Steel and Composite Structures, *Vol. 20, No. 5 (2016) 983-997*
DOI: http://dx.doi.org/10.12989/scs.2016.20.5.983

The effect of curvature on the impact response of foam-based sandwich composite panels

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(*Received October 12, 2015, Revised December 24, 2015, Accepted December 29, 2015*)

Abstract. The aim of this study is to investigate the impact behavior and impact-induced damage of sandwich composites made of E-glass/epoxy face sheets and PVC foam. The studies were carried out on square flat and curved sandwich panels with two different radius of curvatures. Impact tests were performed under impact energies of 10 J, 25 J and 80 J using an instrumented drop-weight machine. Contact force and displacement versus time and contact force- displacement graphs of sandwich panels were presented to determine the panel response. Through these graphs, the energy absorbing capacity of the sandwich panels was determined. The impact responses and failure modes of flat and curved sandwich panels were compared and the effect of curvature on sandwich composite panel was demonstrated. Testing has shown that the maximum contact force decrease while displacement increases with increasing of panel curvature and curved panels exhibits mixed failure mode, with cylindrical and cone cracking.

Keywords: sandwich composite; curved panel; impact; foam core

1. Introduction

Sandwich composite structures can be successfully used as a valid alternative in many areas where a lightweight material with high bending stiffness and high strength is needed. The concept behind these structures is the attachment two thin but stiff skins to the lightweight but thick core. Although these superior performance sandwich composites are particularly susceptible to low velocity impact damage than similar metallic structures. Sandwich composite materials may encounter low-velocity impacts during maintenance or operating conditions. Though the induced damage may be barely visible or invisible, especially for low-velocity impacts, the strength and reliability of the structure can be affected. Hence, the behavior of sandwich structures under impact has received increasing attention.

A large number of studies have been performed on the effect of impact loading on composites. In laminated composite, laminate thickness, material of the fiber and orientation angle affects the low velocity impact response and energy absorption capability of composites (Belingardi and Vadori 2002, 2003). The effect of plate dimensions and impactor masses on contact duration, maximum impact force and damaged area has been demonstrated by numerical and experimental studies (Aslan *et al*. 2003, Uyaner *et al*. 2007). In destructive and non-destructive inspections, the

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http://www.techno-press.org/?journal=scs&subpage=6 ISSN: 1229-9367 (Print), 1598-6233 (Online)

exposed to the same energy level, different impact damage area has been observed for three geometry of the impactor (Mitrevski *et al*. 2005, 2006). The effect of different impact velocities on contact force, rebounding speed and displacement has been investigated in another study (Yapıcı and Yapıcı 2012).

The impact behavior of flat laminated composites has hitherto been studied widely with different materials and various parameters. There are few studies that address the low-velocity impact response of curved laminated composite panels. Kistler and Waas (1998, 1999) studied with cylindrically curved laminated panels to investigate the effect of impactor velocity, panel curvature, thickness, and both in-plane and out-of-plane boundary conditions on the resulting impact force and panel displacement. During their other investigation it was observed that the flatter panels responded to impact with larger peak forces than more curved panels, as well as smaller peak displacements and contact durations. Ganapathy and Rao (1998) carried out a nonlinear finite element analysis to predict the progressive failure in laminated composite cylindrical/spherical shell panels subjected to low-velocity impact by making various assumptions. The effect of preloading on the impact response of curved laminates was considered by Saghafi *et al*. (2014). They applied pressure to the upper and lower surfaces of specimens and consequently showed that the preload caused more damaged area, less total absorbed energy. Increased preload led to an increase in maximum load and a decrease in displacement.

Although extensive research has been devoted to the impact behavior of flat and curved laminated composites, the work on sandwich composites, especially curved ones is somewhat limited. Many researchers have conducted impact tests on flat sandwich composites with different face sheets and core materials. Dynamic responses of flat $[0_2/90_2/0_2/\text{FOAM}]_s$ sandwich plate with graphite/epoxy faces and FR10110 rigid foam core were investigated by Lee *et al*. (1993). Load–strain response of woven carbon/epoxy face sheets and PVC foam core sandwich panels under central point impact and central point quasi static loading has been compared by Schubel *et al*. (2007). Leijten *et al*. (2009) investigated the effect of thickness, density and type of foam core as well as thickness of face sheet on low-velocity impact behavior of flat sandwich panels. Srivastava (2012) conducted impact energy tests on the sandwich structures using Izod impact, Charpy impact and weight drop impact testers. His results indicate that weight drop impact energy gives lower dynamic fracture toughness while the energy absorption behavior is higher values. Hazizan and Cantwell (2002) improved an energy balance model with changing the impact energy of the falling impactor as well as the properties of foam core in order to predict the impact response of a foam based sandwich structure. It was shown that the impact response of foam based sandwich structures depends on the elastic properties of the foam core material. Zhou *et al*. (2012) investigated the low velocity perforation resistance of sandwich structures. Their finding showed that shear mode of failure is important in determining the perforation resistance of thin-skinned sandwich structures. However, the impact response of foam based sandwich structures also depends on the curvature. Little effort has been directed to determining impact response of curved sandwich panels even though they are extensively used in various engineering applications. You *et al*. (2010) conducted experimental investigations on a non-metallic honeycomb sandwich structures with glass/epoxy skins. They showed that radius of curvature is an important structural parameter on mechanical performance of composites. Shen *et al*. (2010) presented an experimental study in order to show effects of air blast loading on curved sandwich panels with aluminum face sheets and aluminum foam core. The authors showed that the blast intensity, core thickness and face sheet thickness were the principal parameters responsible for the final deflection of the curved sandwich panels. As can be seen from literature survey, understanding of the impact response of curved sandwich composites is essential for designing of the sandwich structures.

