

EXPERIMENTAL STUDY ON LOW VELOCITY IMPACT RESPONSE OF CFRP-ALUMINUM FOAM CORE SANDWICH PLATES

S. Ahmed¹, S. Lee¹, C. Cho^{1*}, K. K. Choi²

¹ Department of Mechanical Engineering, Inha University, Incheon, Korea,

²Dept. of Electrical and Computer Engineering, Illinois Institute of Technology, IL, U.S.

* Corresponding author(cdcho@inha.ac.kr)

Keywords: *Sandwich structure, Low velocity impact, Carbon fiber reinforced plastic, Aluminum foam, Energy absorption characteristics*

1 Introduction

Structural members made up of two stiff, strong skins separated by a light weight core are known as sandwich structure. The facings are loaded primarily in tension or compression to resist bending while the core made up of lightweight and soft material resists the shear stresses. In all of these examples, the faces and core are made from the same material with the faces almost fully dense as comparison the core foam [1]. Low velocity impacts are common phenomena observed in normal situations such as items falling on a composites casing of a body, automobiles bumping into each other at low speeds, rocks hitting a vehicle's composite bodywork, and ballistic impacts on military aircraft all create such type of impact scenarios. Low velocity impact of composite sandwich panels constructed from glass-fiber reinforced face sheets surrounding honeycomb core was studied by Erickson et al [2]. They have found that the nature of the core materials greatly influence the damage mechanism and impact force transfer in the sandwich composites. Kiratisaevae and Cantwell [3] also investigated low velocity impact response of aluminum foam sandwich based on fiber-reinforced thermoplastic and fiber-metal laminate (FML) skin, and found that these systems

are capable of absorbing energy through localized plastic deformation and crushing in the metal core.

Present work aims to experimentally characterize the low velocity impact behavior of a sandwich structure made of closed-cell aluminum foam core and carbon fiber reinforced plastic (CFRP) skins. The purpose is to compare the ability of sandwich plates to absorb the impact energy as a function of the core material density and the skin material.

2 Experiment

2.1 Specimen preparation

For the investigation, closed-cell aluminum foams with density ranging from 0.18 to 0.21 Mg/m³ were used as the core of the sandwich and foams with average density of 0.32 Mg/m³ were utilized for complete penetration test. Two 4-ply unidirectional CFRP plates were used as the skin material on either side of the core. The face sheets of sandwich plate are laminates, which are made of unidirectional carbon fiber and epoxy resin matrix USN125C prepreg (SK chemical, Korea). 4-ply unidirectional CFRP plate has been produced by curing it in autoclave and then cutting into the dimension of 100 mm × 100 mm with the thickness of 0.6 mm. Sandwich samples were fabricated by bonding the face sheets to the core with adhesive.

Table 1 Mechanical properties of CFRP face sheet

Face sheet Material	Tensile Strength (GPa)	Tensile Modulus (GPa)	Fiber Density (kg/m ³)	Resin Density (kg/m ³)	Resin Content (%)
USN125C	4.41	235.36	1770	1200	30

Table 2 Mechanical properties of closed-cell Al foams of different densities

Density (Mg/ m ³)	Relative density	Yield strength (MPa)	Young's modulus (GPa)
0.2	0.08	1.39	0.22
0.3	0.11	1.73	0.47

Table 3 Low velocity impact results for closed-cell Al foams having different densities impacted with 10 kg and 20 kg

Density (Mg/ m ³)	Drop weight (kg)	Impact energy (J)	Velocity of impact (m/s)	Impact height (m)	penetration
0.33	10	5	0.938	0.05	No
0.33	10	6	1.089	0.06	Yes
0.32	10	30	2.43	0.303	Yes
0.31	20	3	0.548	0.015	No
0.32	20	5	0.708	0.026	No
0.32	20	6	0.966	0.046	Yes
0.32	20	7	0.838	0.035	Yes
0.32	20	30	1.72	0.156	Yes

Table 4 Low velocity impact parameters for closed-cell Al foams with different density and CFRP plate impacted at 100 J

Material	Peak load (kN)	Deflection at peak load (mm)	Energy to max. load (J)	Total energy (J)	Impact velocity (m/s)	Absorbed energy (J)	Time to max. load (ms)	
Al	0.21	0.33	5.93	1.51	3.73	3.28	2.22	1.81
	0.20	0.23	5.95	1.20	2.50	3.28	1.29	1.81
	0.18	0.20	6.14	1.03	1.99	3.30	0.96	1.86
CFRP	1.45	4.99	3.69	6.49	3.30	2.79	1.51	

Table 5 Low velocity impact parameters for CFRP-Aluminum foam sandwich impacted at 27 J, 50 J and 100 J.

