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Numerical and Experimental Study of the Use of Mineral Pumice in the Core of the Sandwich Panel to Absorb the Shock Wave

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Abstract

Reducing the effects of unwanted shocks and waves is a very common problem in engineering. Some materials, due to their inherent properties, can be used as energy absorbers, such as foams, porous materials, and granular materials. porous granular materials that were considered in this study due to their low density and energy absorption capacity. But to use the granular material as the core of the sandwich panel, you have to think of a way to hold the granules together. In this article, using molding with resin, aluminum and polyurethane foam, an attempt has been made to make cores for sandwich panels from mineral pumice. the use of foam showed better performance than the other two materials. These adsorbents have the property of substrate flexibility and impact absorption and low density of porous materials at the same time. The properties of the core were obtained using a pressure test and used in software. Explosion experiments are free and Abaqus software is used in the simulation. The results show that the panel with a thicker back cover has a better performance in absorbing explosion energy. Increasing the thickness of the core has also increased energy absorption.

Keywords

energy absorption, polyurethane foam, pumice, explosion

1 Introduction

An engineering structure can be subjected to different loads depending on its application and location of use during its lifetime. One type of load that a structure may face is impact or explosive load. Impact loading is very common and can be seen in various structures such as car chassis, car bumpers and columns during accidents, crushers, etc. The use of materials such as metal foams and polyurethane to absorb explosive energy and reduce its damage is common, which is due to the high ability of these materials to absorb energy. In addition, relatively inexpensive granular materials such as sand, iron filings, mineral pumice, soot, etc. can provide a suitable substrate for the shock wave damping caused by the explosion.

Porous and granular materials have been considered in various protective applications due to their effect of reducing shock waves. The special complexities governing the behavior of grain environments have made it impossible for many models defined for them to accurately predict the behavior of grain materials in the face of shock waves. On the other hand, the complexity of the governing equations causes that the numerical solution of these equations is also associated with many computational problems and costs [1]. Therefore, a lot of work has been done experimentally and numerical simulation in this field.

Levy [2] uses the state model developed for porous materials for granular materials and the one-dimensional state of these equations is solved by numerical code and shows that it is a good agreement compared to the experimental work of other researchers. In a study by Britan et al. [3], a study on shock wave reduction in granular filters was performed. In this study, the effect of parameters such as particle shape has been neglected and it has been determined that the use of one-dimensional models to simulate them can be in good agreement with reality. They found that by increasing the filter length or decreasing the particle diameter, the amplitude of the output shock wave decreases and the particle density and lateral friction do not have much effect on reducing the gas pressure in the filter.

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Vitali F. Nesterenko [4] in a laboratory study entitled "Shock (Blast) Mitigation by "Soft" Condensed Matter" investigated the effect of using excavation in a metal tank in an explosion test. It has been observed that by using this material, the deformation rate of the tank has been drastically reduced and its destruction has been prevented. Hangai et al. [5] have investigated the effect of porosity and structural cavities on the compression properties of aluminum foam. The foam made in this research was cast. Shim et al. [6] investigated shock wave attenuation in structures protected by aluminum foam.

For this purpose, they have used experimental testing and numerical simulation with LS-DYNA software. Vesenjak et al. [7] investigated the behavior of metal foams under explosion load using numerical simulations and experimental tests. Mahmoud et al. [8] investigated explosive loading on reinforced concrete slabs with aluminum foam boards. Rotariu et al. [9] investigated the measurement of pulse attenuation in environments of porous granular materials by experimental test method. They estimate the amount of wave attenuation using a square steel sheet behind a pack of granular materials by measuring the permanent change in angle of the sheet. Zhou et al. [10] investigated the geometric parameters and density gradients of the nucleus versus blast. For this purpose, the samples made were subjected to blast loading by free explosion test. Sun et al. [11] studied a sandwich panel with a metal foam core with a back and front plate made of aluminum, steel and carbon fiber alloys against blast. In this study, the deformation and failure modes, the effect of the dorsal and anterior plate material and the core density gradient on the deformation of the dorsal plate have been investigated. Bloodworth et al. [12] investigated the effect of foam inserts on their helmets against explosions. They studied the passage of the wave through their helmets and the damage they could do. The denser the foam, the stronger its effect. While various articles have reported that foams successfully reduce explosions after application at a certain thickness, this study has shown that many polyurethane open cell foams do not perform well in the limited volume of their caps.

Rahmani and Muslimi numerically investigated the use of a combination of mineral pumice and aluminum. In their research, using quasi-static pressure testing, they obtained the properties of aluminum casting specimens on mineral pumice and numerically simulated them. The behavior of this material against the blast wave was studied numerically, their study shows that this material has a behavior close to aluminum foam in both quasi-static and shock loading modes [13, 14].

The idea of using mineral pumice as an explosion absorber was a good idea due to its low density and high energy absorption. The problem is that because the ingredients are granular, they need fillers to hold the mineral shells together and create an integrated structure. For this purpose, in this research, an attempt is made to make a panel using the available common fillers, which in addition to eliminating this defect, also improves the absorption of explosive energy. Also, due to the novelty of this type of core for the panel, it is obvious that no numerical, experimental and analytical work has been done on these panels. Calculate the thickness and material of the back and top plate, the size of the mineral shell, the type of filler.

2 Numerical simulation

In order to extract the necessary parameters for numerical simulation, Compression testing is performed on standard samples. The aluminum and foam samples are shown in the Fig. 1. The samples are 80 mm long and 50 mm in diameter. Samples are made with two sizes of almond shell (with a maximum grain size 4 cm) and chickpea (with maximum grain size 1 cm). Samples with chickpea size pumice have a larger volume than shells and the density of samples with polyurethane foam is about 450 kg/m^3, samples with almond shells have a smaller volume of shells and their density is 370 kg/m^3. Fig. 1 shows samples made of aluminum and polyurethane foam, and Fig. 2 shows the steps of compressing the sample with polyurethane foam.

