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Low velocity impact behaviour of glass fabric/ epoxy honeycomb core sandwich composites

Abstract: In this paper, the low velocity impact characteristics of honeycomb sandwich panels with varying cell sizes such as the maximum load absorbed, absorbed energy and failure modes were investigated. Low-velocity impact tests were carried out at different energy levels using an instrumented drop-weight apparatus as per ASTM D3029-95. Honeycomb core sandwich composite panels were made with glass fabric/epoxy honeycomb core with different cell sizes i.e., 8, 12, 16 and 20 mm using the vacuum bag molding technique. Tests were conducted at impact energies that ranged ranging from 7 to 50 J. The energy absorption mechanism and the damage process are analysed with parameters derived from the load-time and energy-time curves. It is observed that at low energy levels, the core buckles while it gets crushed at higher levels. This buckling of the core is due to damage to the epoxy resin that allows the glass fiber to bend freely, and core crushing is due to the breakage of the glass fiber reinforcement within the core. It is inferred that for a given core height, as the cell size increases, the peak load at which cracking occurs in the face sheet decreases drastically. This is attributed to the fact that a core with a smaller cell size has fewer load paths to distribute the absorbed energy. It is evident from the post impact damage analysis that three types of failure modes occur viz., crack initiation, cracking of the face sheet along with debonding, and the crushing of cells. The common damage pattern observed on the front facing has a square shape which is the same as the shape of the indentor.

Keywords: honeycomb sandwich composite; impact behaviour; low velocity impact; sandwich structures.

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1 Introduction

Sandwich construction is of particular interest and is widely used, because the concept is very suitable and amenable to the development of lightweight structures with high in-plane flexural stiffness. Composite sandwich structures exhibit static properties such as high stiffness-to-weight ratio and high buckling loads which are of great importance in the aeronautics field [1]. However such structures are susceptible to low-velocity impact damage, which reduces the structural stiffness and strength. Low-velocity impact testing is a proven method to study the damage tolerance of composite materials. Damage that occurs due to low-velocity impacting is considered potentially dangerous because the damage might be left undetected. Impact damage is generally not considered to be a threat in metal structures because, owing to the ductile nature of these materials, large amounts of energy may be absorbed. In contrast, composites can fail in a wide variety of modes and only barely display impact damage which nevertheless severely reduces the structural integrity of the component. Most composites are brittle and so can only absorb energy by elastic deformation and through damage mechanisms, not by plastic deformation.

To understand the impact response and damage behaviours of sandwich structures, many researchers have studied the behaviour of structures under low velocity impact loading [1–5]. Castanie et al. [2] reported that the sandwich structure is relatively sensitive to impact loading due to its poor thickness reinforcement and that this may cause a premature failure of the structure. As a result, one of the main drawbacks is linked to a lack of knowledge on the effects induced by impact damage. Mines et al. [3] have described the low velocity perforation performance for a series of materials and geometry combinations and observed that their failure mechanism and energy absorption capability are governed by core and impact velocity. Dear et al. [4] have studied the damage behaviour of honeycomb sandwich panels from the onset of damage to catastrophic failure. Zhang et al. [6] revealed that there was a significant reduction in flexural properties due to impact induced damage and that the residual flexural strength is more susceptible to damage than residual modulus.

A vital element of sandwich construction is the effective bond between the facesheets and the core material. The joint must be stiff and strong, as well as tough, in order to allow the sandwich structure to sustain high loads over a long service life. The core, which is typically a low strength, lightweight material, is responsible for transmitting shear forces between the facesheets [7]. Kang et al. [8] conducted an experimental study to identify the strength reduction behaviour and its statistical properties for a sandwich structure subjected to low velocity impact. The strength reduction behaviour was evaluated via the residual strength prediction model. Composite sandwich panels constructed from glass-fiber-reinforced face sheets surrounding both foam-filled and nonfilled honeycomb cores were impacted using a drop-weight impactor at three energy levels and three temperatures by Erickson et al. [9].

Experimental studies were carried out using sandwich composite panel specimens, consisting of both polyurethane foam core and aramid honeycomb core (Nomex) type constructions by Raju et al. [10]. These specimens were subjected to impact damage at energy levels ranging between 7.56 and 15.6 J. A repair effectiveness factor was conceived and introduced to quantify the efficiency of the repair technique. Current sandwich composite impact theory does not consider impact energies that result in facesheet cracking, which is very common. Low energy impacts were considered because even in the absence of fiber breakage, the laminate mechanical performance can be drastically affected. These experimental impact tests are necessary to determine impact force and energy performance. Anderson and Madenci [11] conducted an experimental investigation concerning the low-velocity impact response of sandwich composites. Impact tests were conducted to characterize the type and extent of the damage observed in a variety of sandwich configurations with graphite/epoxy face sheets and foam or honeycomb cores.

Although many researchers have studied the effect of essential components of sandwich structures on damage following impacts, the damage behaviour of sandwich structures is greatly governed by both the material properties of the core and stiffener and their thickness and more research is necessary to understand the impact damage behaviour of sandwich structures composed of various essential components. In this study, sandwich composite panels made with glass fabric/epoxy honeycomb core with different cell sizes were fabricated using the vacuum bag molding technique and the impact behaviour is analysed by conducting an instrumented low-velocity impact test. The main aim of this work is to present and discuss some experimental results obtained during a low-velocity impact testing conducted on glass fabric/epoxy honeycomb core sandwich panels. Understanding damage phenomena is the key point of the general problem of impact on sandwich structures with honeycomb. Since these structures are composed of a core and laminated face sheets and their damage behaviour is affected by both

