Investigation of Energy Absorption in Aluminum Foam Sandwich Panels By Drop Hammer Test: Experimental Results

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Investigation of Energy Absorption in Aluminum Foam Sandwich Panels By Drop Hammer Test: Experimental Results

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ABSTRACT. The sandwich panel structures with aluminum foam core and metal surfaces have light weight with high performance in dispersing energy. This has led to their widespread use in the absorption of energy. The cell structure of foam core is subjected to plastic deformation in the constant tension level that absorbs a lot of kinetic energy before destruction of the structure. In this research, by making samples of aluminum foam core sandwich panels with aluminum surfaces, experimental tests of low velocity impact by a drop machine are performed for different velocities and weights of projectile on samples of sandwich panels with aluminum foam core with relative density of 18%, 23%, and 27%. The output of device is acceleration-time diagram which is shown by an accelerometer located on the projectile. From the experimental tests, the effect of weight, velocity and energy of the projectile and density of the foam on the global deformation, and energy decrease rate of projectile have been studied. The results of the experimental testes show that by increasing the density of aluminum foam, the overall impression is reduced and the slop of energy loss of projectile increases. Also by increasing the velocity of the projectile, the energy loss increases.

Introduction. Sandwich panels with composite face sheets and foam core are widely used in lightweight constructions, especially in aerospace industries due to their advantages over the conventional structural constructions, such as high specific strengths and stiffness and good weight saving [1]. An early study [2] has indicated that using composite materials instead of aluminium for the face sheets results in higher performance and lower weight. In the meanwhile, as a new multi-functional engineering material, aluminium foam has many useful properties such as low density, high specific stiffness, good impact resistance, high energy absorption capacity, easy to manufacture into complex shape, and good erosion resistance [3, 4], so it is usually used as core material of sandwich panels. However, it has also been found that composite sandwich panels are susceptible to impact damage caused by runway debris, hailstones, dropped tools and so on [2]. The resulting impact damage to the sandwich panel ranges from face sheet indentation to complete perforation, with the strength and reliability of the structures dramatically affected. Unlike for their solid metallic counterparts, making predictions of the effects of low-velocity impact damage are difficult and are still relatively immature. Hence, the behaviour of sandwich structures with aluminium foam core under low-velocity impact has received increasing attention.

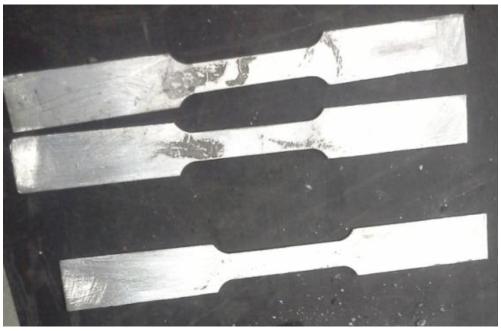
Recently, a number of studies have shown that localized impact loading on a sandwich structure can result in the generation of local damage, which can lead to significant reductions in its load-carrying capacity [5]. Investigations have been carried out on sandwich panels with foam core under quasi-static and impact loadings to explore the perforation energy absorbing mechanisms, mostly on sandwich structures with polymeric foam cores [6–8]. Wen et al. [6] have analysed marine sandwich construction and they have identified the major energy absorbing modes as fragmentation under the penetrator and global panel deformation. Mines et al. [7] conducted a series of quasi-static perforation tests and low-velocity impact tests on square panels based on polymer composite sandwich structures. They suggested that higher impact velocities tend to increase the energy absorption, which is attributed to an increase in the core crush stress and skin failure stress at high strain rates. More comprehensive and detailed summaries of previous experimental studies can be found in a thorough review article of the impact response of sandwich structures given by Abrate [8]. While polymeric foams have been applied for many years, metallic foams have gained a significant and growing interest for applications in sandwich structures currently, for the reason that in comparison with polymer foams they exhibit excellent recycling efficiency, high specific stiffness, good thermal conductivity and high melting point. Kiratisaevee and Cantwell [9] investigated the impact response of sandwich panels with ALPORAS® foam cores and fiber-rein- forced thermoplastic or fiber-metal laminate (FML) face-sheets. Impact tests were conducted by using a drop hammer at velocities up to 3 m/s. The resistance of these sandwich panels was found to be rate sensitive over the full range of conditions examined. Ruan et al. [10] have experimentally investigated the mechanical response and energy absorption of sandwich panels subjected to quasi-static indentation, which consist of aluminum face sheets and ALPORAS® foam core. The effects of several parameters, such as face sheet thickness, core thickness, boundary conditions, adhesive and surface condition of face sheets on the mechanical response and energy absorption during indentation are identified. While most of the existing investigations into the impact responses of composite sandwich structures with metallic foam cores have focused on high-velocity impact [11–16], only minimal attention has been paid on low-velocity tests, and few detailed parametric studies have been reported yet.

In the present study, a series of perforation tests were conducted on the sandwich panels with an aluminum foam core and two face sheets, which were subjected to low-velocity impact. The perforation responses of the sandwich panels are investigated and the deformation and failure modes observed during perforation are described in detail. The mechanical properties and collapse mechanisms of aluminum foam sandwich panels are correlated to the physical and geometric properties of the face sheets and foam core, so the effects of face sheet thickness, core thickness and relative density, as well as the effect of impact energy on the energy absorption capacity of sandwich panels are analyzed.

1. Experimental investigation

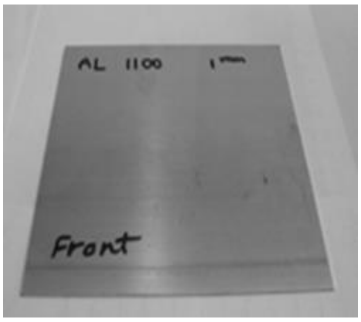
Specimens and material properties. The face sheets of sandwich panels are made of Aluminum series 1000 (AL-1000). The thickness of both face sheets (top and bottom of foam core) is 1 mm. Uniaxial tensile tests were carried out to obtain the stress–strain curves using the Zwick Tensile Testing Machine according to the Standard E8 in the Laboratory of Amirkabir University of Technology in Iran. Face sheets have been tested in 6 samples and 3 directions (0^o, 90^oand45^o). Figures 1 and 2 demonstrate AL-1000 samples, top face sheet and Testing Machine. Also, Table 1 gives material properties for the face sheets and they are averaged from a number of repeated tests at strain rate of 10^{-3}/s. It should be noted that the surface of the laminates is marked by coding number such as “Front AL 1100 1mm”, so the visual patterns are not the actual named.

The aluminum foam used as the core material in the experiments is a closed-cell foam with ~~the~~ average cell size of approximately 2–5 mm, which is produced by ALPORAS method using Al (A356/ SiCp) as base materials.



(a)

(b)



(c)

Fig. 1. (a) Al samples before tensile test. (b) Al samples after tensile test. According to E8 Standard (c) top face sheet.