Impact energy (J)	Peak load (kN)	Deflection at peak load (mm)	Energy to max load (J)	Total energy (J)	Impact velocity (m/s)	Absorbed energy (J)	Time to max load (ms)
27	1.72	10.92	14.09	26.33	1.57	12.25	7.84
50	1.73	8.61	10.65	26.37	2.212	15.72	4.04
100	1.89	11.12	15.41	26.93	3.154	11.52	3.63

2.2 Low velocity impact testing

Impact tests were conducted using an instrumented impact drop device DYNATUP 9250HV (INSTRON, US) as shown in Fig. 1. DYNATUP is equipped with impulse data acquisition system. Using this machine, the impact energy and velocity can be varied by simply adjusting the mass and height of the dropping weight. During the testing, specimen was held with clamped edge conditions in the fixtures located at the bottom of the testing machine. The weight of the cross-head was kept at 20 kg and it was guided by two smooth guide columns. The impactor end of the drop mass was fitted with a 15.88 mm instrumented tup with hemispherical end to record the transient response of the specimens. CFRP-Al foam sandwich samples were placed between the pneumatic clamps during the impact tests. Drop heights were adjusted to obtain the desired impact energy levels. To measure the velocity of the tup just before it strikes the specimen, a velocity detector is also fitted with the machine. Transient response of the samples includes impact energy, load, velocity, and deflection as function of time. For characterization of CFRP-aluminum foam sandwich, the impact energy and load data were plotted against the time. The data for different impact energy level were obtained from the transient response data. Impact parameters like peak load, absorbed energy, time to peak load, deflection at peak load were extracted from the curves.

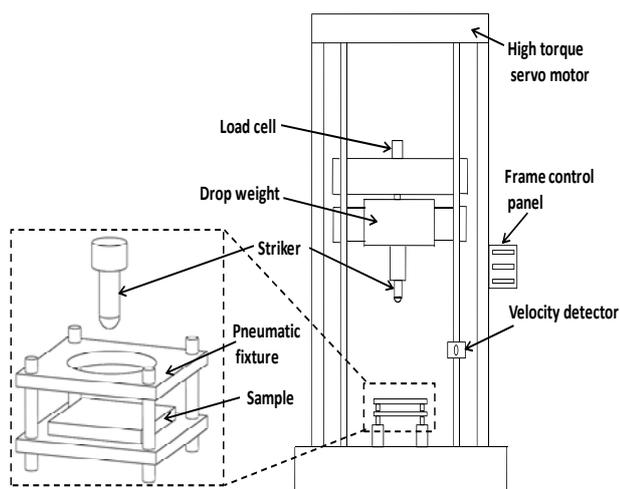


Fig.1. Schematic of Drop-weight test equipment

3 Results and Discussion

3.1 Low velocity impact of closed cell aluminum foams for the evaluation of penetration velocity

Low velocity impact has been performed on closed-cell Aluminum foams with average density of 0.32 Mg/m³ to evaluate the minimum impact energy and velocity required for complete penetration. The mass of the drop weight were kept 10 kg and 20kg by varying heights, different energies of impact were obtained. The parameters such as impact energy, velocity at impact and impact height have been presented in Table 3.

In this test, the minimum energy of impact was started from 3 J and it is noticed that there was no complete penetration occurred at 3 J as well as 5 J of impact. At 6 J and onward such as 7 J and 30 J the complete penetration of specimens was found. The critical velocity and minimum energy of impact at which the complete penetration was observed are 0.966 m/s and 6 J.

3.2 Low velocity impact of closed cell aluminum foam and CFRP plate

First the impact responses of closed-cell aluminum foam and CFRP plate face sheet were evaluated separately. Three Al foam of density 0.18, 0.20 and 0.21 and CFRP plate were tested at energy level of 100 J. The average impact velocity for all the specimens was 3.28 m/s. Various parameters that includes energy, peak load, deflection, velocity as a function of time recorded by data acquisition system of DYNATUP machine of the aluminum foams and CFRP plate are given in Table 5. The *total energy* is defined as the energy absorbed by the sample during the impact event. The difference of the total energy (energy at the end of the impact event) and the energy to peak load is considered as the *absorbed energy*. Fig.2 and 3 show the impact behavior of Al foams. The Al foams have three different densities. It is clear in the figure that the maximum load recorded for the foam densities of 0.21, 0.20, and 0.18 are 0.316 kN, 0.231 kN, and 0.200 kN, respectively. And the corresponding time taken to exert peak load is 1.809 ms, 1.809ms, and 1.858 ms, respectively. The time represents the beginning of propagation of energy phase and the consequent fracture through the Al foams in a ductile manner. Finally, the load reaches to zero level and the impact event ends. The energy absorbed by the three Al

foam types is found to be 2.223 J, 1.293 J, and 0.957 J, respectively. Fig.5 shows the impact behavior of the CFRP plate made of 4-ply unidirectional laminates. As shown in this Figure, the peak load for the CFRP plate is 1.445 kN. The time it takes for peak load is 1.513 ms. In the case of CFRP plate, the fracture occurred in brittle manner and there was a sharp decrease in the load curve after maximum load. The energy absorbed for the CFRP plate was found to be 2.791 J.