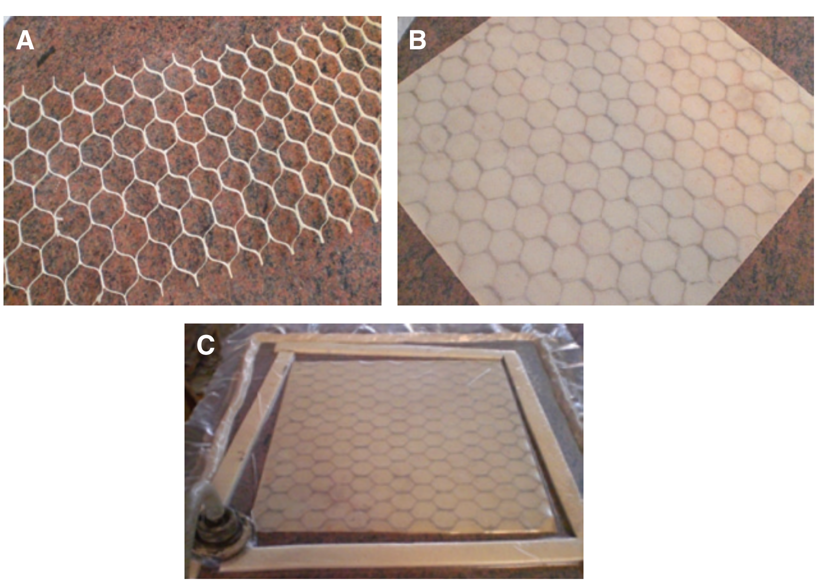


Figure 1 Fabrication of honeycomb sandwich panel. (A) Honeycomb core, (B) honeycomb core with face sheet, (C) honeycomb sandwich panel under vacuum.

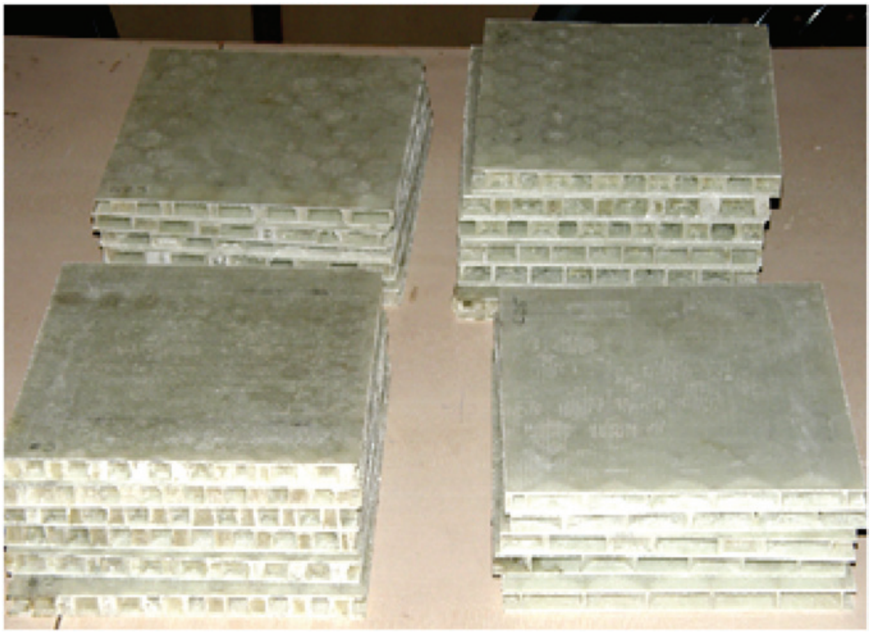


Figure 2 Honeycomb sandwich panels.

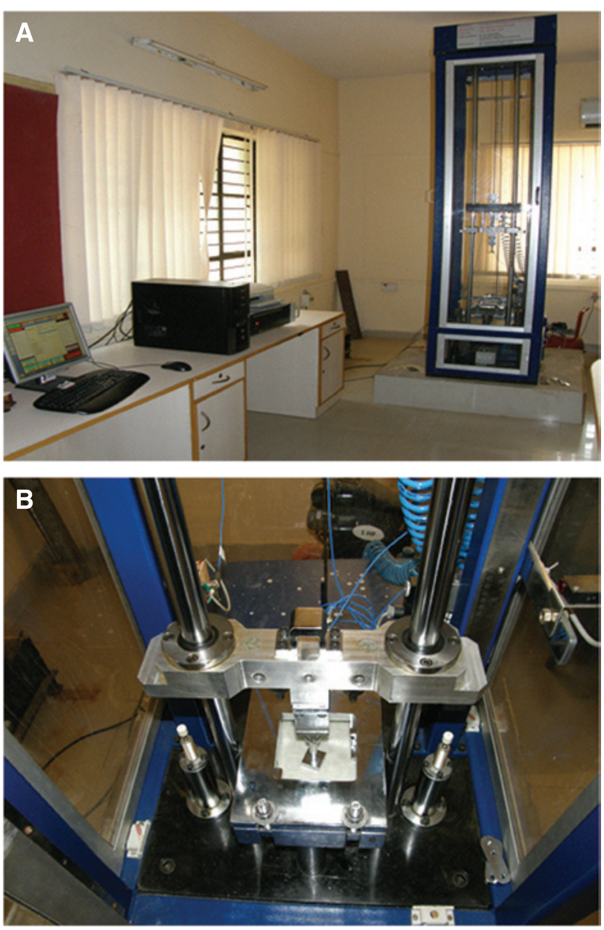


Figure 3 Low velocity impact test setup. (A) Instrumented falling weight impact testing machine. (B) Specimen clamping fixture.

materials, their damage behaviours under impact loading deserve careful investigation to ensure the reliability and safety of the sandwich structures. Core crushing is a complex mechanical phenomenon characterised by the appearance of various folds and failures in the hexagonal structures. For this reason, a detailed experimental study has been performed to characterise the damage created by the low-velocity impacts.

2 Fabrication of the sandwich composite

Glass fabric/epoxy honeycomb core sandwich panels were manufactured using vacuum bag molding. Bi-woven glass 'E' cloth, which is commercially available, and has a tensile strength of 3445 MPa, compressive strength of 1080 MPa and density of 2.58 g/cm^3 was used to make the face sheet. The cloth ply was trimmed to the correct size and impregnated in an adhesive made from a

Table 1 Impact test parameters.