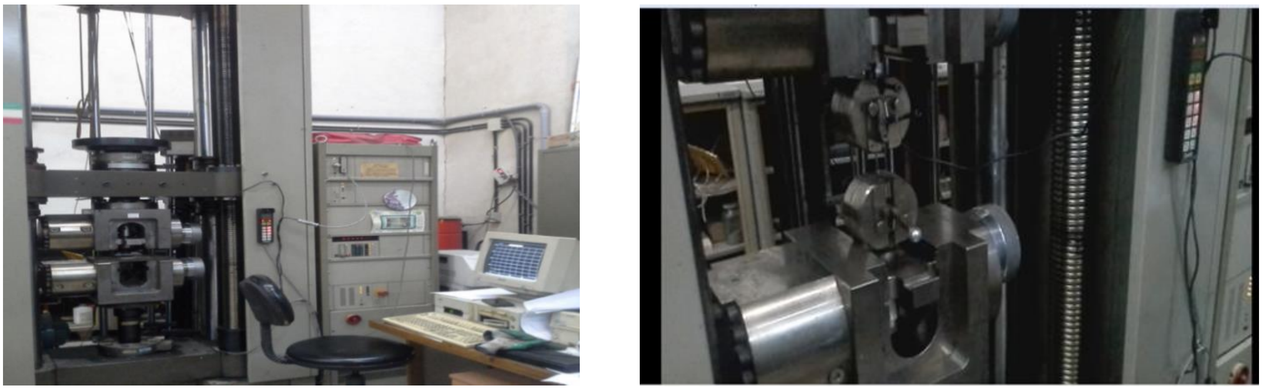


Fig. 2. ZWICK TENSILE TESTER, Laboratory of the Amirkabir University of Iran.

Table 1. Properties of the face sheets

Material property	σ_Y(MPa)	v	E(GPa)	ρ(kg/m^3)	σ_u(MPa)	ε_D(MPa)
value	117	0.3	70	2700	124	0.2

Foam core samples shown in Figure 3 were used in the uniaxial compression tests and the average values of their mechanical properties with three relative densities, are shown in Table 2. Two different thicknesses of aluminum foam cores, namely 20 and 30 mm, were used to investigate the effect of foam core thickness. A commercial two-component impact-resistant adhesive SA102 was used to glue the face sheets and the foam core. Great attention has been given to achieve the perfect bonding between face sheets and foam core for a satisfactory structural performance, so the debonding effect will not be considered in this study. The final sandwich panel specimens are square plates with $20 \times 20 \times 22\ \mathrm{mm}^3$ and $30 \times 30 \times 32\ \mathrm{mm}^3$ in dimensions. To ensure the repeatability of the tests, three specimens were tested for each selected case.

Table 2. Aluminium foams material properties

Parameters	Type	Type 2	Type 1
Relative Density	27%	23%	18%
Young's modulus (GPa)	1800	1660	1500
yield stress (MPa)	5.2	4.6	3.6
plateau stress (MPa)	5.4	4.7	3.8
densification ratio	0.52	0.5	0.5
Poisson's ratio	0.3	0.3	0.3

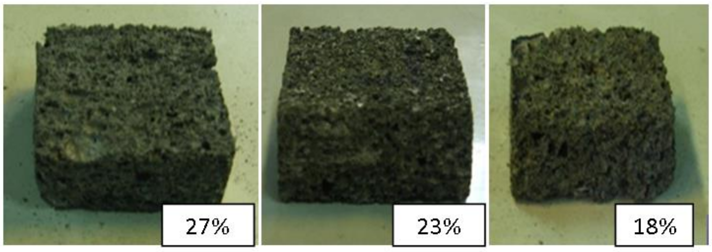


Fig. 3. Samples of Aluminum Foams with different relative densities.

Quasi-static tests. To determine the level to which dynamic behavior should be considered under low-velocity impact, the sandwich panels were first tested under quasi-static loading for subsequent comparison with the impact loading cases. A ZWICK test system in the Engineering and Material Testing Center, Amirkabir University, was used to perform the quasi-static perforation. Specimens were fully clamped along all edges using two steel frames with a span of $100 \times 100\ \mathrm{mm}^2$, leaving an exposed square in the center. The main projectile is conical-nosed and two different projectiles with identical diameter of 40 mm were used for comparison in this study. One is a flat-ended projectile and the other is a hemispherical-nosed projectile. The geometry and dimensions of projectiles are shown in Figure 4. A constant crosshead speed of 1.2 mm/min was applied to load the samples until full failure and the force-displacement histories were recorded. Figure 5 shows the behavior of the Foam after the Compression test.

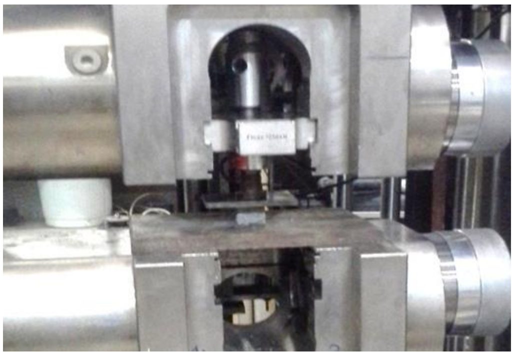


Fig. 4. Zwick Compression Tester, quasi static test.

Fig. 5. Behavior of the Foam after the Compression test.

Low-velocity impact tests. Low-velocity impact tests were conducted on a drop weight machine (Drop Hammer). The specimens were impacted at various energy levels in order to achieve different damage levels. The impact mass was varied from approximately 14 to 35 kg and the drop height ranged between 50 mm and 200 mm. An accelerometer was embedded inside the hammer just above the impactor tip to get the velocity and displacement history. For more details, the reader is referred to Reference [17].

An important issue in measuring the mechanical properties of foams is the effect of the specimen size, relative to the cell size. The size effect is also particularly important for foam core sandwich panels, as in some components the foam core may have dimensions of only a few cell diameters. As for sandwich beams with laminate skins and foam core, the size effect has already been experimentally demonstrated for shear failure in four-point bending [18].

The size effect can be avoided if the foam plate has at least eight cell diameters in thickness [19]. However, the thin and stiff face sheets will give a better distribution of load throughout the area when subjected to loads, which would lead to a lower localized mean load and diminish the size effects.

2. Experimental Results. In this section the damage of sandwich specimens composed of two 1 mm thick Aluminum faces and an Aluminum foam-core by the projectile is studied and the effect of various parameters such as impact velocity and core density on the amount of energy absorbed by the specimen are characterized.

