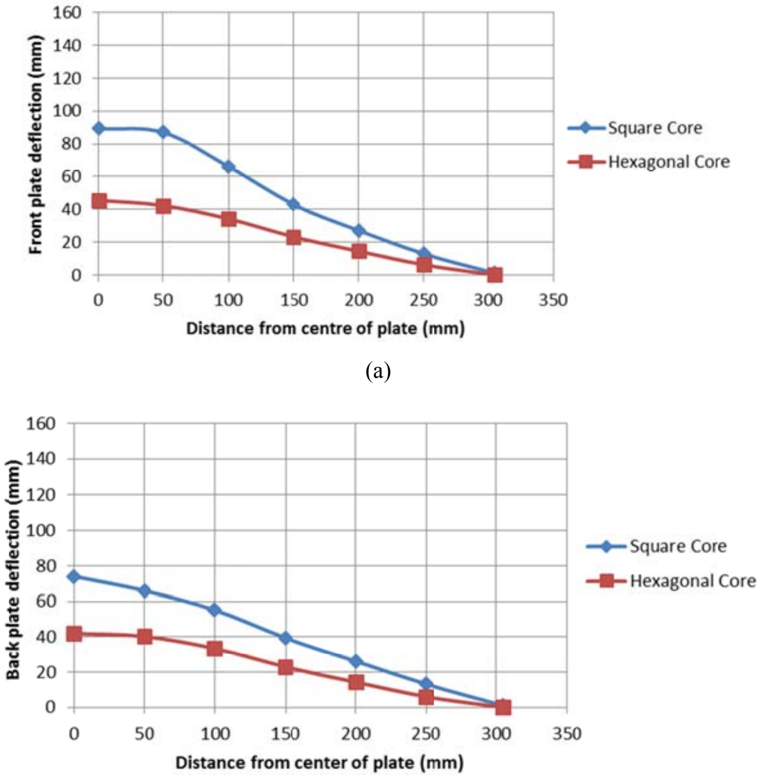

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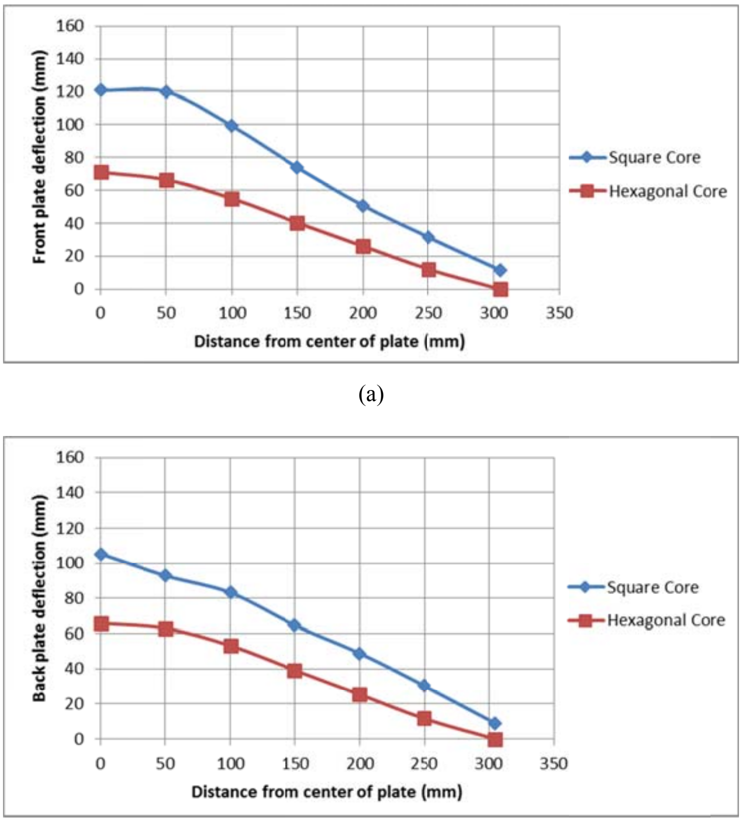
Fig. 10 Comparison of deflections in square and hexagonal core panels (2 kg TNT): (a) front plate; (b) back plate



(a)

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Fig. 11 Comparison of deflections in square and hexagonal core panels (3 kg TNT): (a) front plate; (b) back plate

The effectiveness of the hexagonal cell wall thickness has been investigated, and results for different thicknesses are presented in Figs. 12-14.