The compression tester device provides a displacement force diagram from which an engineering strain stress diagram can be obtained. The strain stress diagram of the sample with pea size pumice is shown in Fig. 3 and the core strain stress diagram with almond size pumice is shown in Fig. 4. The compression and fracture steps of the sample are numbered according to the numbers in Fig. 2 on the strain stress diagram of Fig. 3. According to the strain stress diagram, the behavior of the sample is almost elastic until just before

Fig. 1 Compression test samples

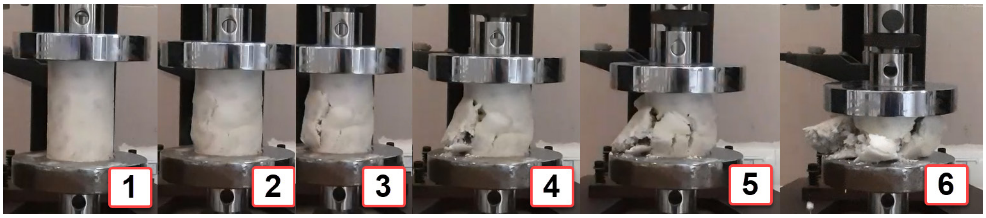


Fig. 2 Compression test (sample compression steps)

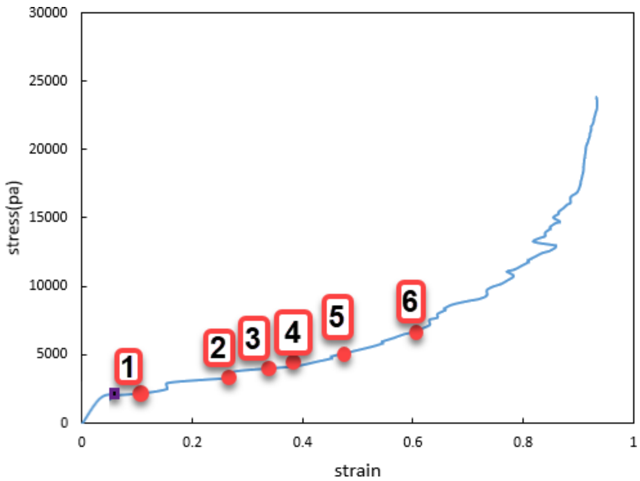


Fig. 3 Strain stress diagram from core compaction test with pea-sized pumice

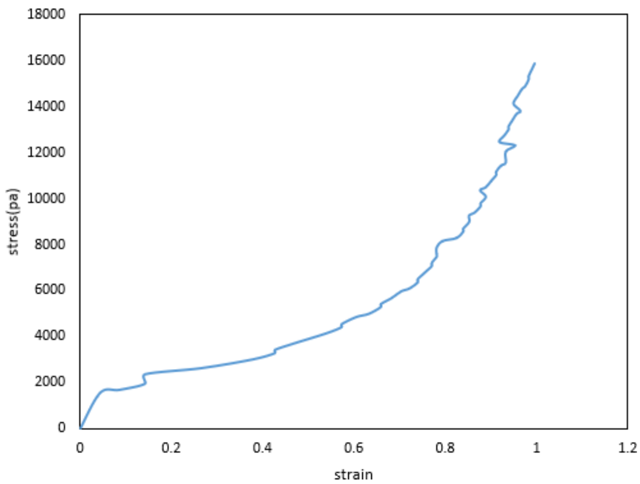


Fig. 4 Strain stress diagram from core compaction test with almond-sized pumice

point 1 (indicated by the small square sign). After point 1, the deformation of the sample becomes more intense, the sample becomes barrel-shaped, so far only the pumice grain inside the sample are crushed and no crack of foam is seen on the surface. At point 2, a crack forms in the wall of the sample and at point 3, this crack expands. at point 4, a part of the sample separates and other cracks are seen. at point 5, as the cracks increase, the rate of sample destruction increases; at point 6, the foam is almost completely destroyed. In Fig. 3, these points are shown on the obtained strain stress diagram.

According to the strain stress diagrams and its comparison with the foam behavior, it can be seen that the behavior of the samples in quasi-static loading is similar to foams, so the models used to simulate the foam behavior can be used to simulate Used core fabrication of a panel made of mineral pumice and foam. The diagrams show that the 450-density core has a relatively higher strength than the 370 kg/m^3 core. The behavior of samples made with aluminum casting is similar to aluminum foam in static loading but with higher strength [13, 14].

The aluminum sheets used for the sandwich panel procedures are 1100 series and the steel ones are 37 series, for which the mechanical properties used are presented in Table 1 [15, 16].

By using the values in Table 1, the elastic model of aluminum is determined. Due to the explosive load, the material is more likely to enter the plastic phase and fail. 1100 and 37 steel are presented in Tables 2 and 3 [15, 16].

In order to validate the simulation results, the results are first compared with the research done by Zhu et al. [17] The geometric characteristics as shown in Fig. 5 [17] were subjected to an explosion of 30 g of TNT at a distance of 20 cm from the panel.