Sample no.	Drop height (mm)	Drop mass (kg)	Impact energy (J)
1	500	2.576	12.64
2	1000	2.576	25.27
3	750	5.116	37.64
4	1000	5.166	50.19

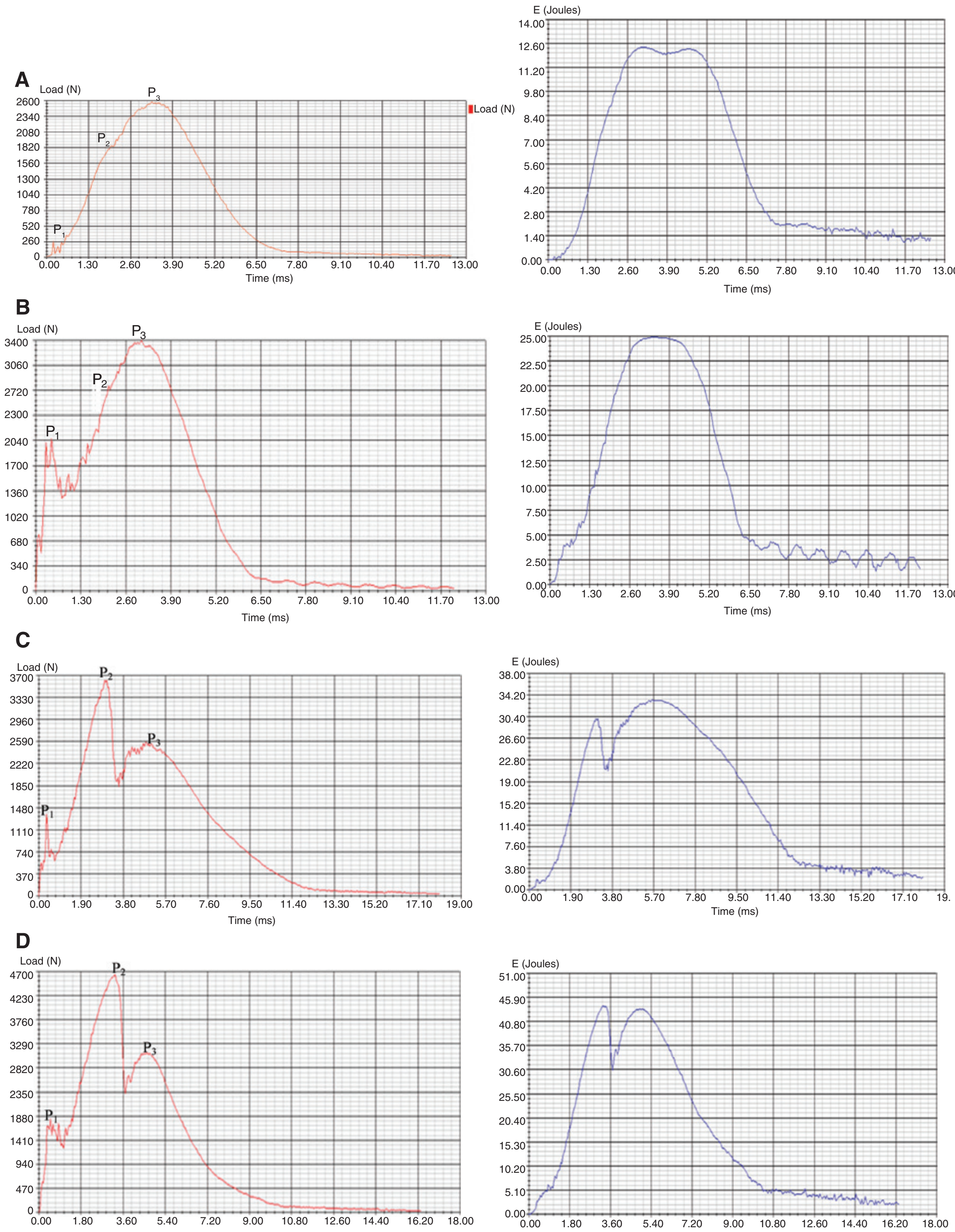


Figure 4 Load-time and energy-time plot for C8 panel at different impact energy levels. (A) Impact energy -12.64 J, (B) impact energy -25.27 J, (C) impact energy -37.64 J, (D) impact energy -50.19 J.