A rigid striker is used to simplify the model of impact test. The procedure of impact is the penetration of the rigid striker to the Aluminum plate or its foam. in all steps of the experiments, after the falling of projectile from the impact machine, the accelerometer measures the projectile acceleration during the energy imposition to the specimen and returning back. The Graph software is used to calculate the area under the acceleration vs. time curve to obtain the velocity vs. time curve and recalculate the area under the velocity vs. time curve to obtain the time-variation of displacement. By multiplying the mass of projectile to its acceleration one can obtain the impact force and by computing the area under the force vs. time curve the impact energy would be obtained. The energy absorbed by the specimen and the depth of indentation play an important role in study of the impact phenomenon. The amount of absorbed energy by the structure can be used as a criterion for its performance. Absorbed energy by the target during the impact E_p equals the change of kinetic energy before and after the impact:

$$\frac{1}{2}m_p V_i^2 - \frac{1}{2}m_p V_r^2 = E_p \quad (1)$$

In which V_i and V_r are the contact velocity and the return velocity of projectile, respectively.

Effect of impact velocity

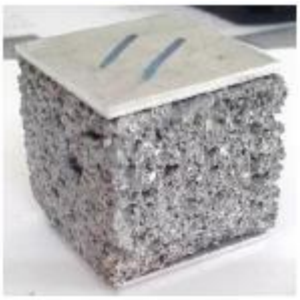
A rigid projectile (with radius of 60 mm, height of 200 mm and mass of 25 kg) is dropped with different velocities and hits the sandwich specimen with dimension of 30x30x32. The relative density of foam is 0.18. So by changing the height from which the projectile is dropped one can controls its velocity according to Eq. (2). Experiments are done according to Table 3.

$$v = \sqrt{2gh} \quad (2)$$

Table 3. Specifications of prepared samples for the study of the effect of impact velocity

#Test	Projectile Radius (mm)	Falling Height (mm)	Mass (kg)	Rate of density (%)	Thickness (mm)
1	60	200	25	18	30
2	60	110	25	18	30
3	60	50	25	18	30

Figs. 6(a-d) show pictures of the specimen before and after the experiments. Plots of time-acceleration, time-velocity, time-displacement, force-displacement, energy-displacement, and time-energy for each test are presented in Figs. 7-12, respectively. As shown in Fig. 8 with the increasing the impact velocity, the projectile acceleration tends to increase with time. As depicted in Fig. 9 the projectile velocity gets down with time in a rather linear manner. Also Fig. 10 shows that the depth of specimen crushing has a linear relation with the height of projectile falling. As shown in Fig. 11 the kinetic energy of projectile is in a linear relation with its displacement. Fig. 12 shows that the rate of energy loss is increased with increasing the impact velocity.



(a)

(b)

(c)

Fig. 6. Pictures of: (a) untested specimen, (b) specimen after the 1st experiment, (c) specimen after the 2nd experiment, (d) specimen after the 3rd experiment.

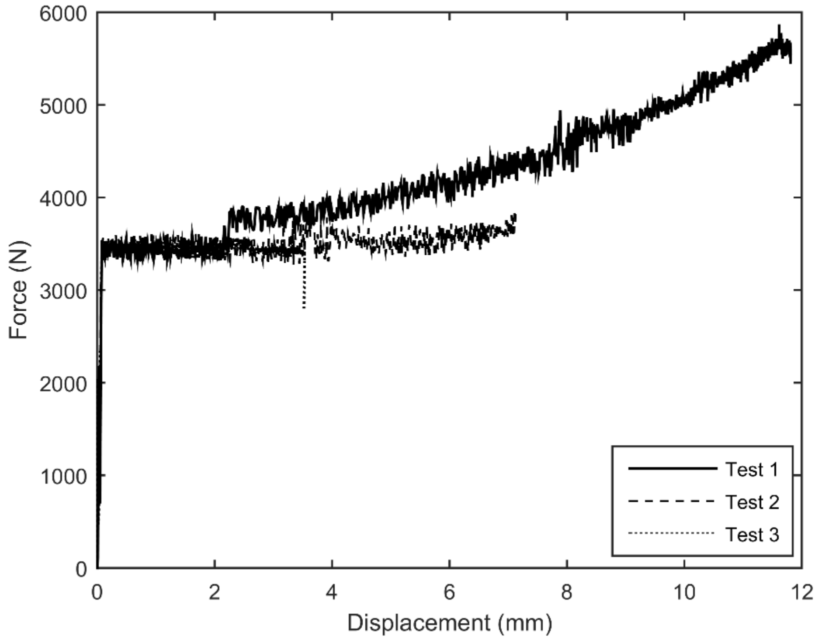


Fig. 7. Variation of projectile force in terms of its displacement.

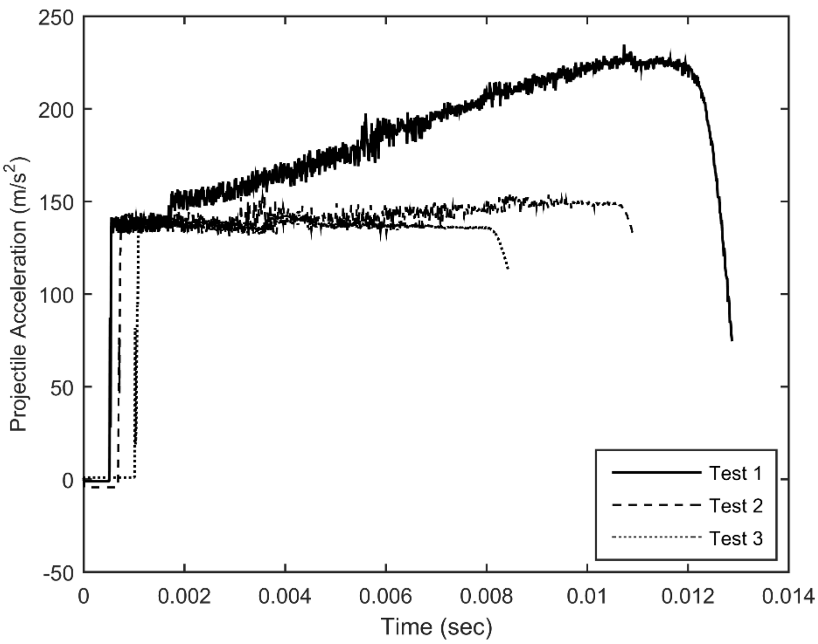


Fig. 8. Time-variation of projectile acceleration.

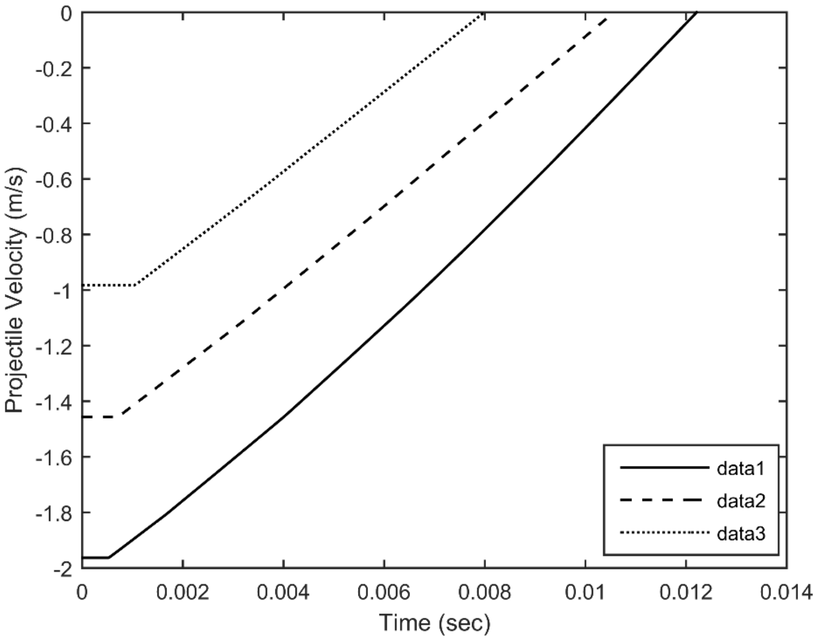


Fig. 9. Time-variation of projectile velocity.