Since the problem has a plane symmetry, there is no need to model the whole panel and a quarter of it can be modeled. Also, only one square with a side of 25 cm from

Table 1 Mechanical properties of AA1100 and St37 steel [15, 16]

	ρ (kg/m^3)	E (Gpa)	v	G (Gpa)
AA 1100	2710	75	0.3	25.5
St-37	7850	200	0.3	80

Table 2 Coefficients of Johnson Cook plastic model AA1100 and St-37 steel [15, 16]

Parameter	AA1100	St-37
$\dot{\varepsilon}$ (1/s)	0.1	0.1
A (Mpa)	135.43	217
B (Mpa)	319.13	233.7
n	0.24	0.5176
C	0.015	0.1056
melting point (C°)	670	1370

Table 3 Fracture coefficients of Johnson Cook model AA1100 and St-37 steel [15, 16]

	AA1100	St-37
D1	0.071	0.05
D2	1.248	3.44
D3	−1.142	2.12-
D4	0.147	0.002
D5	0	0.61

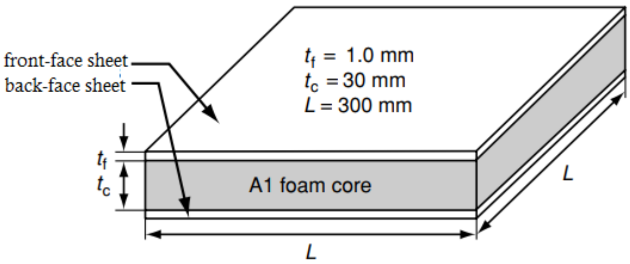


Fig. 5 Geometric dimensions of the validation problem adapted from [17]

the panel is exposed to the wave and the rest is under the gripping support. So a quarter of this square is modeled. The simulation results are compared in Table 4 [17].

The simulation is acceptable considering the percentage difference of the results and considering that the reference results obtained by the experimental test. The error can be attributed to the non-uniform boundary conditions and incompleteness of the characteristics presented in the reference article. A comparison of the deformation profiles of the panel after the explosion can also be seen in Fig. 6.

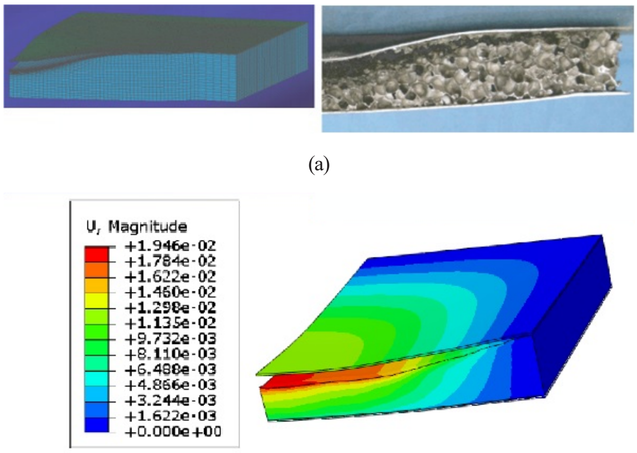
3 Experimental test

As mentioned, different substrate materials can be used to keep the pumice particles together. In this section, three methods of using resin, using foam and using aluminum are examined. Shock tubes have been used to initially evaluate the power of these panel cores to absorb energy. In these cases, the sheets on both sides of the panel are attached to the core using glue. Fig. 7 shows panels made of foam, resin and aluminum cores.

Araldite 2011 glue was used to glue the sheets to the core of the panel. This type of adhesive is a product of

Table 4 Comparison of the present results with Zho et al.'s [17] results

	Present simulation (mm)	Zhu et al.'s [17] simulation (mm)	Difference
Back face sheet	7.4	6.7	9.4
Front face sheet	11.5	10.2	11.3
Center of foam surface	19.46	21	7.2



(b)

Fig. 6 Comparison of simulation deformation (a) Zhu et al.'s [17] simulation and test, (b) present simulation

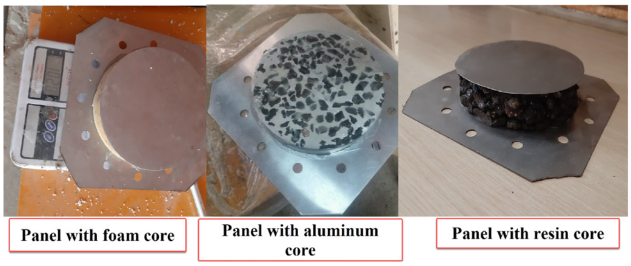


Fig. 7 Panel with three different types of cores

Hansman company. The adhesive properties are shown in Fig. 8 for a variety of materials.

For this research, a small explosive shock tube was used, the schematic map and its actual shape can be seen in Fig. 9. The specimens are attached to the mouth of the tube with 12 screws that assume that the edges of the specimen are trapped. The explosive charge is on the other side of the shock tube and the detonator wire comes out of the end.

The location of the explosive and the location of the panel closure are shown in the Fig. 10.

Fig. 11 shows the test results for coreless steel sheet. The sheet used is 1 mm thick and has an explosive charge of 8 g C4.