The main goal of this work was to present and discuss some experimental results obtained during impact tests on curved sandwich panels consisting of E-Glass/epoxy face sheets and a PVC foam core. The influence of the curvature on the impact response of the sandwich panels under various impact energy levels was discussed. The impact behavior of this particular class of composite material was then analyzed from an energy viewpoint, by means of contact force-displacement graphs. Damage process during impact was also observed by examining the characteristics of contact force-displacement curves and corresponding sectioning images of for each damaged panels.

2. Experimental Studies

2.1 Materials

The sandwich panels used in the present study made of composite laminate face sheets and foam core. The face sheets of the sandwich panel made of four plies dry E-glass fabric material oriented [0°/90°/+45°/-45°] configuration seen in Fig. 1. Epoxy was used for providing adhesion between dry fabric and foam material. Table 1 lists mechanical properties of unidirectional E-glass/epoxy composite obtained from mechanical tests according to ASTM D3039, ASTM D3410

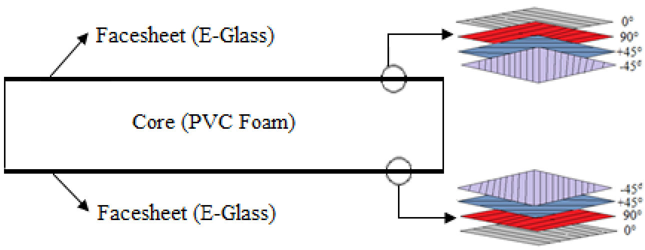

Fig. 1 Materials in sandwich panel

Table 1 Mechanical properties of unidirectional E-glass/epoxy facesheet

E_1 Young's modulus (GPa)	E_2 Young's modulus (GPa)	v_{12} Poisson's rtio	G_{12} Shear modulus (GPa)	X_t Tensile strength (MPa)	Y_t Tensile strength (MPa)	X_c Compression strength (MPa)	Y_c Compression strength (MPa)	S Shear strength (MPa)
31	12	0.3	3.2	706	123	472	183	77

Table 2 Mechanical properties of Airex C70.55 foam core

Density (kg/m^3)	Compressive strength (MPa)	Compressive modulus (MPa)	Tensile strength (MPa)	Tensile modulus (MPa)	Shear strength (MPa)	Shear modulus (MPa)	Shear elongation at break (%)
60	0.90	69	1.3	45	0.85	22	16

and ASTM D7078 Standarts. The core material in sandwich panels is AIREX C70.55 closed cell, cross-linked polymer foam. Mechanical properties of foam core that is taken from the manufacture company's catalog (http://www.3accorematerials.com/products/airex/airexreg-c70.html) are presented in Table 2.

2.2 Test specimens

Sandwich composite panels studied in this work were fabricated by vacuum assisted resin infusion molding (VARIM) method using Huntsman UN3082 epoxy with Huntsman UN2735 hardener. Composite panels were manufactured in two types, flat and curved. The radius of curvature of panels was changed with R = 100 mm, 160 mm and ∞ (Flat) (See Fig. 2). Three specimens were produced for each energy level. All of the sandwich panels had a thickness of 16.5 mm. The face sheets of panels were of equal thickness of 0.75mm, while the foam core was 15 mm thick.

The flat panels were produced on flat aluminum bench while curved specimens were manufactured using special curved molds. Before manufacturing of curved panel, foam core was thermoformed (See Fig. 3) for 45 minutes in furnace at 130°C specified in the technical catalog. Panels were cured at room temperature for more than 24 h. After curing, panels were post-cured at 80°C for 15 h. The panels were cut into specimens of 100×100 mm in dimension using a cutting machine with a diamond coated blade and tested without any treatment or modification. All specimens were visually inspected for any defects which could affect the experimental data.