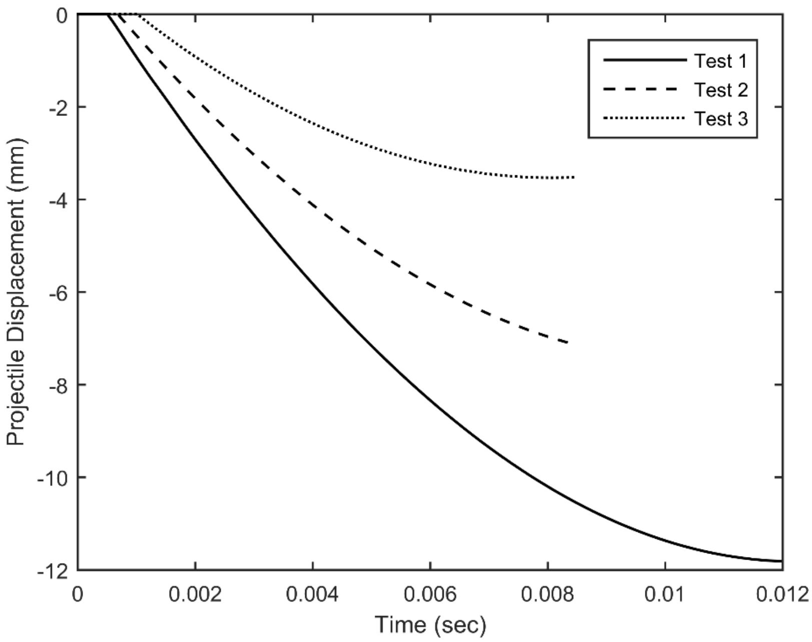


Fig. 10. Time-variation of projectile displacement.

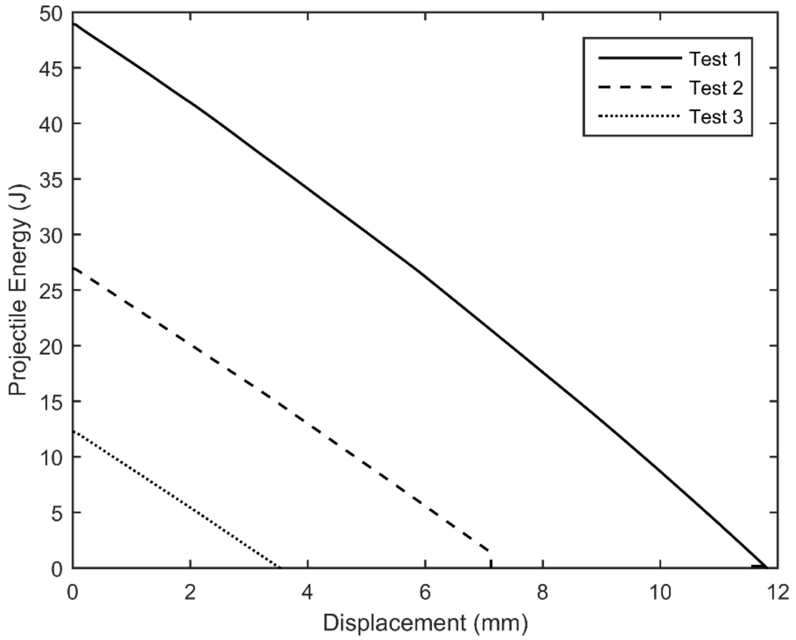


Fig. 11. Variation of projectile kinetic energy in terms of its displacement.

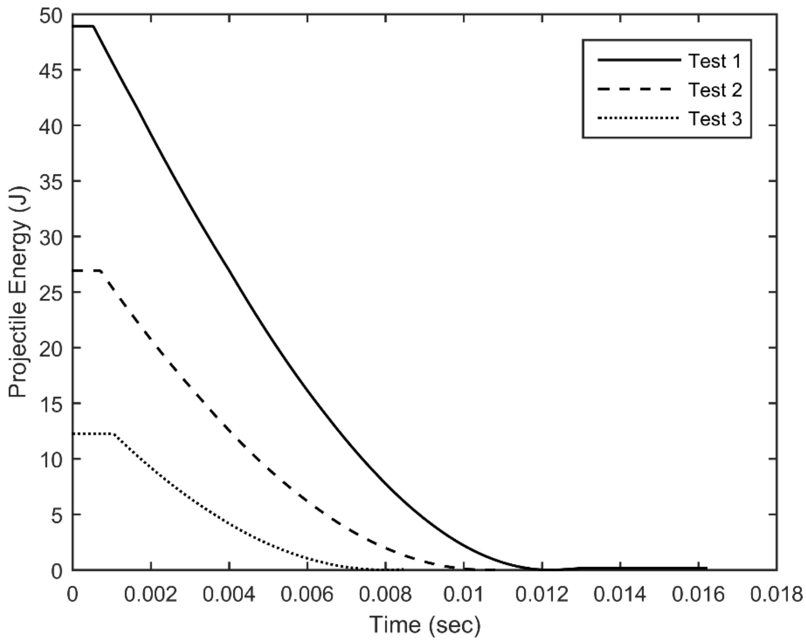


Fig. 12. Time-variation of projectile kinetic energy.

Effect of foam-core density. In this section the effect of Aluminum foam density on the amount of energy absorbed during the impact is measured. Experiments are done according to Table 4. Figs. 13(a-d) show pictures of the specimen before and after the experiments. Figs 14-19 show the time-variation of projectile acceleration, velocity, displacement and energy as well as the variation of force and energy versus projectile displacement for each test.

As expected, increasing the relative density leads to an improvement of impact strength (Fig. 14). The similar trend is observed in Fig. 15. According to Fig. 16, by increasing the core relative density, duration of crush gets shortened. Fig. 17 depicts that sandwich panels with denser core suffer less crush. As shown in Fig. 19 the rate of energy loss is increased with increasing the relative density of panel core.

Table 4. Specifications of prepared samples for study of the foam-core density.