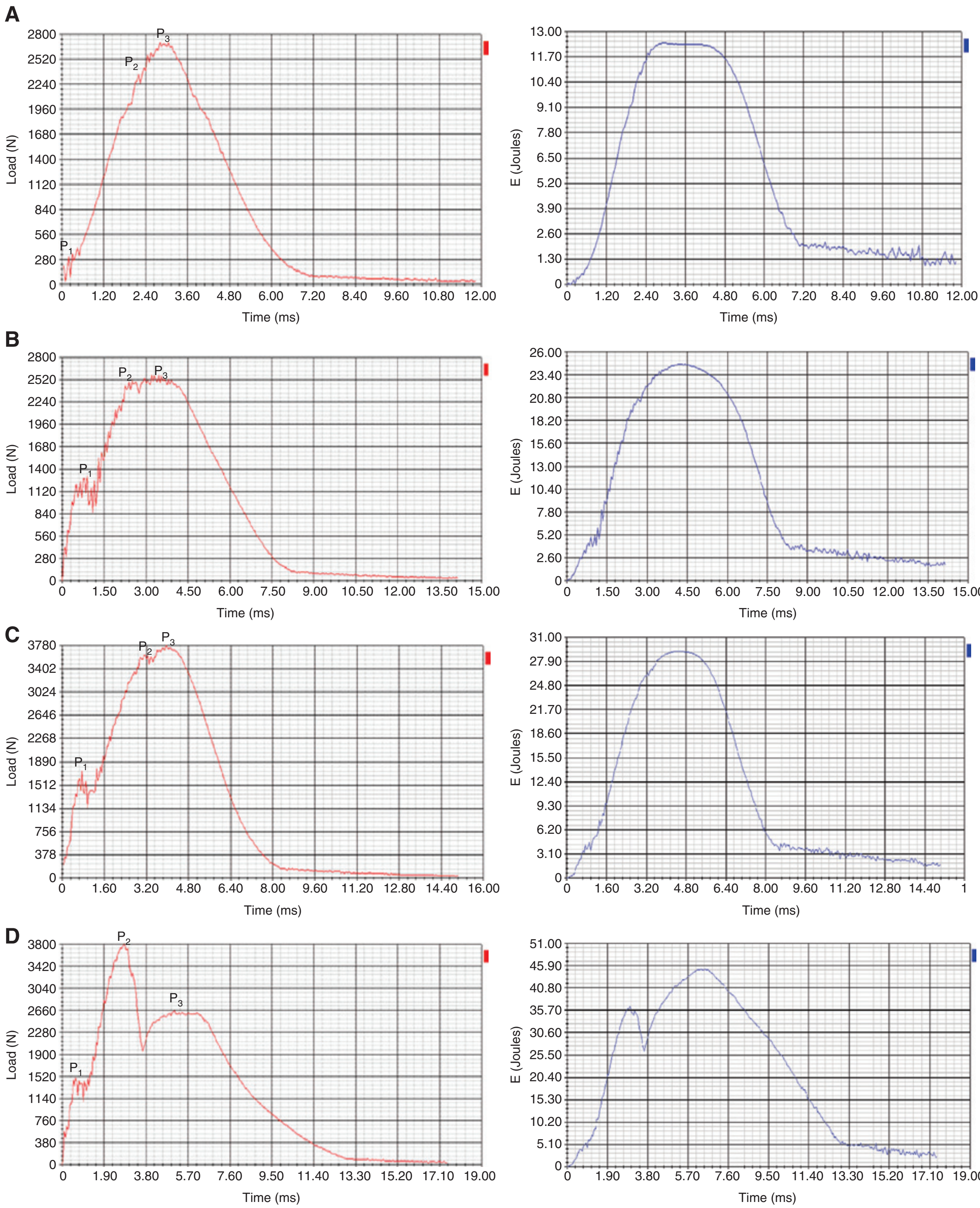


Figure 5 Load-time and energy-time plot for C16 panel at different impact energy levels. (A) Impact energy -12.64 J, (B) impact energy -25.27 J, (C) impact energy -37.64 J (D) impact energy -50.19 J.

mixture of LY556 epoxy resin and HY 951 hardener mixed in a ratio of 10:1. The epoxy resin mixed with hardener has a density of 1.19 g/cm^3, tensile strength of 52 MPa and shear modulus of 1230 MPa. The ply was stacked in 0°/90° orientation and was built to a thickness of around 2.0 mm. For the manufacture of the honeycomb core, the matrix used was epoxy resin LY 556 mixed with hardener HY 951-Huntsman Advanced materials (India) pvt., Ltd., Mumbai, India. Glass ‘E’ fabric was used as reinforcement.

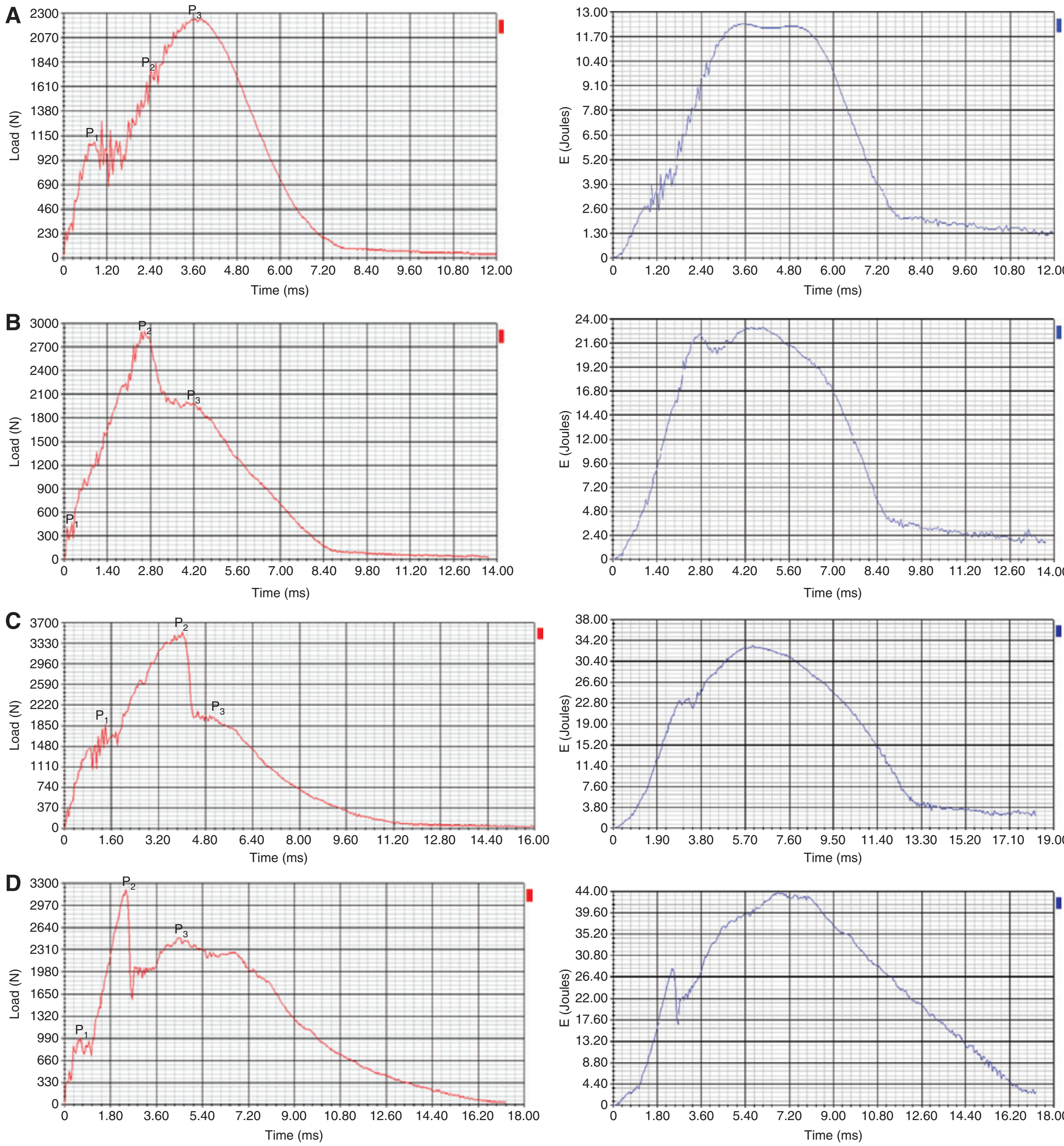


Figure 6 Load-time and energy-time plot for C20 panel at different impact energy levels. (A) Impact energy -12.64 J, (B) impact energy -25.27 J, (C) impact energy -37.64 J, (D) impact energy -50.19 J.

