Failure Mechanisms of Composite Sandwich Beams Under Impact Loading

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ABSTRACT: *An experimental investigation of the failure mechanisms of a composite sandwich beam under central low-velocity impact was undertaken. The beam was made of unidirectional carbon/epoxy facesheets and various core materials including aluminum honeycomb, balsa wood, polyurethane foam and foam-filled honeycomb. Damage of the beam depended on the level of impact energy and the properties of the core material. For low impact energies, the impactor after reaching the specimen bounces transferring energy back to the impactor as kinetic energy. For higher energies core crushing coupled with bending of the upper facesheet took place. The upper facesheet deforms permanently without failure. As the impact energy increases delamination of the facesheets or debonding between the core and the facesheets occurred. For much higher energies wrinkling or perforation of the upper facesheets was recorded. Damage was assessed by visual inspection and photomicrographs taken in a microscope under various magnifications. Macroscopic and microscopic failure mechanisms were recorded. Macroscopic mechanisms include indentation, surface cracking, delamination and perforation. Microscopic mechanisms include fiber breakage and matrix cracking. Results concerning the mechanisms and damage development for various core materials and impact energies were obtained.*

INTRODUCTION

The low-velocity impact performance of sandwich structures is of utmost importance since they are susceptible to damage caused by such loading. The damage mechanisms of composite sandwich construction made up of strong, stiff facesheets and soft, lightweight cores are complex. They involve interaction of various failure modes including indentation, compressive facesheet wrinkling, delaminations of the loaded facesheet, debonding between the facesheet and the core, punch-through, perforation and core failure. A lot amount of work has been devoted to the low velocity impact of sandwich structures. Relevant investigations are listed in references [1] to [7].

In the present work a thorough study of the failure mechanisms of composite sandwich beams under central low-velocity impact was undertaken.

Macroscopic and microscopic failure mechanisms were detected. Results concerning the failure modes and damage development for various core materials and impact energies were obtained.

MATERIALS AND SPECIMENS

The sandwich beams were composed of unidirectional carbon/epoxy (AS4/3501-6) facesheets and various core materials. They include aluminum honeycomb, polyurethane foam, balsa wood and foam-filled honeycomb (a phenolic-impregnated paper filled with polyurethane). The mechanical properties of core materials are shown in Table 1.

The foam cores were bonded to the facesheets with an epoxy adhesive (Hysol EA 9430), while the honeycomb core was bonded with a 0.005 in. thick tape (FM73M epoxy, Cytec-Fiberite^{TM}). The facesheets consisted of 8-plies with a total thickness of 1 mm, while the core had a thickness of 25.4 mm. Beam specimens of span 254 mm, width 25.4 mm and depth 25.4 mm were prepared.

EXPERIMENTAL SETUP

The specimens were simply supported and loaded under central impact in a drop tower apparatus with low-velocity control. The load included a weight, a force transducer, an accelerometer and an impactor. Various impact energy levels corresponding to different heights of the dropping weight were considered. The initial velocity of the impactor was monitored by the signal produced upon interruption of two parallel laser beams. The force pulse generated upon impacting the specimen with the dropping weight was recorded by the force transducer and two accelerometers, one in the upper and the other in the lower facesheet of the sandwich beam. Strains were recorded during the test with strain gages placed at several locations of both facesheets (Fig. 1).

TABLE 1: Mechanical properties of core materials

Property	Balsa Wood CK57	Aluminum Honeycomb PAMG 5052	Foam Filled Honeycomb Style 20	Polyurethane FR-3708
Density, ρ kg/m^3 (lb/ft^3)	150 (9.4)	130 (8.1)	128.3 (8)	128.3 (8)
In-plane long. comp. elast. mod., E_{1c} MPa (ksi)	129.5 (18.8)	9.5 (1.38)	24.1 (3.5)	38.5 (5.6)
In-plane long. tens. elast. mod., E_{1t} MPa (ksi)	93.6 (13.6)	4.5 (0.65)	1.3 (0.19)	416.6 (60.4)
In-plane trans. comp. elast. mod., E_{2c} MPa (ksi)	129.5 (18.7)	6 (0.87)	7.6 (1.1)	38.5 (5.6)
Out of plane comp. elast. mod., E_{3c} MPa (ksi)	5394 (782.3)	2125 (308)	269.1 (39)	108.7 (15.8)
Transverse shear elast. mod., G_{13} MPa (ksi)	58.7 (8.5)	579 (84)	8.5 (1.23)	10.3 (1.49)
In-plane long. comp. strength, F_{1c} MPa (ksi)	0.78 (0.11)	0.2 (0.03)	0.4 (0.06)	1.15 (0.17)
In-plane long. tensile strength, F_{1t} MPa (ksi)	1.13 (0.16)	1.63 (0.24)	0.48 (0.07)	1.1 (0.16)
In-plane trans. comp. strength, F_{2c} MPa (ksi)	0.78 (0.11)	0.17 (0.03)	0.32 (0.05)	1.15 (0.17)
Out of plane comp. strength, F_{3c} MPa (ksi)	9.6 (1.39)	11.8 (1.7)	1.35 (0.2)	1.74 (0.25)
Transverse shear strength, F_{13} MPa (ksi)	3.75 (0.54)	3.45 (0.5)	0.75 (0.11)	1.4 (0.2)