#Test	Projectile Radius (mm)	Falling Height (mm)	Mass (kg)	Relative density (%)	Thickness (mm)
4	60	110	25	27	20
5	60	110	25	23	20
6	60	110	25	18	20

(a)

(b)

(c)

Fig. 13. Pictures of: (a) untested specimen, (b) specimen after the 4th experiment, (c) specimen after the 5th experiment.

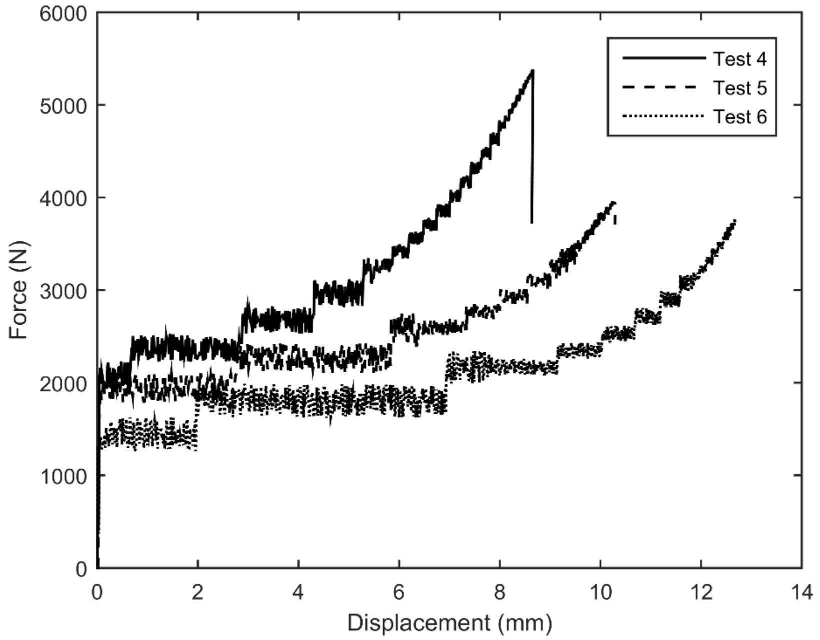


Fig. 14. Variation of projectile force in terms of its displacement.

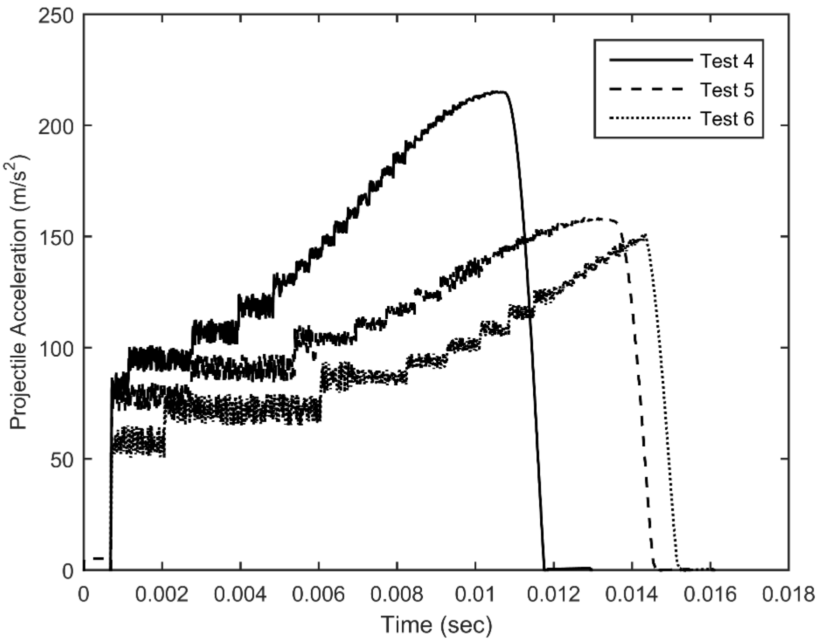


Fig. 15. Time-variation of projectile acceleration.

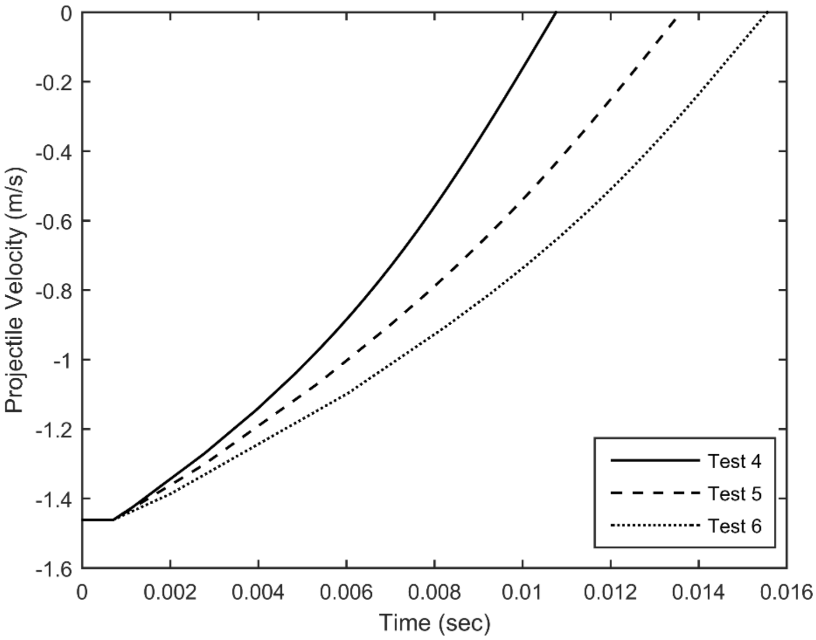


Fig. 16. Time-variation of projectile velocity.

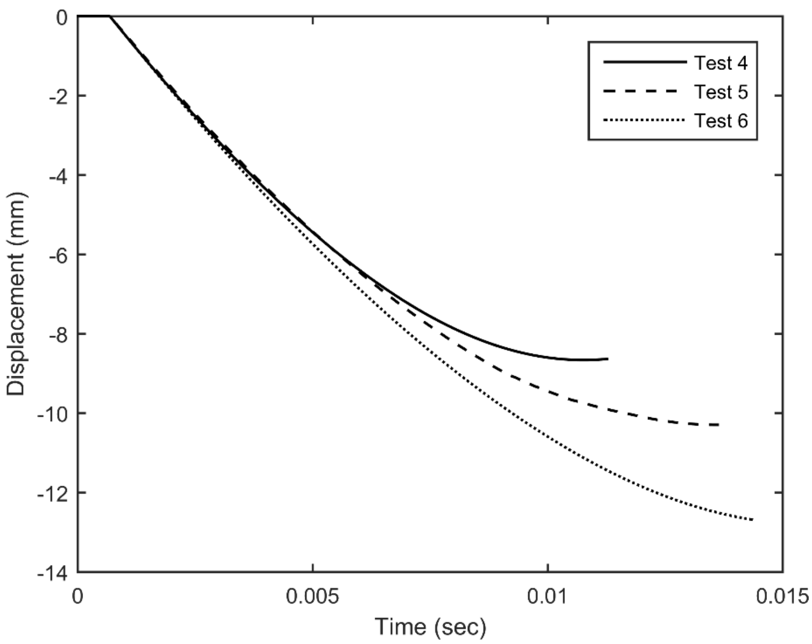


Fig. 17. Time-variation of projectile displacement.