The hexagonal core was constructed in two halves that were joined together by placing the epoxy resin putty on the contact surface and was cut to the required thickness to form the hexagonal honeycomb core. For the fabrication of the sandwich panel, the facings comprised of the glass 'E' fabric were impregnated with the above mentioned resin mixture, coupled with the open honeycomb structure using epoxy resin, and compacted by means of the vacuum bagging technique. The steps involved in the fabrication of the honeycomb sandwich panel are shown in Figure 1. After curing, the sandwich panel was subjected to post curing in a hot-air oven at 100°C for up to 2 h. Four types of sandwich panels of size 500×500 mm were fabricated with different cell sizes, i.e., 8, 12, 16 and 20 mm. The cell shape of the finished honeycomb core is a regular hexagon. The membrane wall thickness of the

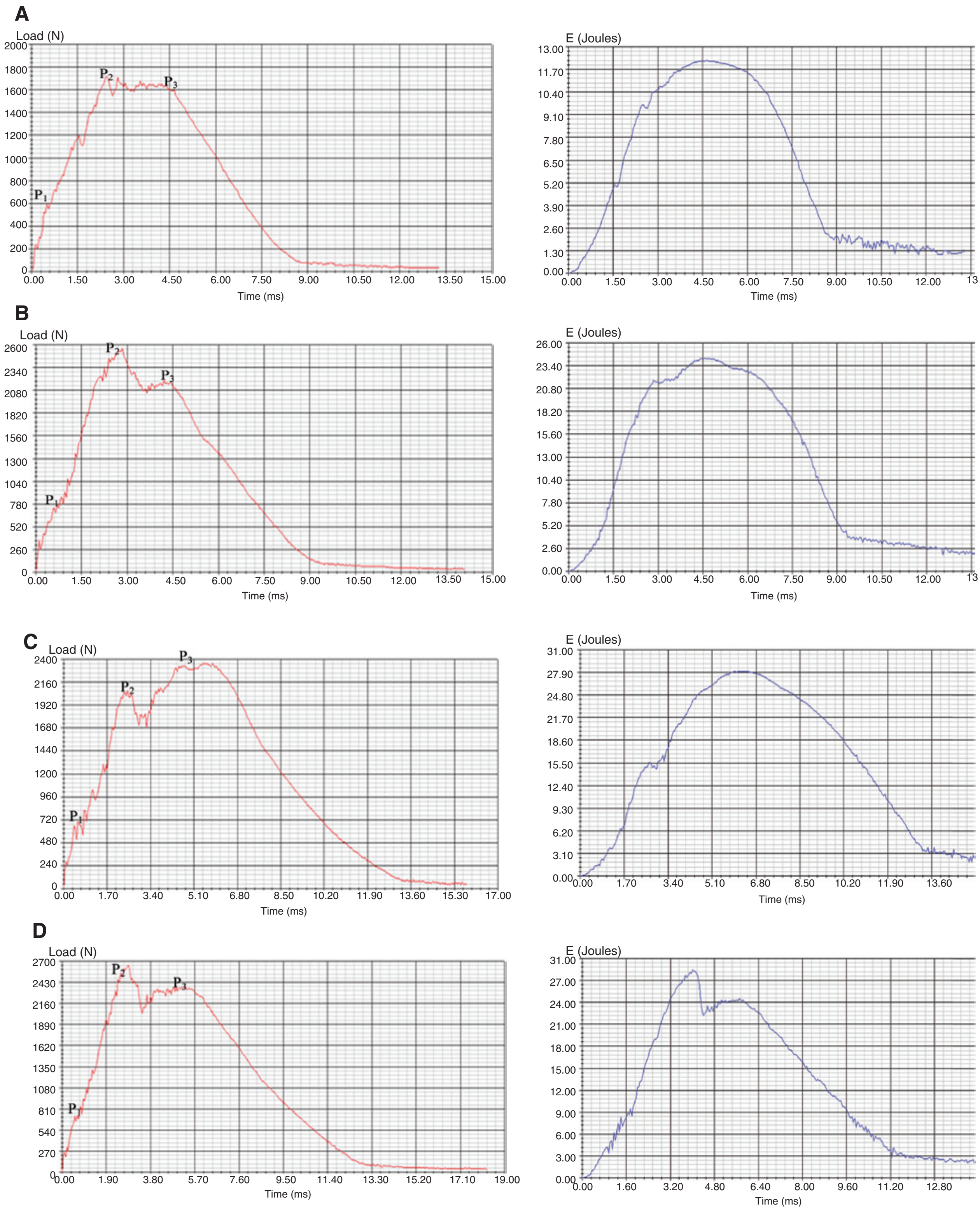


Figure 7 Load-time and energy-time plot for C25 panel at different impact energy levels. (A) Impact energy -12.64 J, (B) impact energy -25.27 J, (C) impact energy -37.64 J, (D) impact energy -50.19 J.

core is 0.2 mm and the height of the core is fixed at 8 mm. The thickness of the top and bottom face sheets has been kept constant at 1 mm. The cell sizes were selected based upon the ease of manufacture and testing requirements, as stipulated by the relevant standards. The fabricated test panels are shown in Figure 2.

3 Materials and methods

Low-velocity impact tests were carried out at different energy levels on the honeycomb sandwich panels, using an instrumented falling weight apparatus to obtain information about the absorbed energy and maximum impact force. Indigenously developed instrumented low velocity impact test equipment was employed to perform non-penetrating impact tests. The maximum impact energy is limited by adjusting the falling height and mass. The Instrumented falling weight impact testing machine is shown in Figure 3(A). In accordance with the ASTM D3029-95 [12] the impact test was performed by hitting the specimen in the centre with a flat square dart. The square dart is made of mild steel, and its dimensions were 25 mm×25 mm.

Figure 3(B) shows the specimen clamping apparatus which has a fixture with a square slot of 100 mm. This is specifically designed in order to assure the consistency of the clamping force through the pre-loading of the four helical springs. The drop mass can be varied from 2.5 kg to 22 kg with a maximum height of fall of 1200 mm. This machine is capable of impacting samples at energies of up to 140 J. For this investigation, samples of the size 150×150×10 mm were impacted. Table 1 lists the impact test parameters including the range of drop heights and impact masses used to achieve the desired impact energy. An inbuilt data acquisition system-Elcome Technologies Pvt. Ltd, India, along with impact software were used to

Table 2 Low velocity impact energy parameter values.