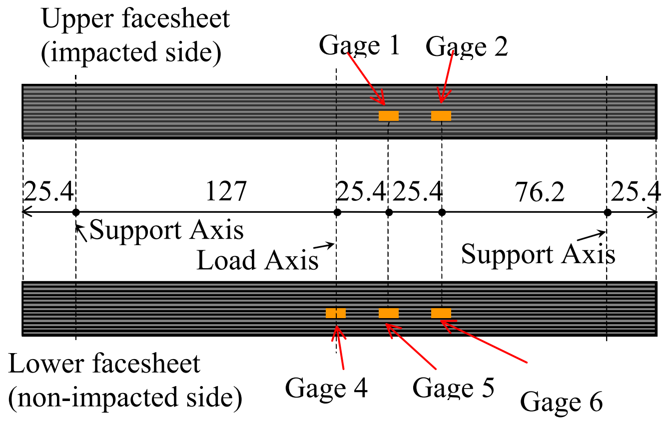

Figure 1: Strain gage locations and numbering at both facesheets for impact tests (dimensions in mm)

LOAD AND STRAIN PULSE HISTORIES

Figure 2 shows the impact load histories of a sandwich beam with four different cores impacted from a height of 127 mm (impact energy 8.8 J). The pulses have a quasi-sinusoidal shape with a duration that varies from 8 ms for the beam with balsa wood to 16 ms for the beam with polyurethane core. For falling weights from a height of 508 mm (impact energy 27 J) the beams were destroyed by punch-through or perforation. The pulse duration increases with the energy level and reaches 30 ms before the beam fails.

Figure 3 shows the strain histories recorded by two strain gages on the upper facesheet (strain 1 and 2 curves) and two strain gages on the lower facesheet (strain 4 and 5 curves) of a sandwich beam with polyurethane foam core impacted by a drop weight from a height of 191 mm. Figure 4 shows the strain versus time behavior at mid-point of the tensile side of the beam (point 4) during the pulse for sandwich beams with various core materials. It is observed from Figures 2 and 4 that the beam with aluminum honeycomb fails earlier than the other ones. Beams with balsa cores take higher loads and outperform the beams with the other cores for the same energy level.

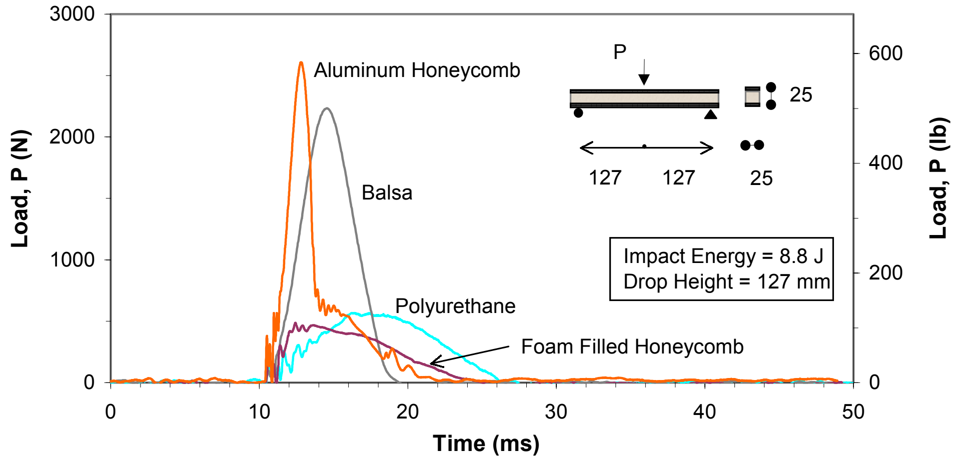

Figure 2: Load history for simply supported sandwich beam under central impact for various core materials (dimensions in mm).