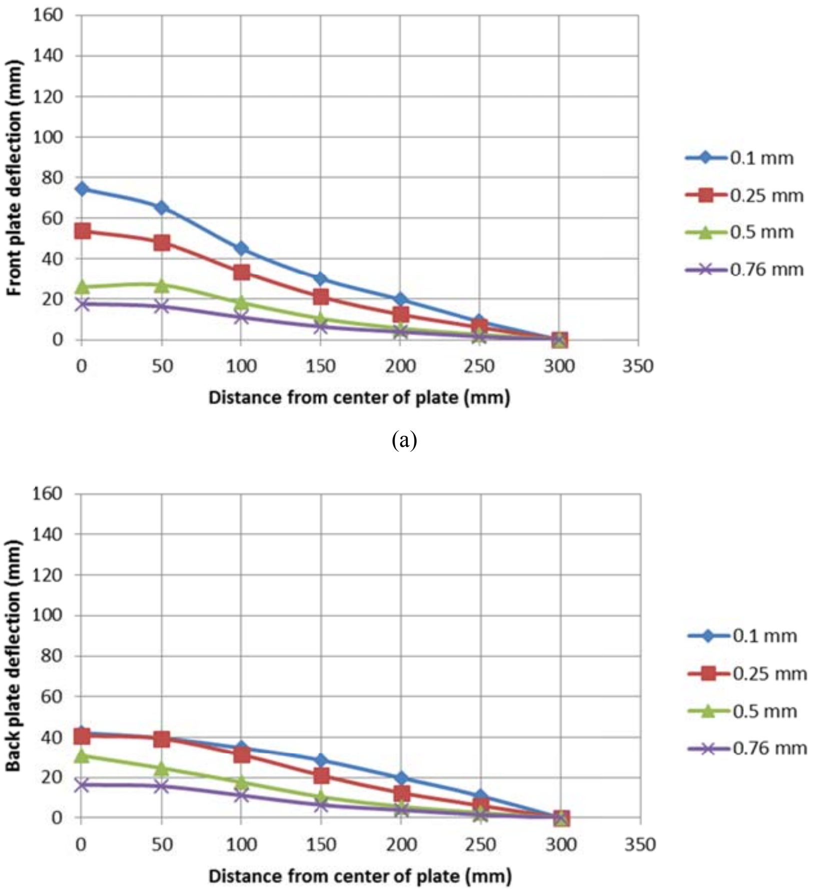

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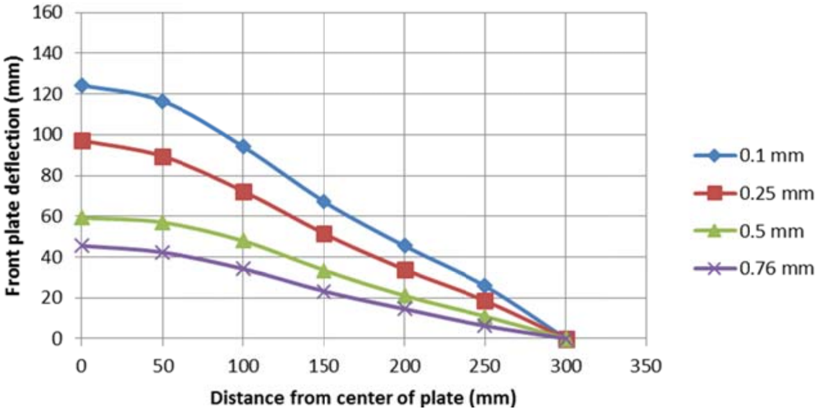
Fig. 12 Comparison of deflections of hexagonal core panels at different thickness (1 kg TNT): (a) front plate; (b) back plate