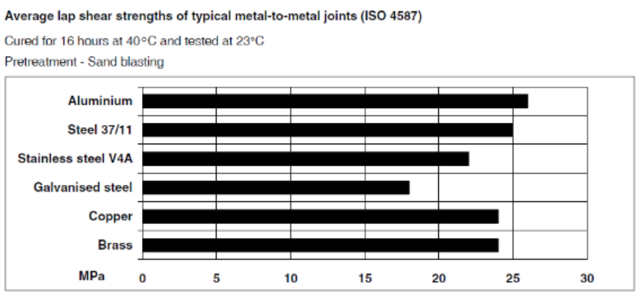


Fig. 8 Specifications of Araldite 2011 glue

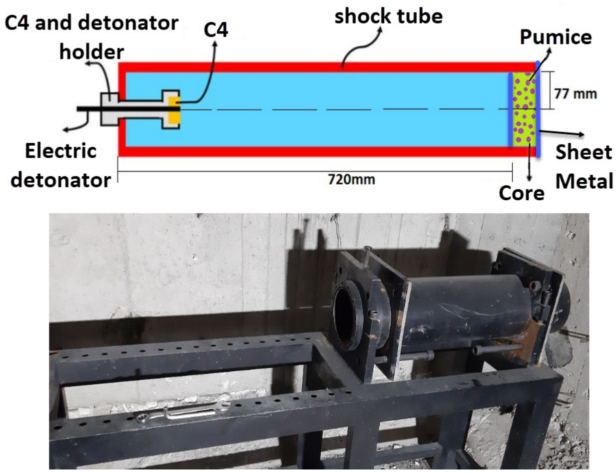


Fig. 9 Shock tube used in the experimental test

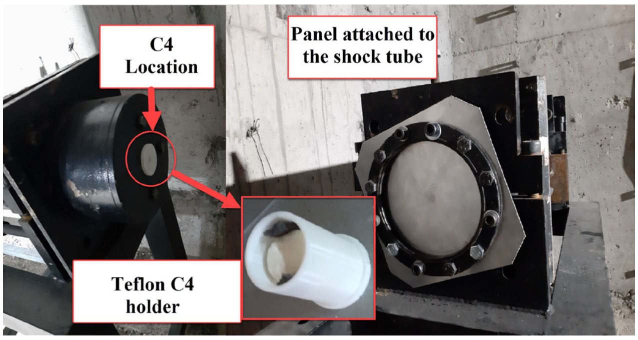


Fig. 10 The location of the explosive and the location of the panel closure

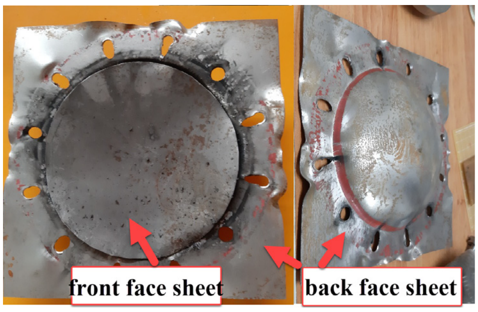


Fig. 11 Sample of coreless steel sheet after explosion test

As a result of this test, the center of the sheet was about 35 mm swollen. But the sheet is not torn.

The next test is to make the core of the panel using resin and pumice. In this experiment, a steel sheet with a thickness of 1 mm was used as face sheet. The thickness of the core is 30 mm and the explosive charge is 8 grams of C4 explosive. Fig. 12 shows the back panel of the panel after the explosion. According to this image, the core has been completely destroyed, the front panel has also been completely deformed, and the pumice also had a the effect of fragments on the back plate, and their effect is quite obvious.

In this case, the back plate of the panel is raised about 28 mm, but the sheet is not torn.

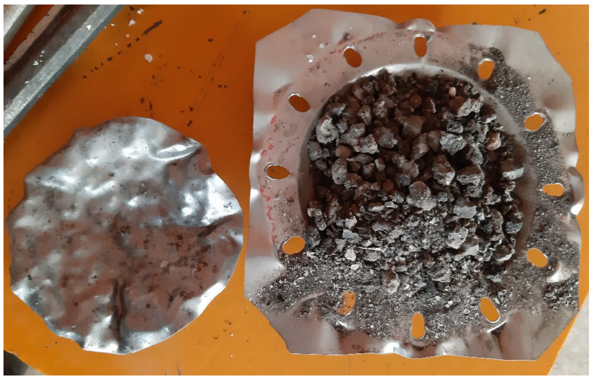


Fig. 12 Panel with core made of resin and pumice after testing

In the next test, foam and pumice are used. The core thickness of the panel is 30 mm and the top and back face sheets of the panel are of steel and it has a thickness of 1 mm and an explosive charge of 8 grams of C4.

Fig. 13 shows the panels after the explosion. Due to the shape of the front sheet of panel, the shape has changed a bit, but it is not very regular. The rise of the back sheet of the panel is obtained after measuring 20 mm. The core is deformed but still integrated and no fracture is seen in the core.

For the next two experiments, the cores were made by casting aluminum on a mineral shell. In both panels, cores are made with a thickness of 30 mm.

In the first test, the face sheet is an aluminum with a thickness of 1 mm. For this experiment, 8 grams of C4 explosive charge was used.

In the second panel, the face sheet is made of three layers of steel with a thickness of 1 mm and an explosive mass of 18 grams of C4. Fig. 14 shows the first and second test panels after the explosion test.

According to Fig. 14, it is clear that in the first experiment, the back face sheet is completely torn (punched) from the edges of the core, and no deformation is observed in the core that indicates energy absorption in it. In the second stage, the C4 was increased to 18 grams. As shown

Fig. 13 Panel with core made of foam and pumice after experiment

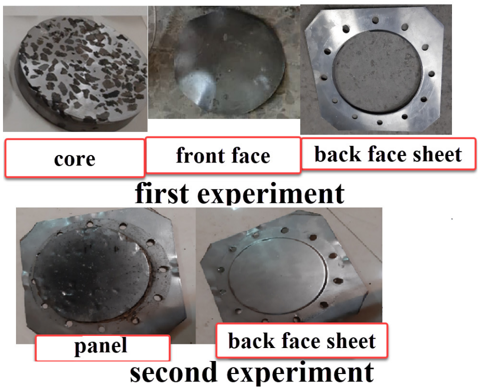


Fig. 14 The result of an experiment with a core made of aluminum and pumice

in Fig. 14, the core acted like a rigid body and no energy absorption occurred. As a result of the second test, a 2 mm protrusion occurred on the back face sheet.