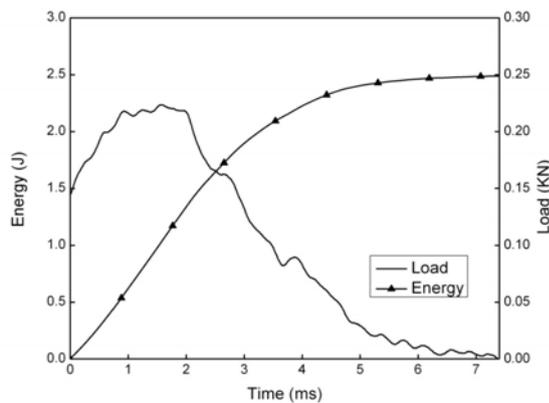


Fig.3 Load and energy versus time curves for closed cell Al foam of density 0.20 impacted at 100 J

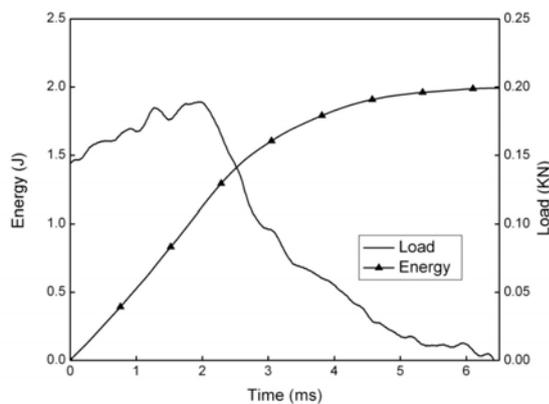


Fig.4 Load and energy versus time curves for closed cell Al foam of density 0.18 impacted at 100 J

Micrographs showing the details of the post impacted Al foams and CFRP plate are presented in Fig.6. It is obvious in the figure that foams failed in localized and ductile damage mode. On the other hand, the CFRP is failed by the matrix rupture due to shear fracture and poor mechanical properties in the transverse direction. The sharp drop in load in the

case CFRP load versus time plot is a qualitative indication of severe damage which can be seen in the Fig. 8.

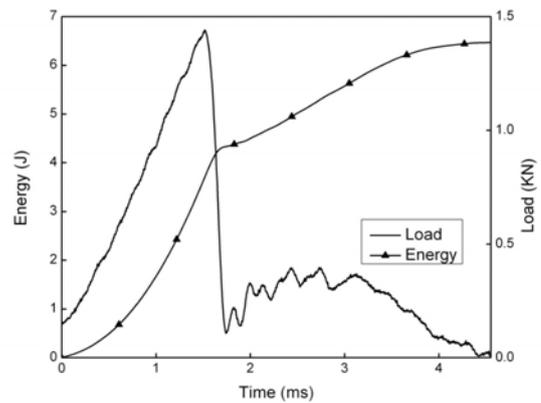


Fig.5 Load and energy versus time curves 4-ply unidirectional CFRP plate impacted at 100 J

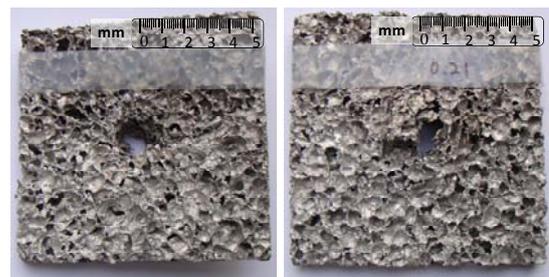


Fig.6 Front (left) and back view (right) of the post impacted sample of aluminum foam of density 0.21 impacted at 100 J

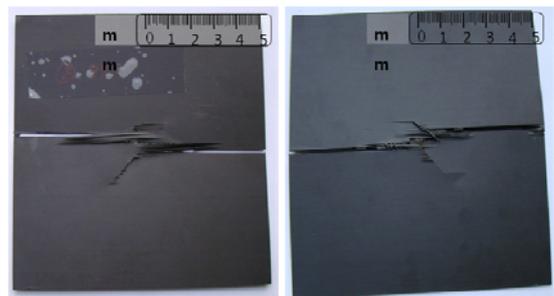


Fig.8 Front (left) and back view (right) of the post impacted sample of 4-ply Unidirectional CFRP plate impacted at 100 J