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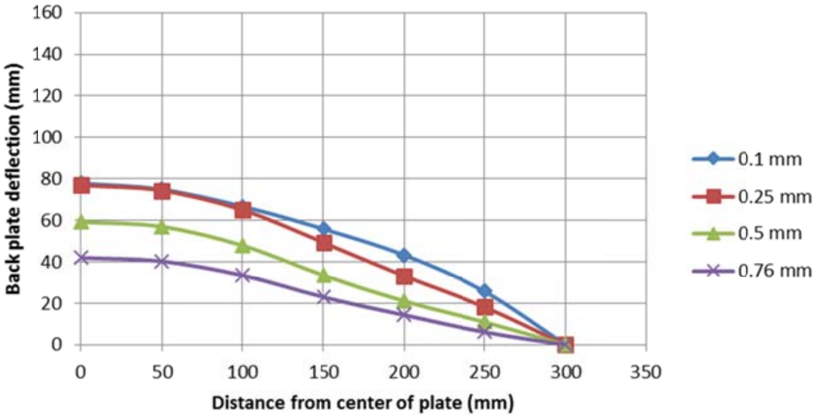

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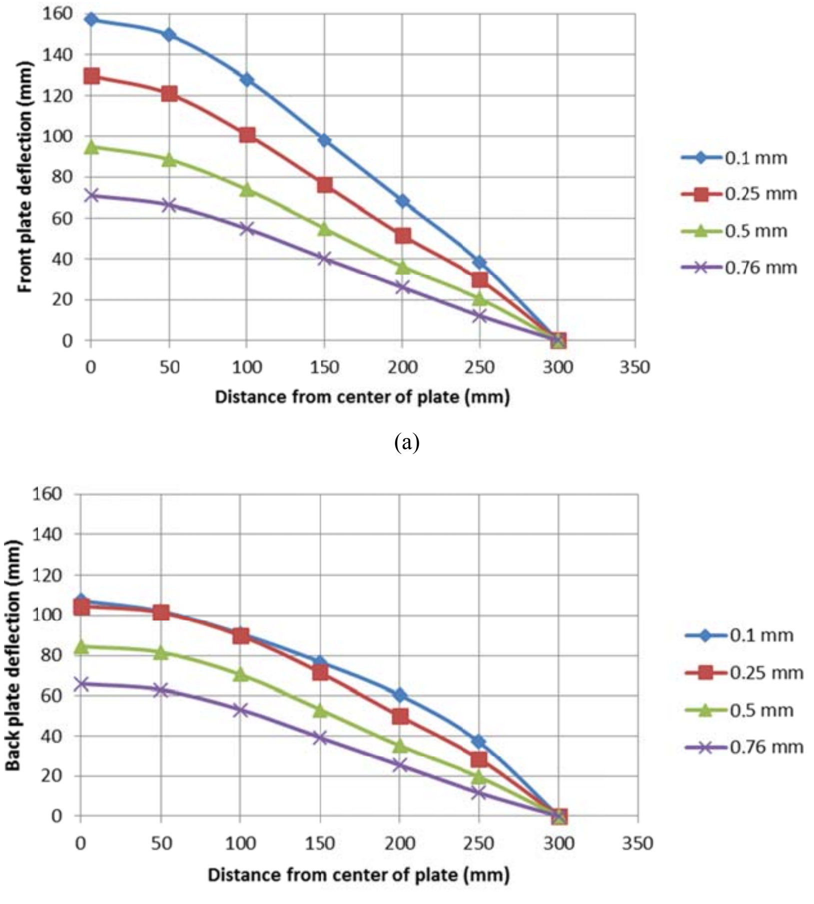
Fig. 13 Comparison of deflections of hexagonal core panels at different thickness (2 kg TNT): (a) front plate; (b) back plate



(a)

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Fig. 14 Comparison of deflections of hexagonal core panels at different thickness (3 kg TNT): (a) front plate; (b) back plate

V. CONCLUSIONS

In this work, it has been proved that honeycomb steel sandwich panels can effectively be implemented as an appropriate means against the terroristic attacks to important buildings. Two different configurations, square vs. hexagonal, have been investigated and it has been concluded that the hexagonal core shape is more effective for the same wall thickness. Finally, the effectiveness of core wall thickness in hexagonal configuration has been studied and results were presented.

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