According to the results of these two tests, the core has not undergone a deformation that can be measured. In fact, the core has transferred most of the energy to the back face sheet. The purpose of this core was to replace it as aluminum foam in some applications, especially construction applications. Also, one of the main features of aluminum foam and the reason for its use in many applications is its low density, and in some cases more than 90% of their volume is air, while the core of the panel made of aluminum is relatively dense It has a high compared to aluminum foams.

In the case of panels with a core made of resin and pumice, relatively much damage has been done to the back face sheet of the panel so a core made of foam and pumice can perform better than the other two types. And in the continuation of the research, it will be examined more.

A summary of the results of the experiments performed by the shock tube for the three types of cores is presented in Table 5.

In order to continue the model and simulation and compare with the experimental test for samples with cores made of foam and pumice, free explosion was used. In the test, a core with a density of 450 kg/m^3 (core made of pea-sized pumice) with 30 cm thick, face sheets made of 1100 aluminum, with a thickness of 1 mm and 30 g of explosive charge C4 at a distance of 20 cm were used. The face sheets on both sides of the panel are not glued in this part. Around the sample is a support in the form of clamped. You can see the support and how to prepare the test in Fig. 15. The dimensions of the panel are 30 by 30 cm, some of which is placed under the clamp, and in fact a square with a side of 25 cm is exposed to the blast wave.

Table 5 Test results of panels test with shock tubes

Experiment	C4 (gr)	Displacement of the back face sheet center (mm)
Without core	8	35
Resin core	8	28
Foam core	8	20
Aluminum core 1	8	failure
Aluminum core 2	18	2

After testing, the results in Fig. 16 are compared with the numerical simulation results.

The front face sheet (side of the blast) and back face sheet of the panel are deformed but not torn or cracked. The core has also deformed but retained its continuity. The deformation of the center of the back plate is measured in the 17.5 mm panel, according to Fig. 16, the value obtained from the numerical simulation is 18.07 mm, which has acceptable accuracy.

4 Investigating the effect of different variables

Various parameters are effective in energy absorption and panel deformation. In this section, the effect of parameters such as density, core thickness, thickness of face sheets and their material, which are among the most effective parameters in energy absorption and deformation of the panel with the core made of foam and pumice are investigated.

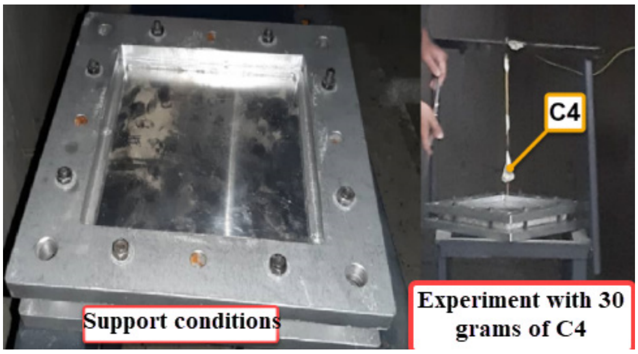


Fig. 15 Preparation of square panel experimental test

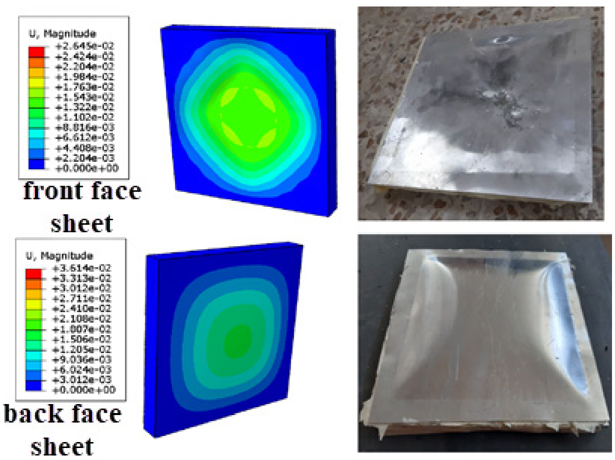


Fig. 16 Comparison of simulation and experimental testing

As mentioned, the core of sandwich panels made of foam and pumice studied in this study has two different densities of 370 and 450 kg/m^3 (according to the size of pumice grains) that the strain stress diagrams of these two types of cores in the Figs. 3 and 4 were presented. In this section, the effect of core density on energy absorption and displacement of the back face sheet of the panel is first investigated.

Fig. 17 compares the center displacement of the back face sheet for panels with different core densities and thicknesses. All panels in this image have a 1 mm thick aluminum face sheet. According to Fig. 17, it can be seen that panels made with pea-sized pumice core, which also has a higher density, the deformation of the center of the back face sheet is slightly less. The energy absorbed in the panel with the core made of pea-sized and almond-sized shells is also compared for panels with different core thicknesses in Fig. 18. Due to the shape of the thicker nuclei, they absorb more energy.

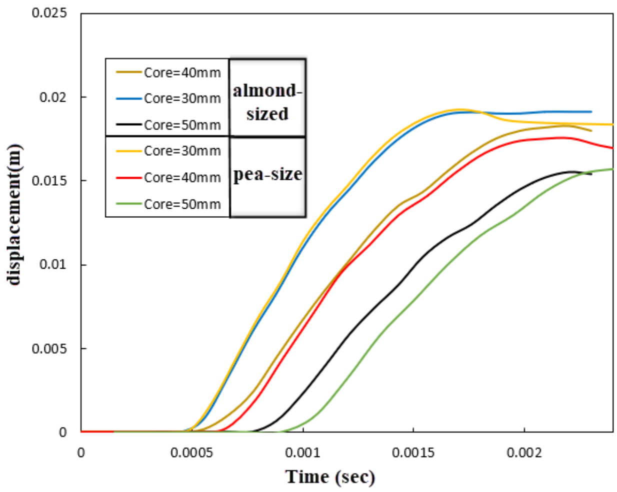


Fig. 17 Investigation of the effect of new density (grain size) on the displacement of the center of the back face sheet