The peak load at which CFRP plate failed is more than that of the aluminum foams with different densities. It has been found as the density of the foam increase the peak load value increases. At 100

J the absorbed energy was higher for CFRP plate as compared to the aluminum foams while the absorbed energy is also increased with the increase in density of the foams. The deflection at peak load and the time to maximum load were relatively less for CFRP plate. The deflection at peak load was increased with the decrease in the densities of foam. It can be observed that the energy absorbed in the aluminum foams is due to the bending of the foams samples.

3.3 Low velocity impact of CFRP-aluminum foam sandwich

To find the dominant failure mode of the CFRP-Al sandwich plates and to examine the energy absorption mechanism, three different impact energy levels were used. The sandwich samples were impacted at the energy levels of 27 J, 50 J and 100 J using a 20 kg impactor.

The damage of the sandwich specimens is mainly started in the form of top face sheet indentation. The failure of the core occurred through collapsing and yielding of the cell wall of aluminum foam, the failure of the interface between the top and bottom facesheets and the core and eventually the failure of the bottom face sheet.

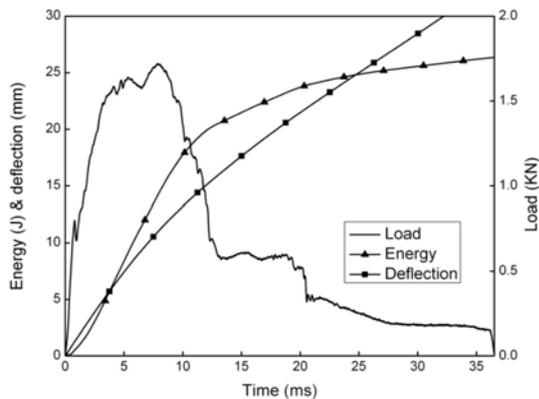


Fig.9 Energy, load and deflection versus time curves for CFRP-Al foam sandwich plate impacted at 27 J

The impact response curves for CFRP-Al sandwich impacted at 27 J with an impact velocity of 1.573 m/s is shown in Fig.9. Considering the load and energy versus time curves, there is a sharp drop in load as the striker encounters the first CFRP plate sheet. The drop in load value occurred due to the penetration of the CFRP face sheet at the impact region. After the first drop in load, it increases again

and rises to a maximum peak as the impactor breaks through into the Al foam core and the back CFRP face sheet. This again increase in load was picked by aluminum foam and back face sheet. Finally, load curve falls to zero as striker pushes entirely through the sample. The maximum load at which sandwich failed was 1.724 kN. The time it takes to attain peak load is 7.836 ms. The energy absorbed for composite sandwich impacted at 27 J was found to be 12.245 J. Table 5 summarizes the results of low velocity impact response of sandwich plate impacted at 27 J. The sandwich sample after impact is shown in Fig.10. It can be seen that the upper CFRP plate failed due to localized indentation at the contact zone. Aluminum foam core prevented the top face sheet from complete damage. The top sheet failed by matrix rupture due to inadequate mechanical properties of unidirectional CFRP in the transverse direction and localized fiber breakage. The permanent and localized penetration of top CFRP plate sheet showed that the damage area of the closed-cell Al foam core and upper face sheet was same. The core failed in the vicinity of impacted area by crushing of cells. The damage of the bottom face CFRP plate was extensive. Failure of the interface between the bottom face sheet and core was found in correspond to the point of impact. The bottom face sheet failed by the matrix rupture in the form of three major cracks along with the complete breakage of one of de-bonded part of the face sheet at the point of impact. The cracks occurred parallel to the matrix but breakage of separated part took place along the fiber of the bottom CFRP plate just below the point on impact. It can be observed by the visual inspection of the impacted sample that the damage area at the bottom of the sandwich is significantly large than the damage area in the top.

The impact response curves of this sample show similar behavior to that noticed in the sandwich impacted at 27 J. In this case, the peak load at which composite sandwich failed was 1.734 kN. A moderate increase in peak load was found. The time it takes to reach maximum load is 4.042 ms. Other parameters like deflection at peak load, absorbed energy, energy to maximum load and velocity of impact for the CFRP-aluminum sandwich impacted at 50 J are given in the Table 5. These parameters are direct indicator of the strength and damage states of the sandwich sample.