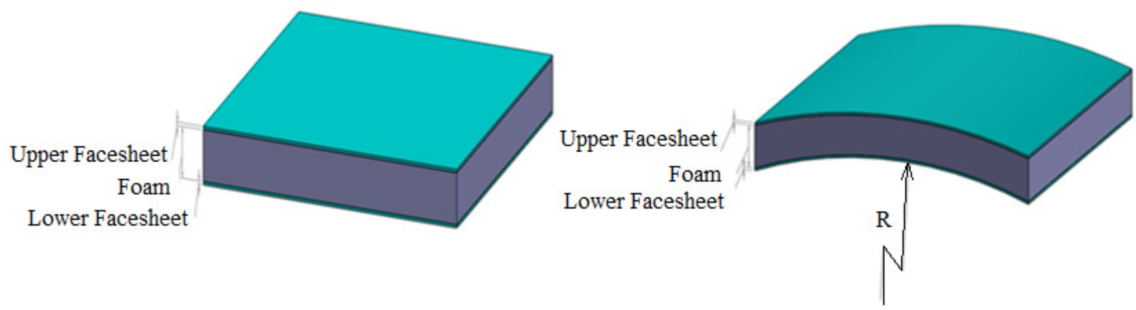

Fig. 2 Illustration of flat and curved sandwich panels

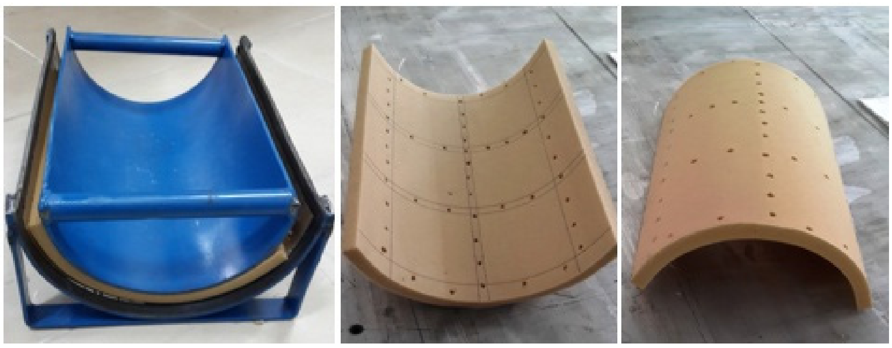

Fig. 3 Preformed foam material

(a) Front view (b) Top view

Fig. 4 Photos of clamping apparatus for curved panel

2.3 Impact tests

Impact loading was applied to the panels by an instrumented drop weight impact test system (CEAST-Fractovis Plus impact test machine). All sandwich composites were subjected to various impacts from a 4.926 kg impactor, which had a hemispherical nose, 12.7 mm in diameter. The drop tests have been conducted selecting different levels of kinetic energy at impact by modification of the drop height. The square composite specimens with dimensions of 100 mm × 100 mm were clamped on a fixed support along a circle having a 76.2 mm diameter which was the area opened to the impact and impact load applied on the upper face sheet and the center of each panel. Fig. 4 shows the clamping apparatus views, specially designed for supporting curved specimens. Lower apparatus was manufactured in panels radius of curvature and panel thickness had been taken into consideration in design of upper apparatus (See Fig. 4(a)). The clamped area created utilizing the weight of the clamping apparatus can be seen in Fig. 4(b). The force applied by the impactor on the specimen was taken from piezoelectric force sensor that can acquire 16,000 points at a frequency of up to 2 MHz. The loadcell of the system had a maximum loading capacity of 22.4 kN and thanks to the data acquisition system of impact test machine, force values was recorded and then converted to acceleration, velocity and displacement as a function of time using Newton’s second law. Also, from the integrating the area bounded by force-displacement curve, energy absorbed by specimen was determined. All tests were performed three times at all energy levels for each specimen.

3. Results and discussion

In this study, impact tests were performed on three types of specimens: flat and curved sandwich panels with two different radii of curvatures. Contact force, velocity and displacement versus time or contact force with displacement were investigated in order to figure out damage modes of curved sandwich panels in an impact event. For this purpose, a number of tests were performed under various impact energies such as 10 J, 25 J and 80 J. The average displacement and peak load values of the specimens were presented in Table 3 with standard deviations. For better understanding of impact response, some images of the damaged specimens were presented.

3.1 Impact response of the flat sandwich panels

Fig. 5 shows the contact force-time, displacement-time, contact force-displacement, velocity

Table 3 The average displacement and peak load values of the flat and curved specimens for 10J, 25J and 80J impact energies

Specimen code	Impact energy level	First peak load (kN)	Displacement at first peak load (mm)	Second peak load (kN)	Displacement at second peak load (mm)	Absorbed energy (J)
Flat	10 J	2.33 (0.85)	6.866 (0.523)	-	-	10.46 (0.82)
	25 J	27.31 (1.10)	5.985 (0.352)	21.10 (1.04)	25.451 (0.327)	25.93 (0.79)
	80 J	23.73 (2.15)	6.671 (0.212)	27.98 (1.67)	24.626 (0.282)	24.05 (0.89)
R160	10 J	21.41 (0.98)	6.801 (0.612)	-	-	10.50 (0.82)
	25 J	26.84 (1.06)	6.598 (0.581)	15.39 (1.84)	27.679 (0.154)	26.32 (0.78)
	80 J	23.93 (1.74)	7.071 (0.265)	25.09 (1.81)	26.621 (0.216)	27.11 (0.99)
R100	10 J	20.01 (1.07)	7.076 (0.556)	-	-	10.53 (0.94)
	25 J	24.95 (0.93)	6.654 (0.343)	16.00 (1.43)	28.651 (0.269)	26.36 (0.83)
	80 J	22.36 (0.55)	7.308 (0.381)	22.79 (0.84)	28.184 (0.237)	27.31 (0.71)

The values given in parentheses are standard deviations.

time curves and cross sectional view of damaged flat specimens at three different impact energy levels.

Fig. 5(a) which indicates the contact force-time histories of the impactor in contact with the specimen during impact event for three impact energy levels gives important information about nature of damage. In the case of 10 J impact energy, it can be seen that contact force increases nonlinearly within the time at the first part of the contact force-time curve (loading section). After the maximum value of the contact force, in the second part (discharging of the load section/unloading section) the curve reaches zero showing less fluctuation than in loading section. Contact duration at this part is due to the friction between the impactor and panel. Associated with increased impact energy, occurring of two peaks in the force-time curve is observed. For instance, when the 10 J of impact energy is applied to the specimens, only one peak is observed in force-time curve of sandwich panels, because it is such the impactor without contact with the lower face sheet of specimen. As it is seen from 25 J curve, damaging in both side of the specimen is clear and two peaks occur. As the first peak indicates that the impactor is on upper face sheet, appearance of a second peak indicative of contact with the lower face sheet of the panel. As can be seen from curves, when the impact energy is high, contact duration at first peak force decreases. Similar situation occurs at time of second peak of contact force. Second peak force of flat panels at 25 J impact energy occurs at 12.23 ms, whereas second peak force at 80 J impact energy is reached at 4.67 ms.

Displacement-time curves in Fig. 5(b) give the displacement of the impactor during contact between the impactor and the panel. There are no sudden ups and downs encountered in the contact force-time curves in these curves. This case reveals that the kinetic energy of impactor is effectively spent. After reaching a maximum value of displacement, decline in the displacement-time curve shows rebounding of the impactor, staying about the same in this curve indicates the impactor began to penetrate the specimen and ascending of it continuously presents the impactor perforated the specimen. By examining the displacement-time curves, it is seen that panels respond to impact with high displacement and low contact durations at high impact energy.