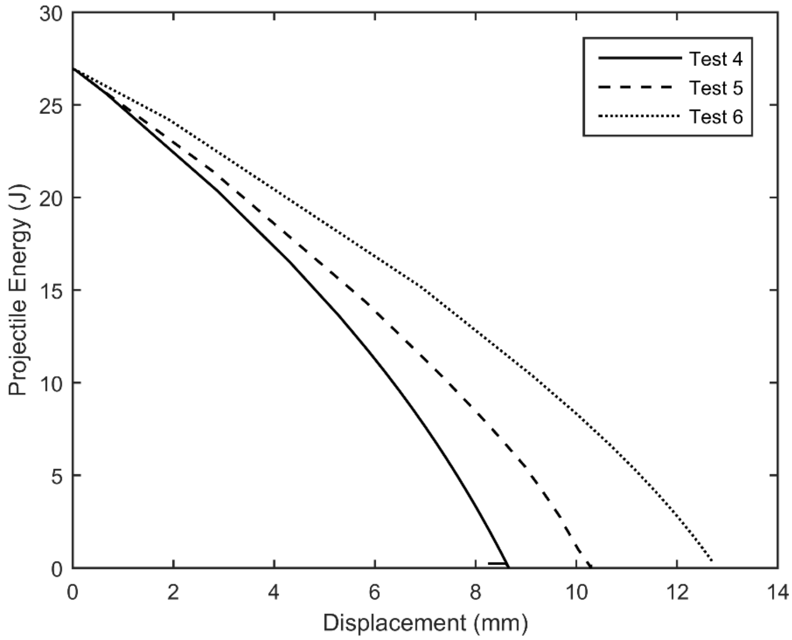


Fig. 18. Variation of projectile kinetic energy in terms of its displacement.

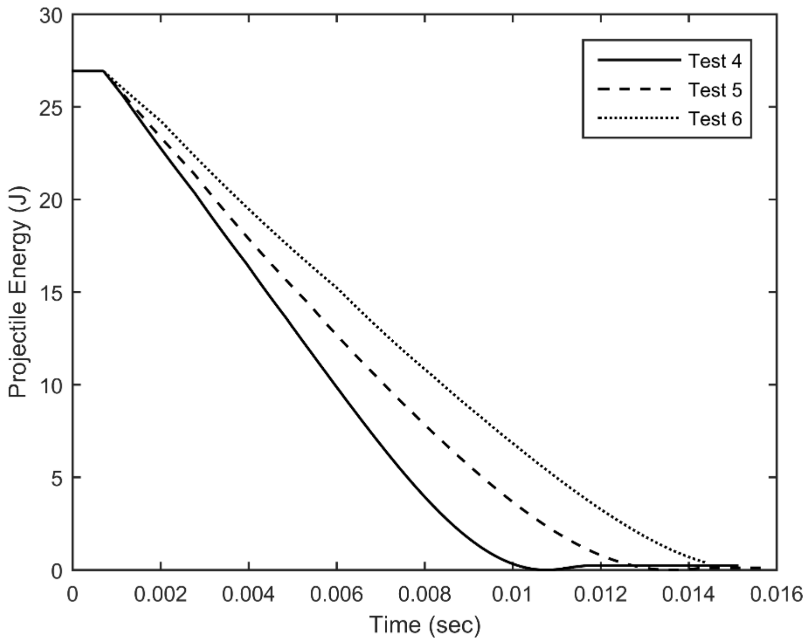
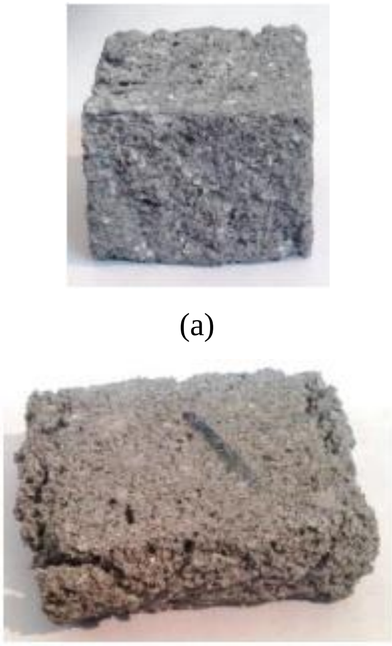


Fig. 19. Time-variation of projectile kinetic energy.

Effect of sandwich skin. The sandwich specimen is impacted by a rigid projectile with the properties of Table 5. Fig. 20 shows the specimen before and after the experiment. The time-variation of projectile acceleration, velocity, displacement and energy as well as the variation of force and energy versus projectile displacement is plotted in Figs 21-26. As shown in these Figures, adjoining the skins to the foam enhances the impact strength, while the total behaviours of neat foam and sandwich panel are rather the same.

Table 5. Specifications of prepared samples for study of the effect of sandwich skin.

#Test	Rigid Radius (mm)	Falling Height (mm)	Mass (kg)	Rate of density (%)	Thickness (mm)
7	60	200	25	18	30



(a)

(b)

Fig. 20. Pictures of: (a) untested specimen, (b) specimen after the 7th experiment.

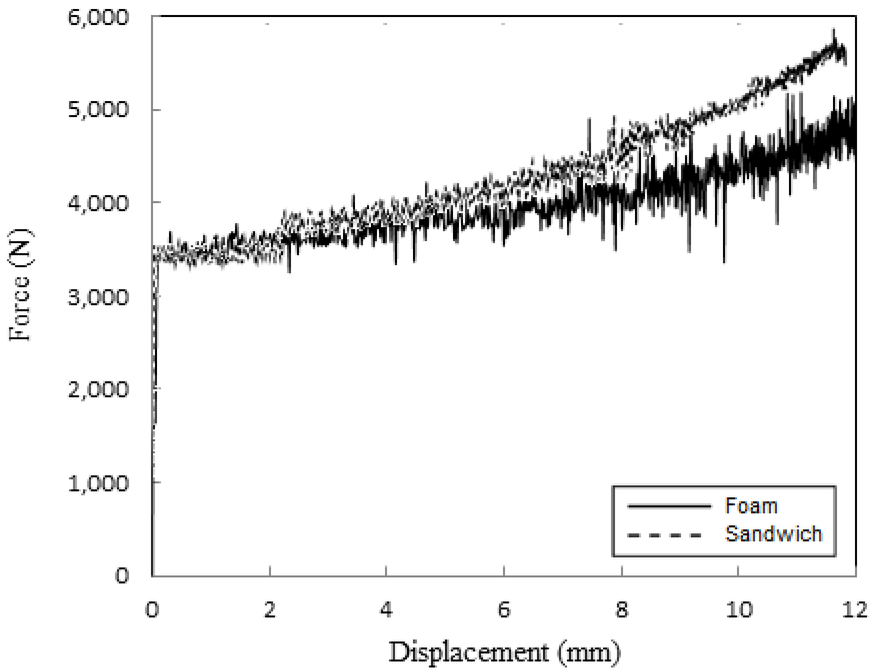


Fig. 21. Variation of projectile force in terms of its displacement for the 7th experiment.