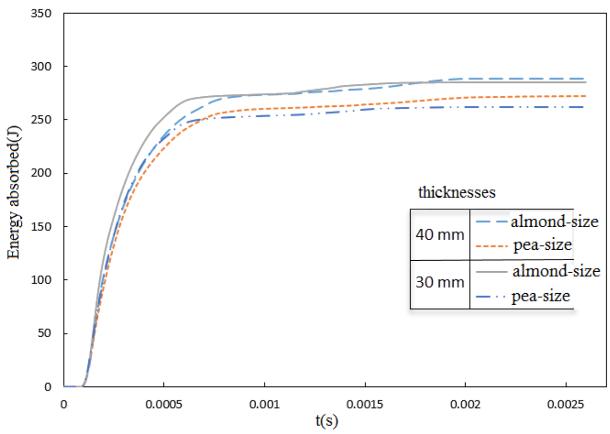


Fig. 18 Energy absorbed in the panel with cores of different densities and thicknesses

The geometric properties of the panel certainly have a great impact on the energy absorption and performance of the panel.

The diagrams in Fig. 17 also show the effect of the change in core thickness for both types of cores with a density of 370 and 450 kg/m^3 (almond size and pea size, respectively).

According to the images, with increasing the thickness of the core, the profile of deformation is more uniform. To compare the displacement of the panel components for different core thicknesses, the panel with the almond-size pumice is shown in Fig. 19. According to Fig. 19, it can be seen that with increasing thickness, although the displacement of the back face sheet is slightly reduced, but the displacement of the core has increased (in fact, the core has become more compact) and the role of the core in energy absorption is greater. Fig. 18 shows the energy absorbed by the plastic deformation throughout the panel. It is observed that the thicker the panel, the more energy is absorbed by the core.

The panel has three main members: the front face sheet (the sheet that the wave first hits), the core and the back face sheet. Fig. 18 shows the energy absorbed by the whole panel, ie all three of these components. Each of these components absorbs some of the energy of the blast wave by deforming the plastic. In order to investigate the effect of each of the panel components, the energy absorbed by the plastic deformation by each of the panel components for panel specimens with a core made of almond-sized pumice and a 1 mm thick aluminum face sheet and with a different core thickness are compared in Fig. 20.

As can be seen in Fig. 20, with increasing core thickness, the role of the core in energy absorption increases and the role of the back and front sheets decreases.

Two different types of face sheets are used in the panels, which are compared in this section. Changes in face sheet material have been investigated for both core densities and for core with different thicknesses. In Fig. 21, the displacement of the back face sheet of the panel for two different materials in the panel is compared with pea-size pumice (density 450 kg/m^3) and almond-size pumice

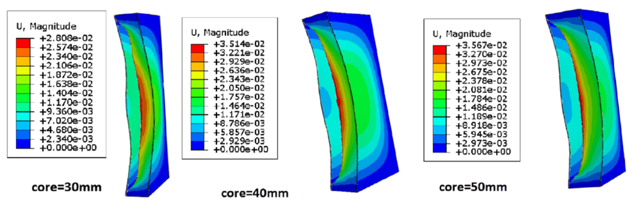


Fig. 19 Displacement contour of panel components with different core thickness

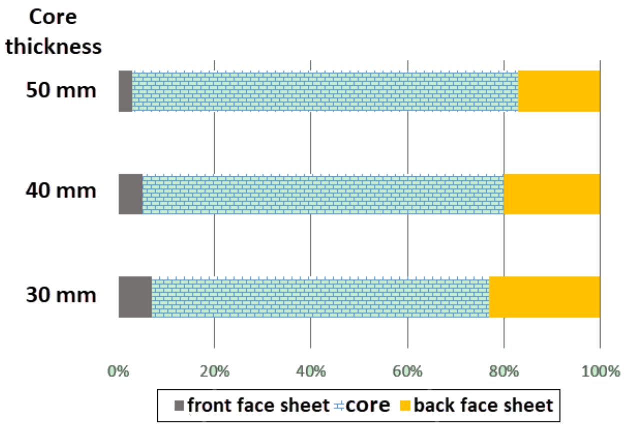


Fig. 20 Change the percentage of energy absorbed in the panel components by changing the core thickness

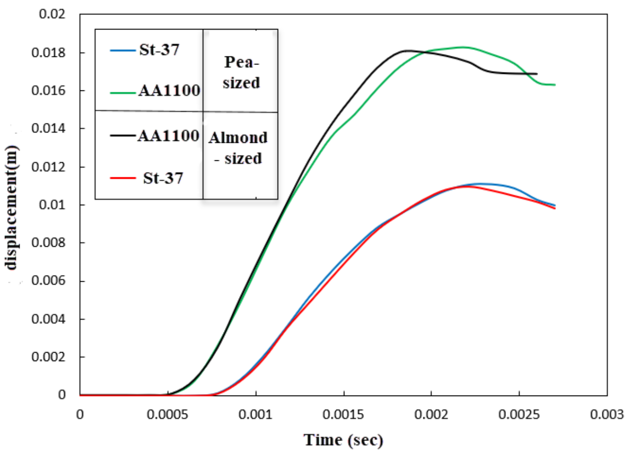


Fig. 21 Displacement of the back face sheet of the panel for different surface materials