Variation of the velocity with time for three impact energies is given in Fig. 5(c). Each curve is of the highest value at the time is zero. The velocity decreases versus time and becomes zero around the time that maximum deflection is reached for non-perforated panels. For 25 J impact energy case the curves have negative values, implying rebounding of the impactor. However, for 80 J impact energy case, velocity curves versus time have no negative values because of no rebounding.

From the Fig. 5(d) presented the variations of the contact force as a function of displacement

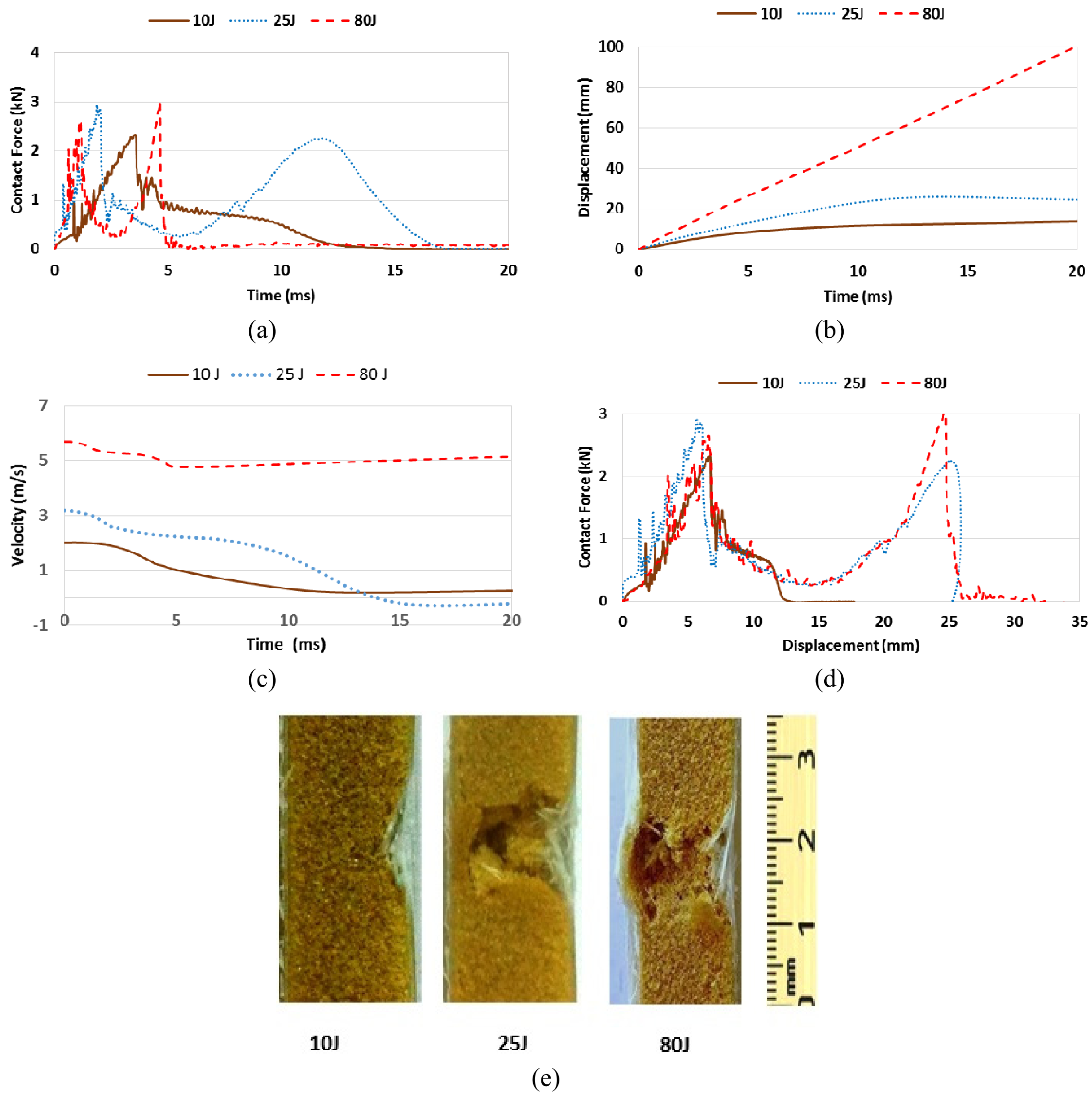

Fig. 5 The flat panel graphics: (a) contact force-time; (b) displacement-time; (c) velocity-time; (d) contact force-displacement; and (e) cross-sectional view of the damaged flat specimens for 10 J, 25 J and 80J impact energies

for three different impact energies, it is seen that the contact force and displacement values increase by increasing the impact energy. Contact force-displacement curves consist of two basic types: closed and open curve. The rebounding case results in closed curves. As the impact energy increases, displacement increases and the rebounding section of curve is getting smaller. When the impactor penetrated to the specimens, the curves remain stable and with the start of perforating, the curve starts opening. Rebounding, penetrating and perforating are three typical situations encountered in impact tests and can be followed by investigation of contact force-displacement curves as seen in Fig. 5(d). For example, as the increasing amount of displacement in the last part of the single-peaked contact force-displacement curve resulting in 10 J of impact energy shows progress of the impactor in the foam, decreasing the amount of displacement in the last section of two peaked curve occurring with 25 J of impact energy indicates the impactor rebounds from the second face sheet. Damaging in both side of the specimen and perforation are clear in the curve for 80 J of impact energy. Damage process of sandwich panels can be followed from section images of damaged specimens shown in Fig. 5(e).