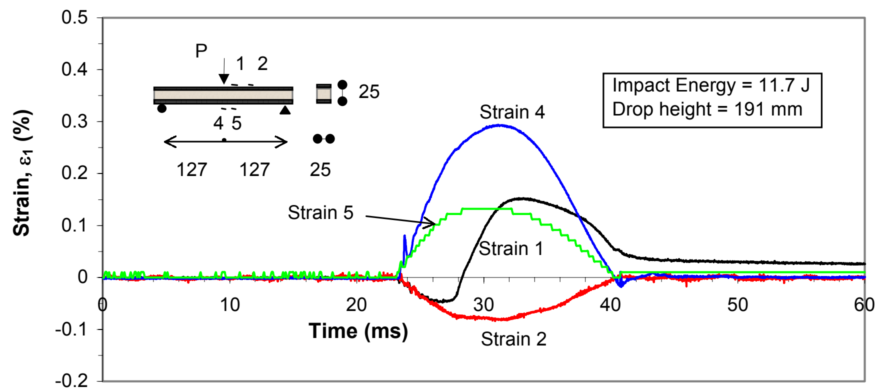

Figure 3: Strain histories for simply supported sandwich beam under central impact (core: polyurethane CK57, dimensions in mm)

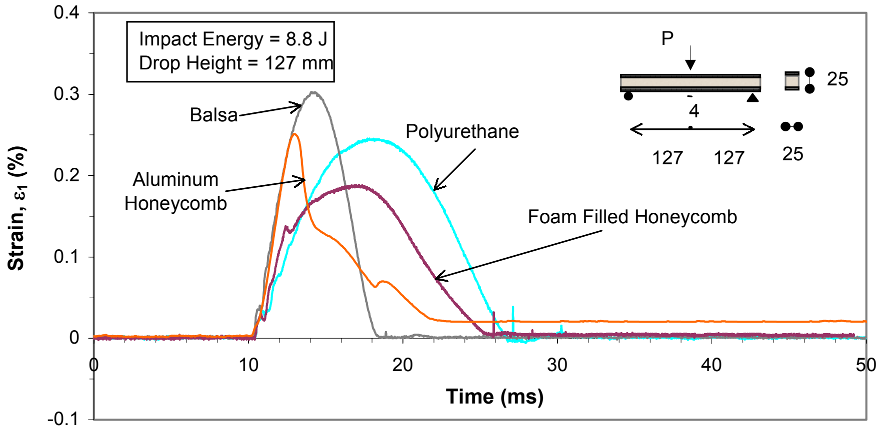

Figure 4: Strain 4 history for simply supported sandwich beam under central impact for various cores (dimensions in mm).

MODELING THE IMPACT BEHAVIOR

A spring model was used to model the impact behavior of the beam. The model consists of a group of springs representing the bending, the shear and the membrane stiffness of the beam, and the contact behavior between the load and the beam. The maximum load and period of the pulse are obtained as

$$P_{max} = v_o \sqrt{km} \tag{1}$$

$$T = 2\pi \sqrt{\frac{m}{k}} \tag{2}$$

where v_o is the impact velocity, k is the equivalent spring constant and m is the mass of the dropping weight.

The predictions of the maximum load and period of the pulse based on the spring model are in good agreement with the experimental results.

FAILURE MODES

Various failure modes of the composite sandwich beams under low velocity impact were observed. They depend on the impact energy level and the core material. The damage of the beams was first assessed by visual inspection and the depth of the core indentation was measured. Delaminations or debondings at the impact area were detected by photomicrographs taken with a microscope at different magnifications. For low impact energies, the impactor after hitting the specimen bounces up, transferring some energy back to the impactor as kinetic energy. Energy is converted into elastic deformation that is recovered upon unloading. No permanent deformation occurs in both facesheets and the core. For higher energy levels, core crushing coupled with bending and stretching of the loaded facesheet occurs. Some permanent deformation in the specimen is observed, but no failure of the facesheets takes place. As the energy level increases delamination and/or debonding occur. Debonding between the core and loaded facesheet takes place when the adhesive shear strength is reached. For increasing energy levels wrinkling and punch through or perforation of the loaded face occurs. Perforation means that the loaded facesheet is broken and the impactor touches the core.

The occurrence of the above failure modes depends on the core material. Beams with aluminum honeycomb core debond at low impact energies. Beams with balsa wood core tend to fail catastrophically. The failure modes include debonding and/or delamination, core crushing and upper facesheet perforation. The failure is mainly concentrated around the impacted area and does not propagate into the lower facesheet, unless very high energy levels are applied. Photographs of various failure modes of composite sandwich beams are shown in Figs. 5 and 6.

Figure 5: Photograph of sandwich beam with balsa wood core impacted from 254 mm height, showing core failure and debonding.

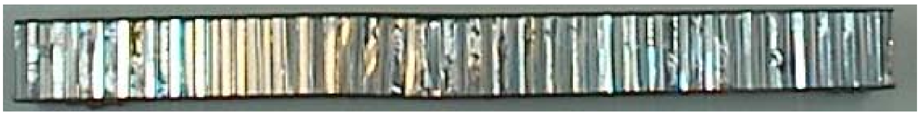

Figure 6: Photograph of sandwich beam with aluminum honeycomb core impacted from 127 mm height, showing debonding and distortion of the specimen.

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