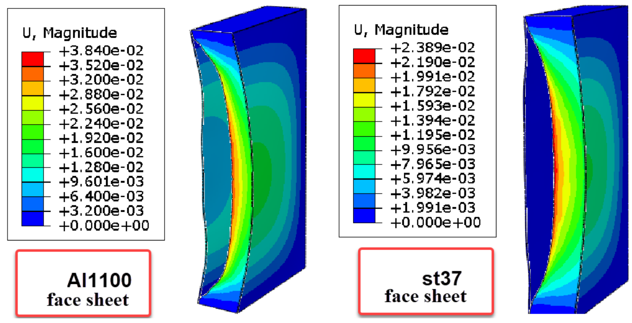


Fig. 22 Displacement contour of panel components with different face sheet

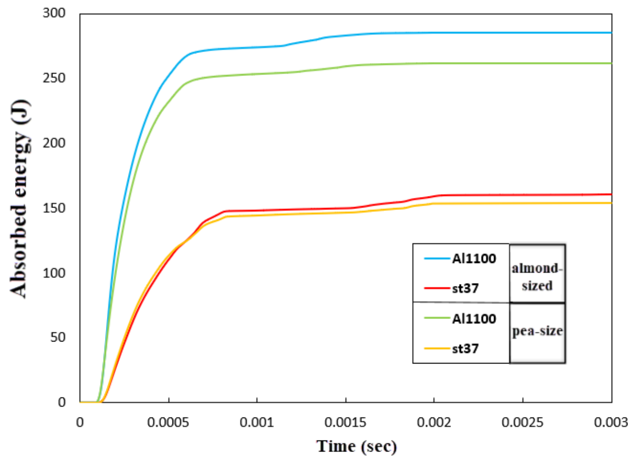


Fig. 23 Energy absorbed by plastic deformation for panels with different face sheet

(density 370 kg/m^3). The thickness of the core is 30 mm for all cases and the thickness of the face sheet is 1 mm. The distance of the explosive charge from the front surface of the panel is 20 cm. displacement contours for both modes with aluminum and steel surfaces are also shown in Fig. 19. According to the contours, it is clear that in the case with aluminum face sheet, the core compression is higher, so it is expected to have more energy absorption under equal conditions. Fig. 21 also shows that the displacement of steel-faced panels is much lower. As can be seen in Fig. 22, the panel with the steel surface has less deformation, and the image also shows that the effect of changing the face plate is the same at both core densities (almond size and pea size).

Fig. 23 also shows the amount of energy absorbed by the panels due to plastic deformation. It is observed that less energy absorption has been done in panels with steel face sheet. It is observed that the energy absorbed in panels with pea and almond-sized pumice with steel face sheet is very close to each other, while this difference is noticeable in panels with aluminum face sheet. In fact, it can be explained that due to the greater strength of steel surfaces than aluminum and due to the close strength of cores made with two sizes of pumice in this case, the effect of the type of core is less.

Due to the greater strength of steel face sheet than aluminum, the effect of each panel component on the absorption of explosion energy is different in panels with different face sheet. Fig. 24 compares the energy absorption of each part of the panel for two different types of face sheet. Fig. 24 shows that in the panel with the steel surface, the effect of the core on energy absorption is somewhat reduced, which in fact confirms the smaller deformation of the core, which is also seen in the Fig. 22.

Two different thicknesses of 1 and 2 mm are considered for panel face sheet. In this section, the effect of sheet thickness for both aluminum and steel sheets is investigated. Fig. 25 shows the displacement of the center of the back cover for panels with almond kernels 4 cm thick and different procedures for 30 g of C4 consumption at a distance of 20 cm.

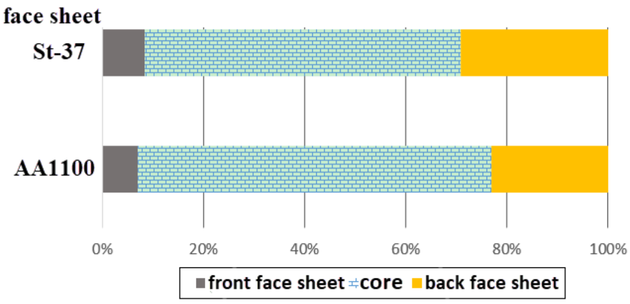


Fig. 24 Percentage of energy absorbed by each part of the panel for two different types of face sheets

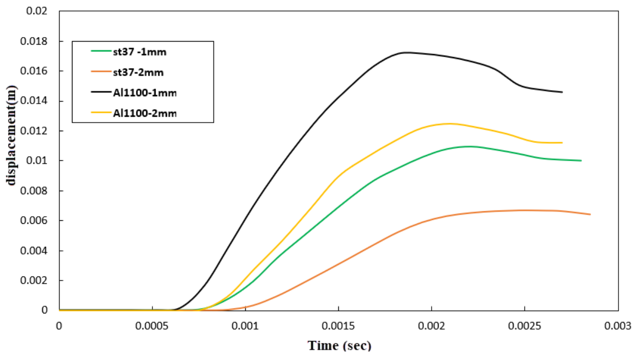


Fig. 25 Compare panels with different thickness of face sheets

It is clear that the thicker and stronger sheet, ie the 2 mm steel sheet, has the least displacement. The energy dissipated in the form of plastic deformation in the panel is compared with the core made by almond-sized pumice for different face sheet in Fig. 26.