3.2 Impact response of the curved sandwich panels

In order to comparison of impact response of flat and curved panels, the same energy levels applied to the flat specimens were used in the impact tests of curved specimens with 160 mm and 100 mm radius. Contact force-displacement and velocity-time curves of curved panels impacted with three different energy levels is presented in Fig. 6 for each radius of curvature.

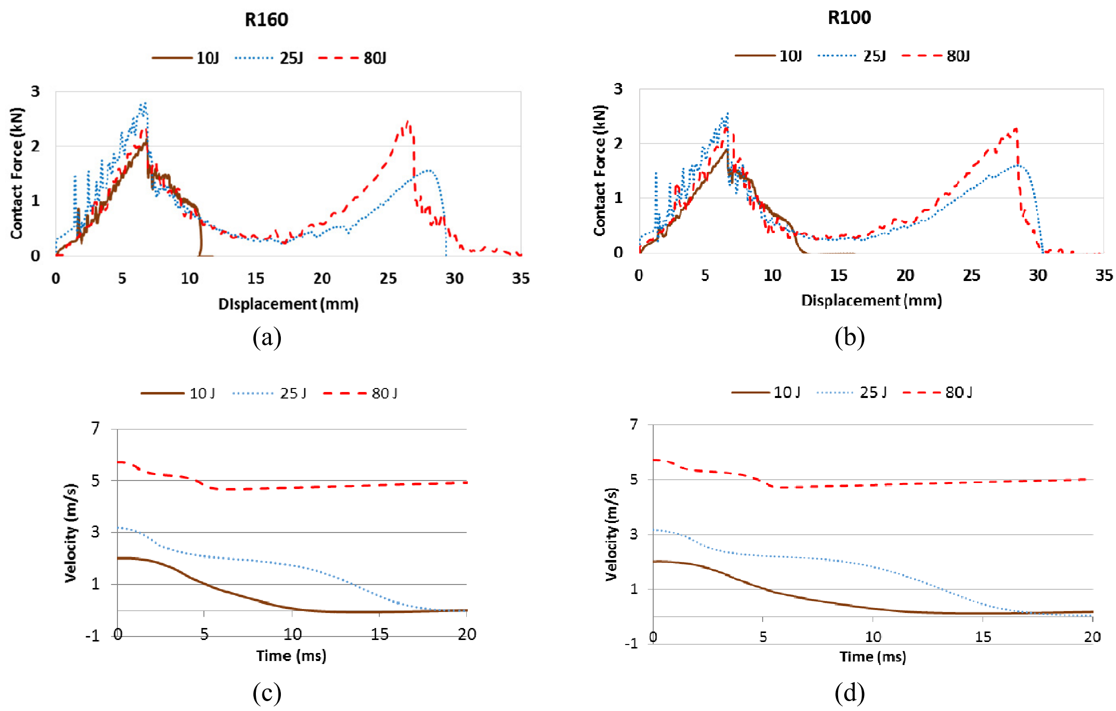

Fig. 6 (a) Contact force-displacement graph of R160 panel; (b) Contact force-displacement graph of R100 panel; (c) Velocity-time graph of R160 panel; (d) Velocity-time graph of R100 panel

As it seen from the curves, although a certain influence of the curvature can be noted on the magnitude of the results, same conclusions as for the graph of Fig. 5 can be drawn. The amount of contact forces and displacement increases similar to the flat panel results with increasing impact energies. From the examination of these graphs, when the impact energy is low, it is not possible to see second peak load. At 10 J of impact energy case, contact force-displacement curve has a single peak for curved specimens with R160 and R100. Upper face sheets of all specimens are perforated with this energy level of impact. When the impact energy is high enough, the second peak load is detectable. Two peaked contact force-deflection curve emerges at 25 J of impact energy. It is concluded that 25 J of energy is enough to contact of the impactor on lower face sheet of the curved specimens. While displacement increases or remains about the same for the curved panels after curve reaches the second peak force, displacement reduces for flat panels. The rebounding of the impactor from the lower face sheet of the flat panel is the indicator that complete perforation of the lower face sheet has not occurred. In the event of impact energy level is 80 J, all specimens are perforated and results show higher contact force at this impact energy level than those of observed at small impact energy. This trend is repeated in all cases for curved panels. In addition, for the 80 J energy level, the second peak load is higher than the first peak load or nearly the same for curved and flat panels.The second peak load indicates the stiffness of lower face sheet to impact loading. The second peak is formed with load transfer to the lower face sheet when the core is compessed under impact loading. The increasing of the compresed foam stiffness attributes to the increasing of the lower face sheet stiffness. Whereas, damaged core within crashed region does not offer support to the face sheet for low impact energy level.

3.3 Damage modes of curved sandwich panels

In order to understand damage process and to establish a relationship between force-displacement curves and damage modes, the contact force-displacement graphs and corresponding images of the specimens impacted by different energies are given in Figs. 7-9.