Specimen designation	Energy (J)	Incident energy (J)			
		12.64	25.27	37.64	50.19
C8	E1	0.28	4	1.52	4.08
	E2	8.4	18.5	33.33	47.09
	E3	12.36	24.881	31.92	42.84
C16	E1	0.52	5.2	4.34	4.08
	E2	9.1	20.28	26.04	45.05
	E3	12.40	25.55	29.22	40.8
C20	E1	2.6	0.48	7.6	2.64
	E2	9.62	23.25	33.18	43.76
	E3	12.35	22.56	32.48	36.96
C25	E1	0.78	2.6	1.24	3
	E2	12.21	20.28	26.82	28.28
	E3	12.22	23.92	22.8	27.05

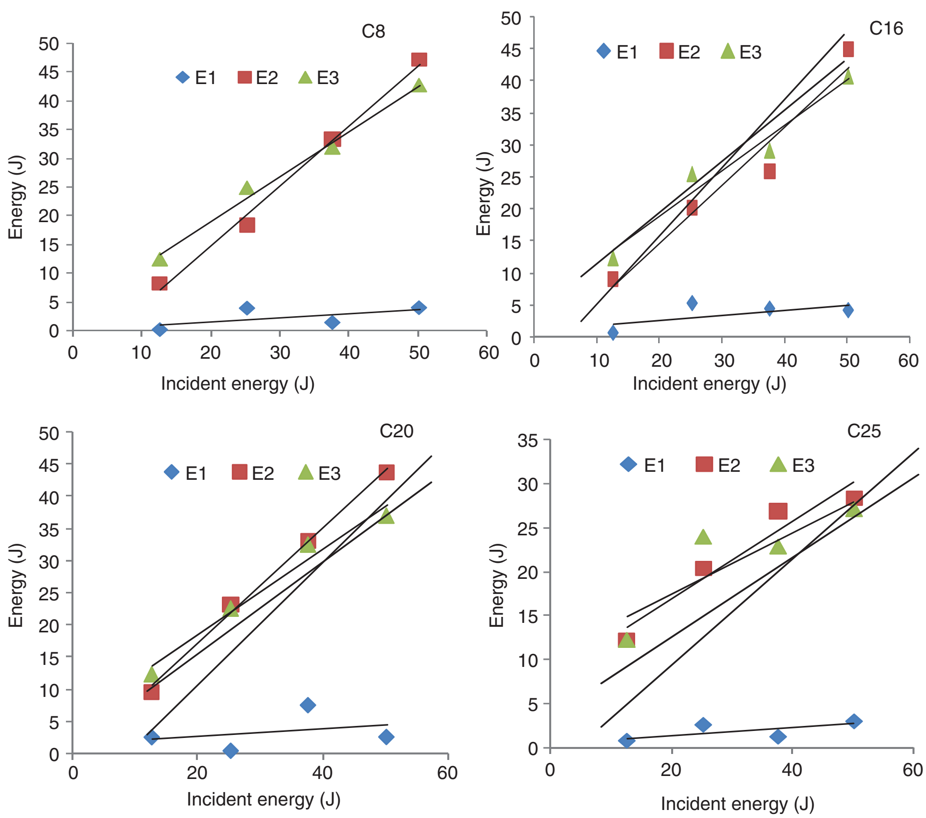


Figure 8 Incident energy versus energy parameter values for specimens of different cell sizes.

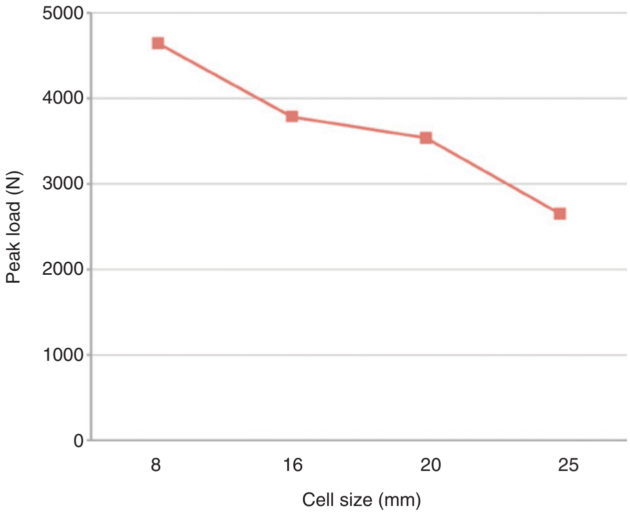


Figure 9 Peak load of sandwich panel of different cell size during impact.

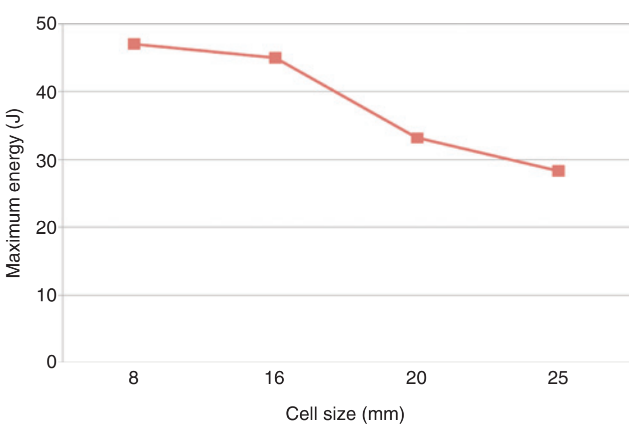


Figure 10 Maximum energy of sandwich panel of different cell size during impact.

monitor the position and acceleration of the impactor. The incident energy was calculated based upon the height history, while the dissipation of energy was derived from both the acceleration and height histories of the impactor, assuming rigid body motion. Tests were conducted under impact energies ranging from 7 to 50 J.

4 Results and discussion

4.1 Impact response of sandwich panels

To understand the influence of cell size on low velocity impact characteristics, falling weight impact tests were carried out on sandwich panels with different cell sizes. Impact tests were conducted on each panel by gradually increasing the impact energy. The damage process during the impact event is associated with the structure's energy absorbing capacity and can be characterised by the load-time and energy-time curves obtained during the impact tests, which are shown in Figures 4–7. The energy absorption mechanism and the characterisation of the damage process is analysed by some of the parameters derived from the curves. Based on these, the impact damage parameters have been utilized to evaluate the role of the cell size on the impact response. From the load-time graphs it is observed that initially the impact load increases with time and reaches a peak (P1). After the first peak, there is a drop in the load, followed by a rise in the load to a second peak (P2) that is followed again by a drop. A further rise to a third peak (P3) occurs after this drop, and this is followed by yet another fall. This behaviour is seen in all the sandwich panels, irrespective of cell size. In general the sequence of the damage due to the low velocity impact is based on three events. First, the formation of the impression of the indentor due to fiber breakages and matrix cracking lead to the failure of the upper skin. Next, debonding of the upper skin from the honeycomb core occurs due to the onset of high bending and shear forces developed by the impact event. Finally, crushing of the honeycomb core occurs. These three events occur in quick succession, with considerable overlap of one another. The load-time and energy-time graphs indicate the onset of these three damage events via three distinctly visible peaks. Accordingly, these three peaks are defined as the incipient load P1, the P2 which indicates the maximum impact load the facing could bear, and P3 which indicates the load at which the core crushing begins. All these loads are an indication of the onset of a particular damage event.