The contribution of each panel component in the blast wave energy absorption for panels with a core made of almond-sized pumice with a thickness of 30 mm is compared with the different thickness face sheet in Fig. 27. It can be seen that in panels with thicker surfaces, the role of core in energy absorption is reduced. Also, in panels

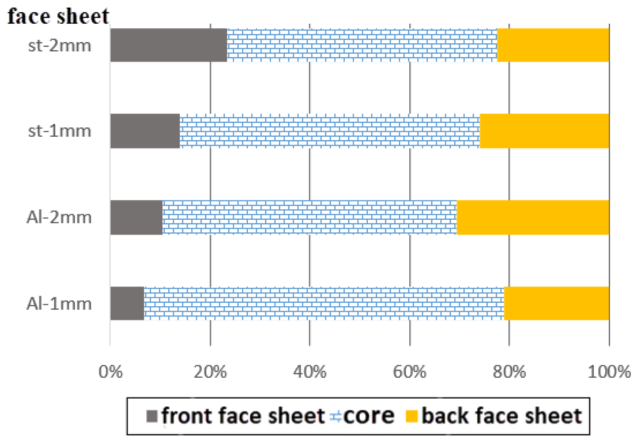


Fig. 27 Contribution of panel components in energy absorption for different thickness of face sheet

with a thicker surface, less energy is absorbed in the back plate, which is also shown by the lower displacement of the back plate.

Another type of layout that can be considered is the use of face sheet with different thicknesses on the front and back of the panel. In these cases, three panels are considered, all panels have a core made of almond-sized pumice and their core thickness is 30 mm and exposed to 30 grams of explosive C4 at a distance of 20 cm. The face sheet are made of aluminum. In the first case, both sheets are 1 mm thick, in the following cases, once the front surface sheet and once the back surface sheet of the panel is 2 mm thick. The energy dissipated by the plastic deformation in these three panel modes is compared in Fig. 28. According to Fig. 28, it is clear that the energy lost in these three states is significantly different. The lowest absorption mode is thicker for the front face sheet and the best absorption mode is thicker for the back face sheet of panel.

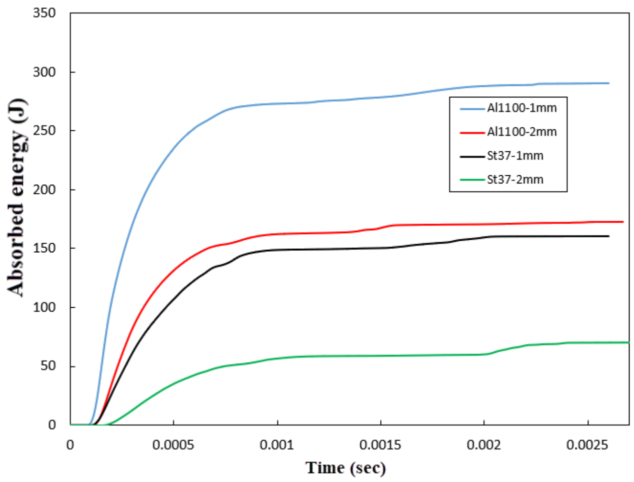


Fig. 26 Comparison of energy absorbed in the panel with different thickness of the face sheet

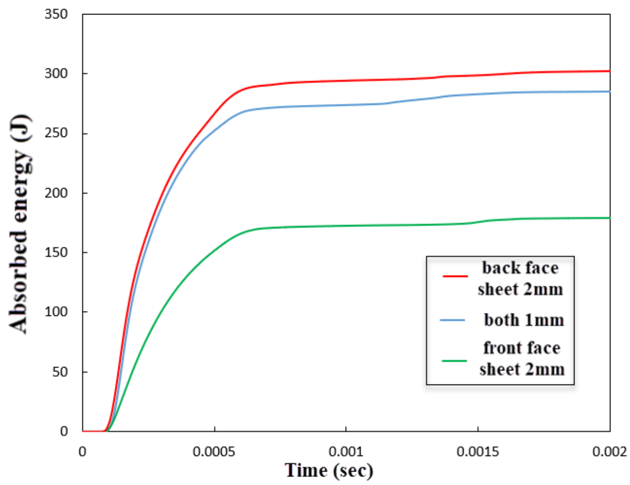


Fig. 28 Comparison of the effect of using different thicknesses for the face sheet on the energy absorption of the panel

The contribution of each panel component to energy absorption is also compared in Fig. 29. According to the image, in the case that the back face sheet is thicker, the role of the core in energy absorption has increased. According to this diagram and the diagram in Fig. 28, it is clear that this mode (thicker back face sheet) has a more substantial function. In fact, in this case, a thicker back layer causes the core to compress better and play a greater role in absorbing energy.

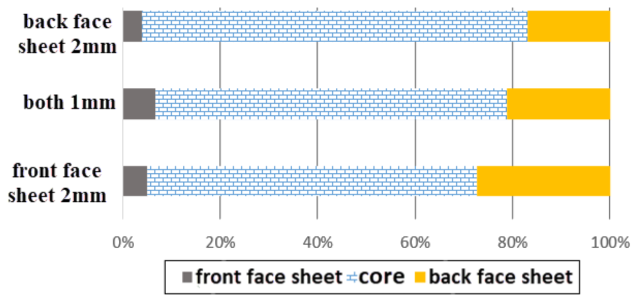


Fig. 29 Comparison of energy absorbed by each of the panel components for three different positions of face plates

5 Conclusion

The results of experimental experiments showed that a core made of pumice and aluminum casting could not absorb energy well. The core made of pumice and resin also did not perform well, so the core made of foam was chosen. In the case of cores made of foam and pumice, deformation is slightly less in panels with denser cores (finer pumice causes higher density). In panels whit steel face sheet, the deformation is significantly less than in aluminum-faced panels. But the energy absorbed in the panel is more with an aluminum surface. In fact, it can be said that if the panel is the main structure, it is better to use a steel surface to prevent damage, but if the panel protects the main structure, it is better to use an aluminum surface to absorb more energy and Prevent the transfer of wave energy to the main structure. A panel with a thicker back face sheet performs better in absorbing blast energy, because in this case the back plate creates support and a firm grip on the back of the panel core, which makes the core more compact and absorb more energy in the core. As the strength or thickness of the face sheets increases, the role of the core in energy absorption decreases.

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