10 J of impact energy case is handled in Fig. 7. As can be seen from force-displacement curves in Fig. 7, although force-displacement curves show almost the same trend for all panels, the peak load decreases and displacement at which load drop occurs increases slightly with the increasing of the curvature. This shows that the upper face sheet and core resistance does not change significantly with curvature. The highest peak load (2.25 kN) and the smallest displacement at which peak load occurs (6.5 mm) appear for flat panel. Sudden load drop in the loading part of the panels indicates damage occurrence in the upper face sheet. After impact, damage modes manifest as delamination, face sheet fracture and foam crushing. From the zoomed images of impacted side of damaged specimens, it is obvious that there is an only local deformation including fiber and matrix breaks of the upper face sheets. Though the damage looks similar in flat and curved panels, damage area and damage shape are different for flat and curved panels. Meanwhile, both indentation of the upper face sheet and core crushing below the partially penetrated face sheet is seen due to compression. When the panel curvature increases, larger damaged area around the contact point of impactor and smaller crushing of core appears. Damage size on upper face sheet of flat panel is small because dominant faiure mode is core crushing. This may be explained that the moments generated in the upper face sheet of flat panels are smaller compared to the curved panels and indentation is relatively high. Therefore, impact energy leads to larger damaged area formed between layers of upper face sheet at curved panels. In other words, there is bigger permanent indentation of the impacted face sheet of flat panel indicating core crushing but smaller

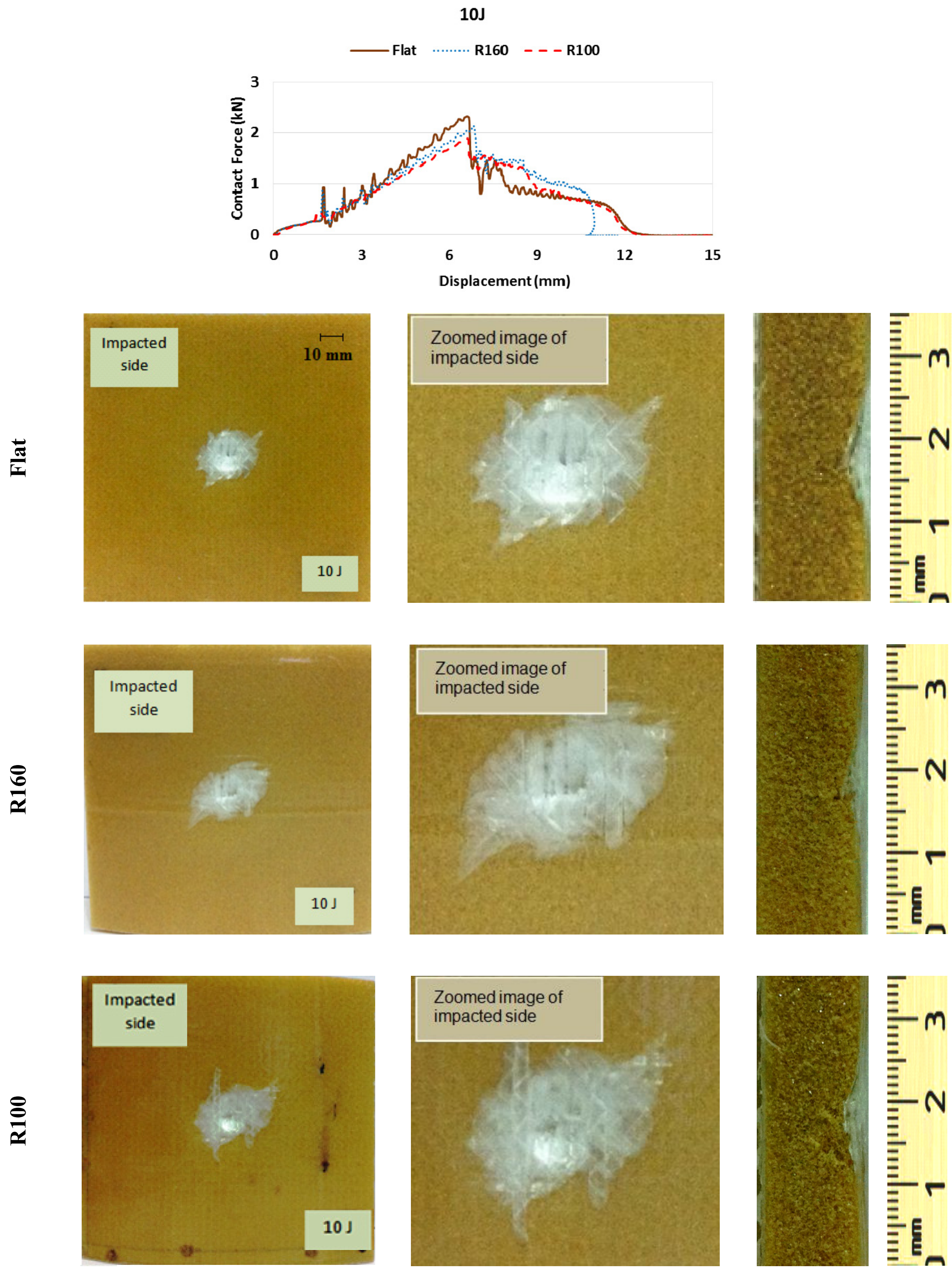

Fig. 7 Contact force-displacement curves with images of damaged specimens for 10 J impact energy

face sheet failure. In addition, the core reaction depends on the curvature of the specimen due to the alignment of the cell structure along the radial direction. The core support to the upper face