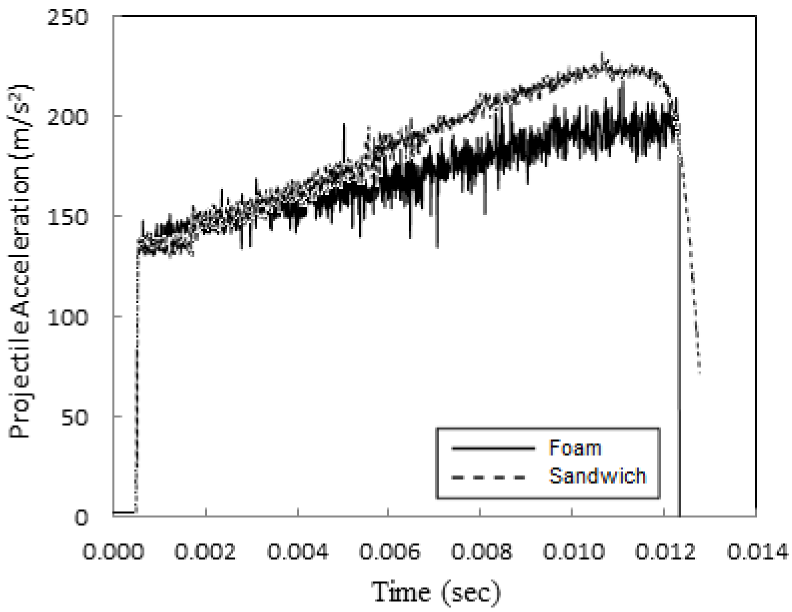


Fig. 22. Time-variation of projectile acceleration for the 7th experiment.

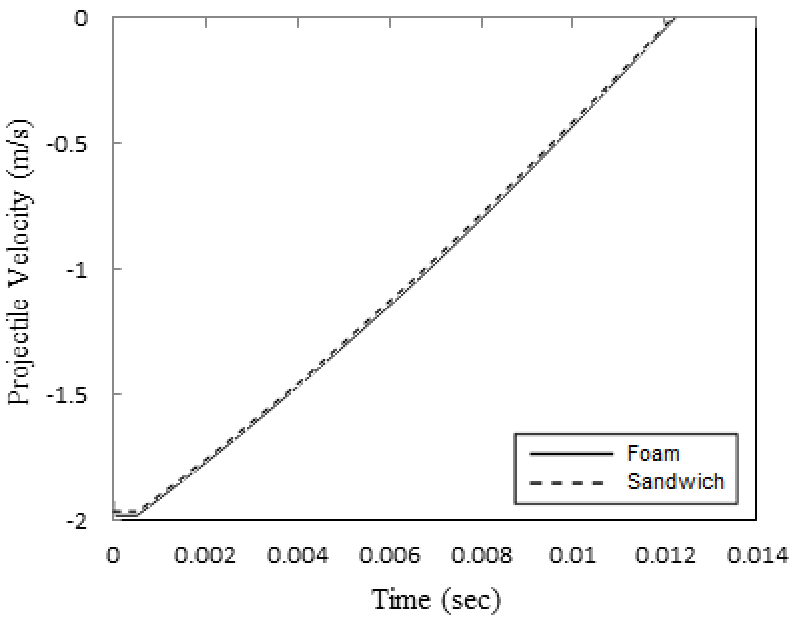


Fig. 23. Time-variation of projectile velocity for the 7th experiment.

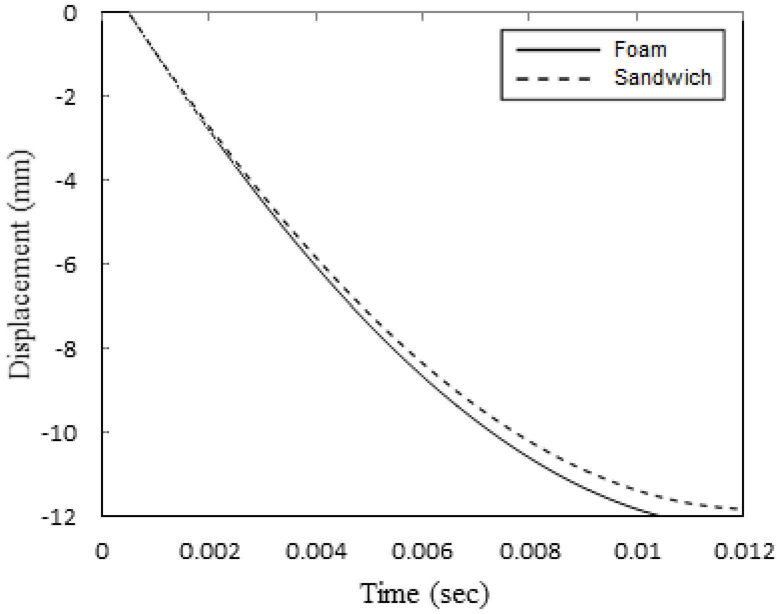


Fig. 24. Time-variation of projectile displacement for the 7th experiment.

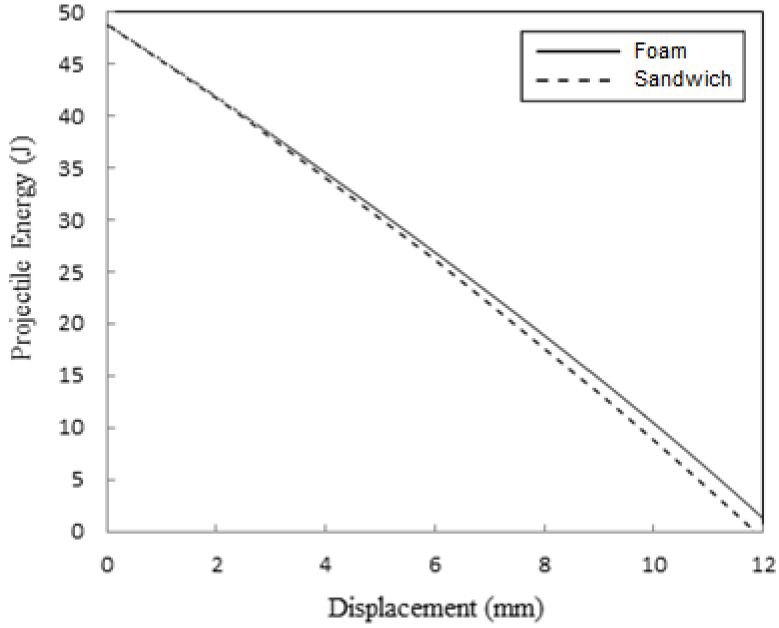


Fig. 25. Variation of projectile kinetic energy in terms of its displacement for the 7th experiment.