From the plots, it is evident that increased stiffness of the skin results in a wider spreading of skin deformation when an impactor is applied. No visible damage is observed on the surface under low velocity conditions but even with no overt damage on the specimen, the facing exhibits fibre breakages and matrix cracking. At low energy levels, the core buckles before it gets crushed at higher levels. This buckling of the core is due to the damage of the epoxy resin that allows the glass fibre to bend freely, and core crushing is due to the breakage of the glass fibre reinforcement within the core. However, the load-time and energy-time indicates the partial occurrence of all the three damage events. The panel with an 8 mm cell size core has a higher peak load and a smaller time to maximum load. However, an increase in the cell size results in a lowering of the peak load and a rise in the time-to-maximum load. This is due to the higher rigidity

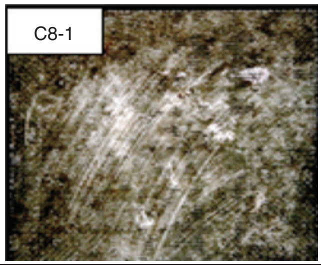
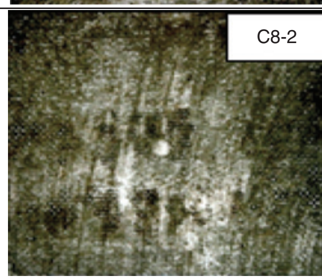
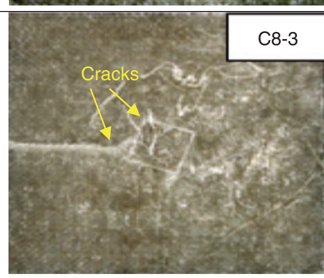
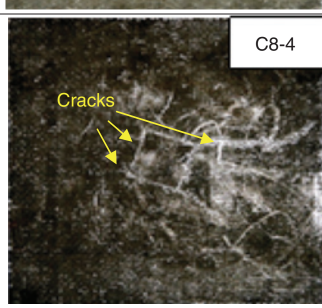
Specimen designation		C8	Remarks
Incident energy J	12.64		No visible damage on the face sheet
	25.27		No visible damage on the face sheet
	37.64		Crack initiated and partially cracked at the top face sheet
	50.19		Extensive cracking at the top face sheet

Figure 11 Post-impact images of specimen C8 at various energy levels.

in compression and less deflection due to impact loading for sandwich panels with smaller cell sizes. It is also noted that in high velocity conditions, the load-time curves become sharper with fast load drops after peak loads [13].

Also to identify the effect of the impact energy on the impact response, the corresponding E1 of the incipient load P1, the E2 value of the load P2, and the E3 value of the load P3 are obtained from the energy-time curve obtained from the impact test. E1 is the incipient impact energy, which is the energy required for damage initiation in the form of fiber breakage; E2 is the energy required for damage in the form of delamination to occur, and E3 is the energy required to crush the core. These values are tabulated in Table 2 and plotted as a function of the incident energy for all sandwich panels with different cell sizes in Figure 8.

It is observed that the incipient energy shows a slight rise as the incident energy increases. Hence, the incipient energy is not affected by the core. The maximum energy is an index, closely related to the impact load carrying capacity of the sandwich panel. The maximum energy decreases as the incident energy level increases for all the panels, with cores of different cell sizes. Also the contact duration is longer for bigger cell sizes and this is due to the reduced structural capacity as the cell size increases. From Figure 9, it is inferred

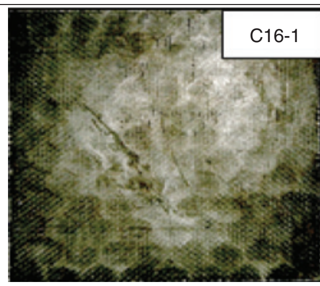
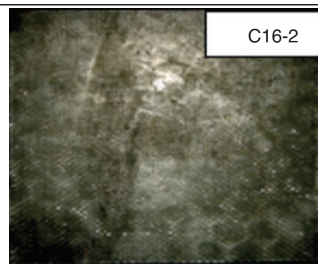
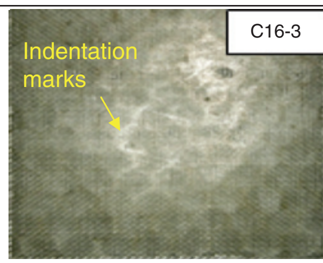
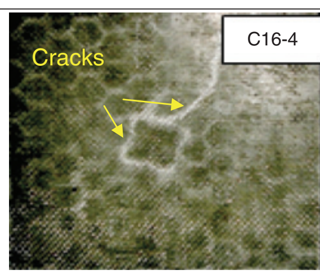
Specimen Designation		C16	Remarks
Incident energy J	12.64		No visible damage on the face sheet
	25.27		No visible damage on the face sheet
	37.64		Impactor indentation seen on the face sheet
	50.19		Top face sheet has cracked

Figure 12 Post-impact images of specimen C16 at various energy levels.

that for a given core height, as the cell size increases, the peak load at which cracking occurs in the face sheet decreases drastically. This is attributed to the fact that the core with a lesser cell size has fewer load paths to distribute the absorbed energy. The energy absorbed is assumed to be a measure of the energy dissipated by the damage mechanism [4]. It shows a decreasing trend as the cell size increases, as shown in Figure 10. This is attributed to the fact that cores with a bigger cell size tend to buckle and hence, energy absorbing potential is lower.

Even though there is some ambiguity in the energy values, the impact behaviour varies with the incident energy and core cell size. Among them the main influential factor is the cell size. This behaviour is caused by the interaction between the facings and the core. The rigidity and compression strength is more for cores of less cell size, and hence, the effect of the cell size becomes more remarkable.

4.2 Post impact damage assessment of sandwich panels

Honeycomb sandwich composites with varying cell sizes were subjected to impact tests at various energy levels.