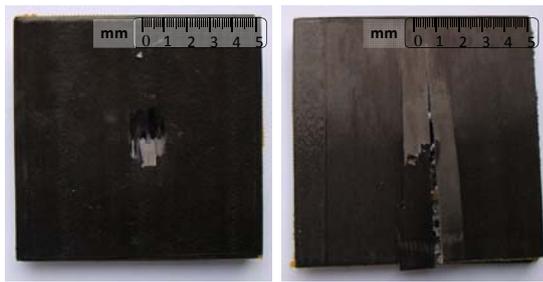


Fig.10 Front (left) and back view (right) of the failed CFRP-Al foam sandwich plate after low velocity impact of 27 J

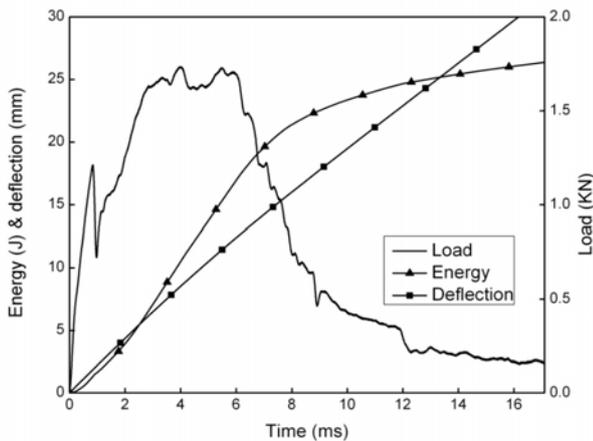


Fig.13 Energy, load and deflection versus time curves for CFRP- aluminum foam sandwich plate impacted at 100 J.

The energy, load and deflection versus time curves for CFRP-Al foam sandwich impacted at 100 J are shown in Fig.13. These curves show trends very similar to those observed for the sandwich samples impacted at 27 J and 50 J respectively. The maximum load attained by the sandwich composite was found to be 1.886 kN. This increase in peak load is significantly higher than previous two impact cases. Now the time to attain the peak load reduced to 3.25 ms. In this impact event the energy absorbed was less than the earlier two impacts. The energy absorbed by the sandwich composites in this impact was 11.522 J. Further, Table 5 summarizes the low velocity impact results for the sandwich composite impacted at 100 J. For impact at 100 J, the CFRP-Al sandwich followed the similar failure trends noticed for the previous two impacts. The failure of the top face sheet and core was once again similar to the earlier two cases.

4 Conclusion

Present work investigated the low velocity impact response of sandwich plate based on closed cell aluminum foam core and 4-ply unidirectional CFRP skin. Closed-cell Al foam and CFRP plate were first tested separately and then as a CFRP-Al foam composite sandwich plate. The CFRP-Al foam sandwich samples were subjected to low velocity loading at 27 J, 50 J, and 100 J. Results of this study showed that energy absorption characteristics of closed-cell aluminum foam improved with increase in its density. It was found that important factor for material penetration, especially closed-cell aluminum foam, is impacting velocity as well as plastic dissipation energy of a material. Less bending deformation was noticed for impact with 10 kg mass. Further, it was found from the experiments that the energy absorption capacity of the sandwich made up of aluminum foam core and CFRP plate is significantly higher than their constituents tested separately. From the experimental results it can be concluded that CFRP plates with higher density can be combine to achieve better energy absorbing and load bearing capacity. In addition, by applying CFRP Plate face sheet with different orientation and improving the core and face sheet interface the energy absorbing mechanism can be enhanced.

Acknowledgement

This work was supported by Inha university.

References

- [1] L. J. Gibson and M.F. Ashby, "Cellular Solids: Structure and Properties", 2nd ed., Cambridge University Press, UK, 1997.
- [2] M. D. Erickson et al., "Effect of Temperature on the Low-velocity Impact Behavior of Composite Sandwich Panels", *Journal of Sandwich Structures and Materials*, Vol. 7, pp 245-264, 2005.
- [3] H. Kiratisaevee and W. J. Cantwell, "Low-velocity Impact Response of High-performance Aluminum Foam Sandwich", *Journal of Reinforced Plastics and Composites*, Vol. 24, pp 1057-1072, 2005.
- [4] O.B. Olurin, N.A. Fleck and M.F. Ashby, "Deformation and Fracture of Aluminum Foams", *Materials Science and Engineering A*, 291: 136-146, 2000.
- [5] H. Kiratisaevee and W. J. Cantwell, "Low-velocity Impact Response of High-performance Aluminum Foam Sandwich", *Journal of Reinforced Plastics and Composites*, 24: 1057-1072, (2005).