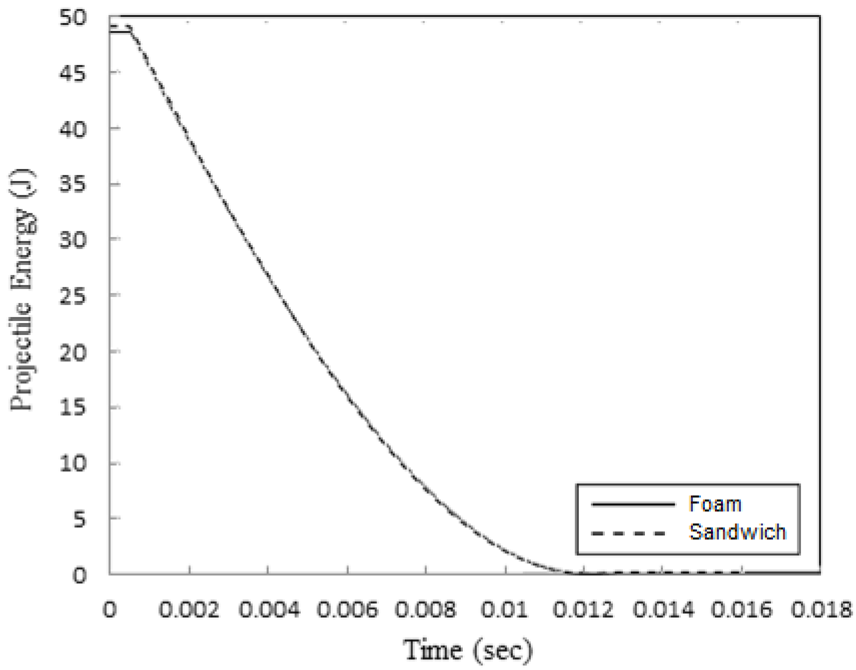


Fig. 26. Time-variation of projectile kinetic energy for the 7th experiment.

Summary. In this paper the behavior of Aluminum foam-core sandwich panels under the low velocity impact has studied and the effect of foam density as well as the impact velocity and the weight of projectile are investigated. Main results of the present research are as follows:

• Composing of Aluminum plate and its foam to form a sandwich structure increases total rigidity of samples in comparison to its constituents and causes the structure to dissipate a major portion of the impact energy through large plastic deformations.

• Increasing the relative density from 18% to 27% reduces the impact damage up to 46% as well as contact duration between the projectile and the sample.

• Change in the initial energy of the projectile does not have not a noticeable effect on the time duration of contact between the projectile and the sample. It is because that with increasing the energy of the projectile the rate of its energy loss gets increased.

• The destructive effect of projectile velocity is more dominant than that of its mass.

• General degradation of structure is a function of the projectile energy. In another words, projectiles with different values of mass and velocity but the same initial energy will cause rather the same effect on the specimen.

• The rate of energy loss of the projectile is directly dependent on its initial energy instead of its mass and velocity.

• Increasing the rigidity of the structure shorten its contact duration with the projectile.

• By reducing the projectile diameter and keeping constant its energy, the damage level of structure is increased.

References

[1] Zenkert D., 1995. *An introduction to sandwich construction*. Sheffield: Engineering Materials Advisory Services Ltd.
[2] Abrate S. 1998. *Impact on composite structures*. Cambridge: Cambridge University Press.
[3] Gibson L.J., Ashby M.F., 1997. *Cellular solids: structure and properties*, 2nd edn. Cambridge: Cambridge University Press.

[4] Ashby M.F., Evans A.G., Fleck N.A., et al., 2000. *Metal foams: a design guide*. Boston, MA: Butterworth Heinemann.
[5] Hazizan M.A., Cantwell WJ., 2003, The low velocity impact response of an aluminum honeycomb sandwich structure. *Compos Part B*, 34 (8), 679–687.
[6] Wen H.M., Reddy T.Y., Reid S.R., et al., 1997, Indentation, penetration and perforation of composite laminate and sandwich panels under quasi-static and projectile loading. *Key Eng Mater*, 141-143 (1), 501-552.
[7] Mines R.A.W., Worrall C.M., Gibson AG., 1998. Low velocity perforation behavior of polymer composite sandwich panels. *Int J Impact Eng*, 21(10), 855-879.
[8] Abrate S., 1997. Localized impact on sandwich structures with laminated facings. *Appl Mech Rev*, 50(2), 69-82.
[9] Kiratisaevee H., Cantwell W.J., 2005. Low-velocity impact response of high-performance aluminum foam sandwich structures. *J Reinf Plast Compos*, 24(10), 1057-1072.
[10] Ruan D., Lu G., Wong Y.C., 2010. Quasi-static indentation tests on aluminum foam sandwich panels. *Compos Struct*, 92(9), 2039-2046.
[11] Villanueva G.R., Cantwell W.J., 2004. The high velocity impact response of composite and FML-reinforced sandwich structures. *Compos Sci Technol*, 64(1), 35-54.
[12] Hanssen A.G., Girard Y., Olovsson L., et al., 2006. A numerical model for bird strike of aluminum foam-based sandwich panels. *Int J Impact Eng*, 32(7), 1127-1144.
[13] Zhao H., Elnasri I., Girard Y., 2007. Perforation of aluminum foam core sandwich panels under impact loading-an experimental study. *Int J Impact Eng*, 34(7), 1246-1257.
[14] Hou W., Zhu F., Lu G., et al., 2010. Ballistic impact experiments of metallic sandwich panels with aluminum foam core. *Int J Impact Eng*, 37(10), 1045-1055.
[15] Buitrago B.L., Santiuste C., Sanchez-Saez S., et al. 2010. Modelling of composite sandwich structures with honeycomb core subjected to high-velocity impact. *Compos Struct*, 92(9), 2090-2096.
[16] Ivanez I., Santiuste C., Barbero E., et al., 2011. Numerical modelling of foam-cored sandwich plates under high-velocity impact. *Compos Struct*, 93(9), 2392-2399.
[17] Yu J.L., Wang X., Wei Z.G., et al., 2003. Deformation and failure mechanism of dynamically loaded sandwich beams with aluminum-foam core. *Int J Impact Eng*, 28(3), 331-347.
[18] Bazant Z.P., Zhou Y., Daniel I.M., et al., 2006. Size effect on strength of laminate-foam sandwich plates. *J Eng Mater Tech*, 128(3), 366-374.
[19] Tekoglu C., Gibson L.J., Pardoen T., et al., 2011. Size effects in foams: experiments and model. ing *Prog Mater Sci*, 56(2), 109-138, doi 10.1016/j.pmatsci.2010.06.001