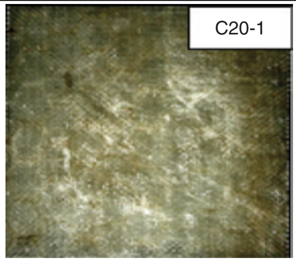
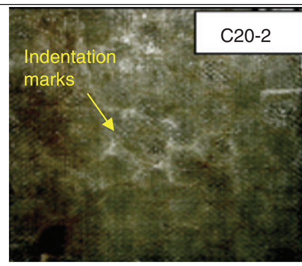
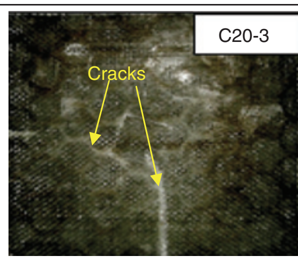
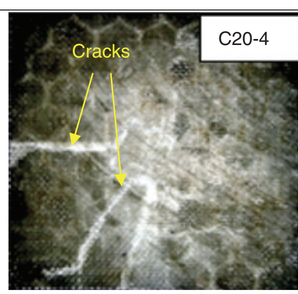
<table>
<tr><th colspan="2">Specimen designation</th><th>C20</th><th>Remarks</th></tr>
<tr><td rowspan="4">Incident energy J</td><td>12.64</td><td>
</td><td>No visible damage on the face sheet</td></tr>
<tr><td>25.27</td><td>
</td><td>Impactor indentation seen on the face sheet</td></tr>
<tr><td>37.64</td><td>
</td><td>Crack initiated and partially cracked at the top face sheet</td></tr>
<tr><td>50.19</td><td>
</td><td>Extensive cracking at the top face sheet</td></tr>
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Figure 13 Post-impact images of specimen C20 at various energy levels.

The specimens were examined and the surface damage was assessed with photographs. Figure 11 shows photographs of the 8 mm cell size specimen impacted at different energy levels. At an energy level of about 12.64 J, no visible damage is observed on the face sheet nor is any observed after the energy level is increased to 25.27 J. The top face sheet is partially cracked at about 37.64 J and extensive cracking on the top face sheet is observed at 50.19 J. Figure 12 shows photographs of 16 mm cell size specimens impacted at different energy levels. No visible damage on the top face sheet is observed up to 25.27 J. The top face sheet is partially cracked at about 37.64 J and extensive cracking on the top face sheet was experienced at 50.19 J. Figure 13 shows photographs of 20 mm cell size specimens impacted at different energy levels. No visible damage on the top face sheet is observed at 12.64 J. At about 25.27 J, an impactor indentation is seen on the top face sheet, and extensive cracking on the top face sheet is seen at 50.19 J. For the 25 mm cell size specimen, an impactor indentation is seen on the top face sheet even at 12.64 J. At 25.27 J, cracks are seen on the top face sheet, and severe debonding and crushing of the core is seen at 50.19 J which is shown in Figure 14.

At 12.64 J incident energy, there is no visible damage on the top face sheet except for the C25 cell size specimen. Upon increasing the energy level to 25.27 J, an impact

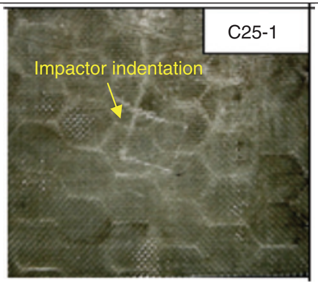
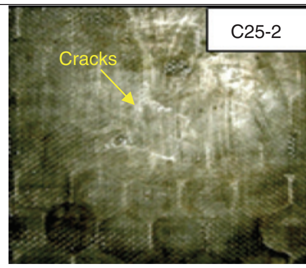
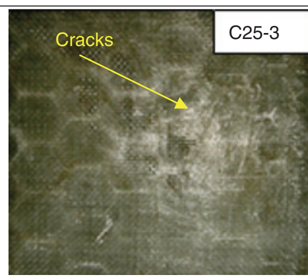
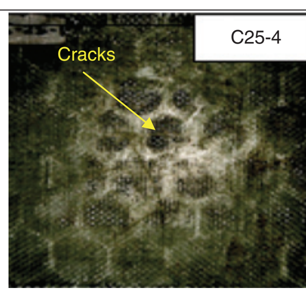
Specimen designation		C25	Remarks
Incident energy J	12.64		Impactor indentation seen on the face sheet
	25.27		Crack initiated and partially cracked at the top face sheet.
	37.64		Extensive cracking at the top face sheet
	50.19		Severe de-bonding and the core has crushed

Figure 14 Post-impact images of specimen C25 at various energy levels.

indentation is visible in the C20, and a crack is visible in the C25 specimen, whereas no visible damage is observed on the C8 and C16 cell size specimens. These undamaged top face sheets show good impact resistance characteristics, as a substantial portion of the impact energy is released back to the striker. The damage to the specimen is due to the maximum energy reached at about 37.64 J and 50.19 J. It is clearly evident that three types of failure modes are identified viz., crack initiation, cracking of the face sheet and debonding, and the crushing of cells. The common damage pattern on the front facing has a square shape, the same shape as the impactor.

5 Conclusion

Low velocity impact tests were conducted on specimens to gain a better understanding of low velocity impact phenomena.

The impact response of the sandwich structure was investigated by observing the load-time and energy-time curves. The impact response is shown to be greatly influenced by the core cell size. From the impact damage parameters, the damage resistance of the sandwich structures appears to be dependent on the core cell size; the lower the core cell size, the greater the impact resistance.

The maximum energy decreases as the incident energy level increases for all panels, and for cores of different cell sizes. Also, the contact duration is longer for bigger cell sizes and this is caused by the reduction of structural capacity as the cell size increases. It is concluded that the energy absorbed is a measure of the energy dissipated by the damage mechanism. The surface damage of the impact test specimens was assessed with photographs taken of the surface of specimens. The common damage pattern on the front facing is a square shape similar to that of the impactor.

Acknowledgments: The authors gratefully acknowledge their indebtedness to the Department of Mechanical Engineering, PES Institute of Technology, Bangalore, for providing access to their test facility and Reinforced Plastic Industries, Bangalore, for their timely help in the development of the sandwich panels.

Received March 28, 2013; accepted March 5, 2014; previously published online April 29, 2014

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