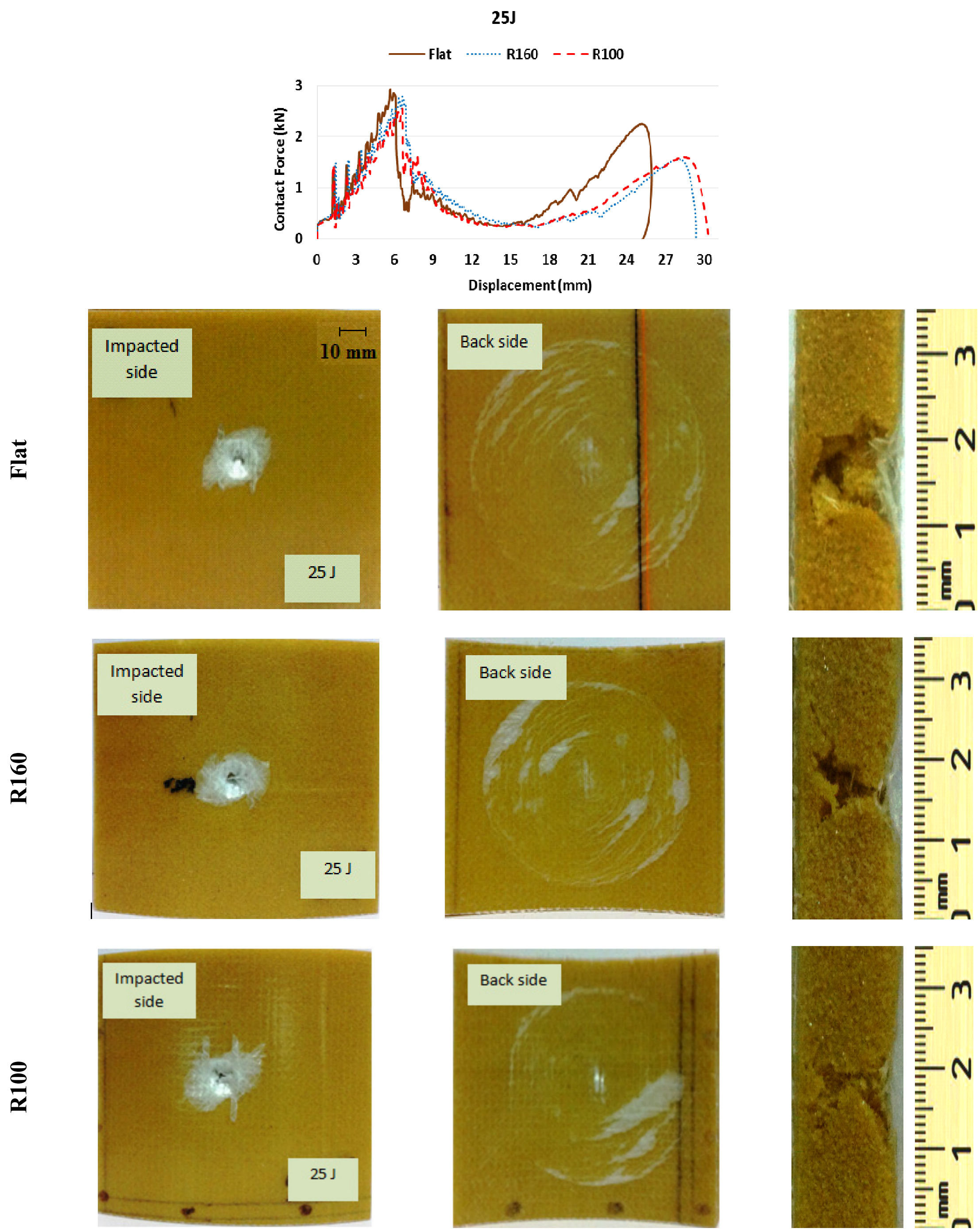

Fig. 8 Contact force-displacement curves with images of damaged specimens for 25 J of impact energy

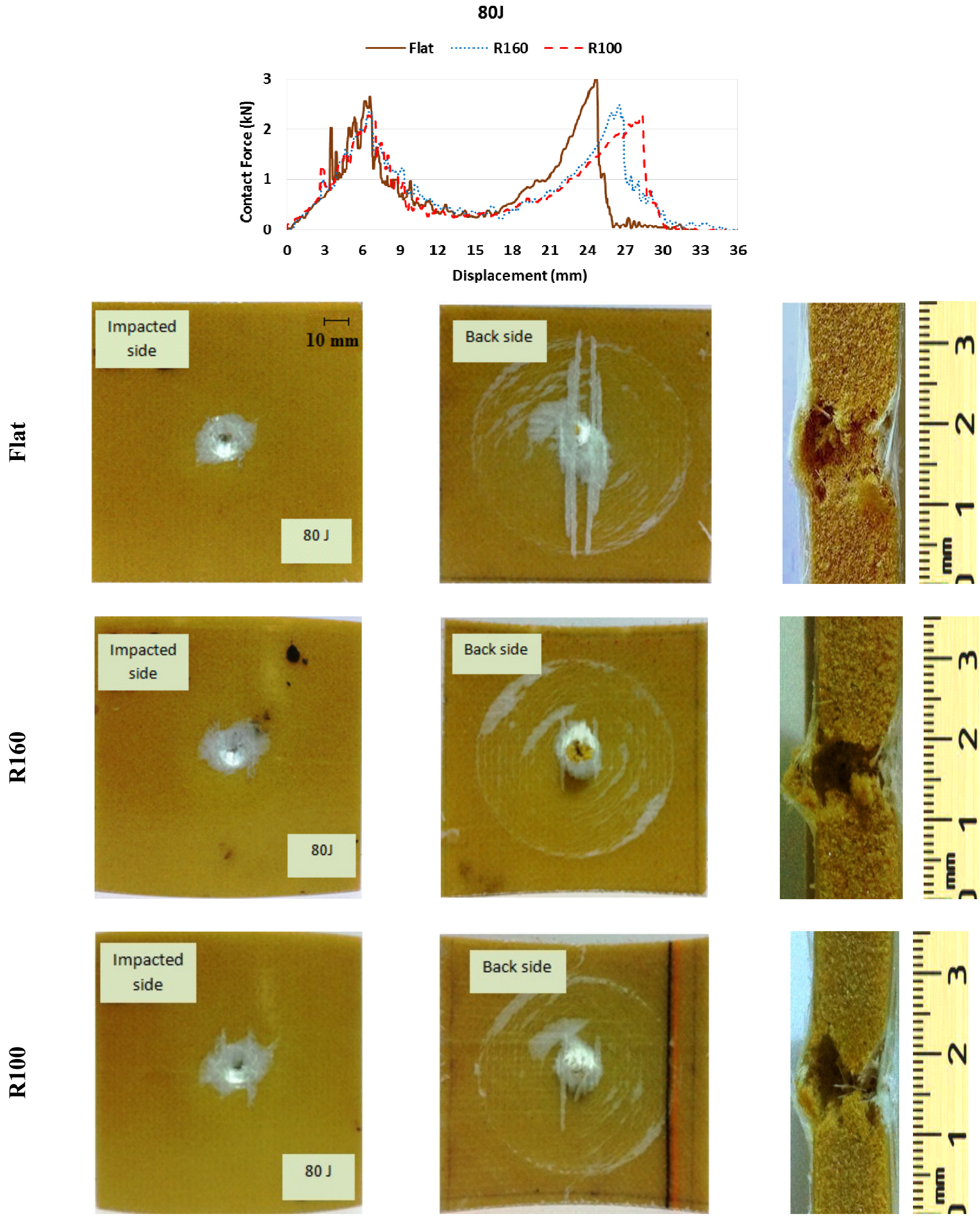

Fig. 9 Contact force-displacement curves with images of damaged specimens for 80 J of impact energy

sheet decreases due to the eccentricity of the cell when curvature increases. The planar shape of the damage area at the upper face sheet of flat panels is circular whereas different shaped damage is seen in the direction of the fibers for curved panels. In addition, visual examination of the impacted specimen shows any damage on the back side of the panels at 10 J impact energy.

In 25 J of impact energy case (See Fig. 8), the contact force-displacement curves show almost similar trend until displacement at which first peak load drop occurs. After this point difference between the curves becomes apparent. The second peak force of curved specimens decreases compared to flat one and curves extend to the right with increasing of the curvature. This result indicates that panel becomes softer and more susceptible to damage. In other words, displacement is dependent of the panel curvature at high impact energy level. When 25 J of energy applied to the specimens, fiber-matrix cracks of upper face sheet and the separation between layers of lower face sheet occur. While there is a rebound section and no perforation of flat specimen, the curved specimens are on the perforation threshold.

In 80 J of impact energy case (See Fig. 9), the contact force-displacement curves show almost the same trend compared with the curves obtained for 25 J impact energy. However, all specimens perforate and there is no rebound section of the curves at 80 J impact energy level. Sudden drop in the second peak load is seen. Depending on the increasing curvature, curves shifts to the right similar to those of other impact energy. When the damage states are compared between flat and curved specimens at 80 J impact energy level it is observed that damaged region on the back side of the panel is clear compared with the damaged region of the specimens applied 25 J impact energy. Damage area formed at lower face sheet has been more local for the specimen with high curvature due to the differences in stiffness loading to different failure modes. Curvature affects either global stiffness or contact stiffness due to the radial compressive properties of the core.The section images of damaged specimens show that perforation zone is cylindrically-shaped for flat panels (Zhou *et al*. 2012), although cone crack exhibits for curved panels.

3.4 Absorbed energies of curved sandwich panels

The kinetic energy of the impactor before impact took place is the impact energy. While a portion of impact energy is absorbed by specimen, the other part remains on the impactor as kinetic energy. The energy absorbed by specimen is in the form of bending energy and energy absorbed by damage creation including delamination, fiber breakage and matrix cracking, foam crushing etc. The amount of energy absorbed by the sandwich panel is important in indicating of the impact resistance. Contact force-displacement curve is used in the calculation of the energy absorbed by the panel. The area under this curve gives the absorbed energy. Table 4 shows the absorbed energies at 80 J of impact energy level for each radius of curvature and flat specimens. As can be seen from table, the amount of energy absorbed by the specimen until perforation increases with increasing of panel curvature. The most effective panel is the curved panel with R100 which exhibits the highest absorbed energy of 27.3 J.

Table 4 Absorbed energies of impacted sandwich panels

Specimen code	Absorbed energy (J)
Flat	24.05 (0.89)
R160	27.11 (0.99)
R100	27.31 (0.71)

4. Conclusions

The main goal of this study is to investigate the effect of curvature on the impact response of sandwich panels. For this purpose square sandwich composite panels, flat and two different radii of curvatures were manufactured. Contact force–deflection graphs of curved and flat sandwich panels were presented to determine the impact response of the sandwich panels. Using these graphs, the energy absorbing capacity of the sandwich panels were determined and the impact responses of flat and curved sandwiches are compared. Finally, damage modes of the sandwich panels were observed.

The major conclusions of this study are summarized as follows:

- The contact force increases and contact duration decreases by increasing the impact energy for flat and curved panels.
- If the impact energy of the impactor is high enough, two peak load are seen at force-displacement curves. The first peak is the indicator of the impactor contact to the upper face sheet, the second peak is the indicator of the impactor contact to the lower face sheet.
- For the highest impact energy, while the second peak load attributed to the load carried by the lower face sheet is higher than the first peak load or nearly same, second peak load is lower than the first peak load for the lower energy level. In addition, displacement where peak loads occur decreases as impact energy increases.
- During impact event, various damage modes appear as delamination, face sheet fracture and transverse shear fracture and crushing of foam. The type of impact damage changes with curvatures and impact energy level. While the flat panels show local damage area, the curved panels have more extended damage area at the upper face sheet of sandwich panels.
- Increasing of panel curvature increases the amount of energy absorbed by the sandwich panel when perforation takes place.

Acknowledgments

Financial support for this study was provided by The Scientific and Technological Research Council of Turkey (TUBITAK/Project Number: 113M917) and Celal Bayar University Research Funds (2013-122).

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