Chapter 9
Dynamic Energy Absorption of Eco-Core and Other Commercial Core Materials

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Abstract Eco-Core is a fire resistant syntactic foam that was developed to be used as a core material for sandwich structures. Core materials are subjected to multiaxial stress state in general and potentially to high strain rates. To evaluate the suitability of Eco-Core for applications involve dynamic effects as for blast mitigation and shock absorption military applications, its energy absorption needed to be evaluated. Also, it needed to be compared with energy absorption of other commercial core materials to determine its reliability. Specimens of 11 mm diameter and 3.2 mm length were prepared using Eco-Core (500 kg/m^3), PVC foam (100 kg/m^3), Balsa wood (202 kg/m^3) and Rohacell-A (75 kg/m^3). All specimens were confined with aluminum sleeve of 11 mm inner diameter and 0.9 mm thickness. Confined specimens were tested on Split Hopkinson Pressure Bar (SHPB) apparatus at strain rate ranged from 3120/s to 3490/s. Test results showed that energy absorption per unit volume of Eco-Core (11 MPa) is far superior to other tested commercial core materials (more than twice of Balsa wood the nearest material). The energy absorption per unit mass of Eco-Core (22 kN m/kg) is marginally better than other tested commercial core materials (as good as Balsa wood).

Keywords Energy absorption • Eco-Core • PVC foam • Balsa wood • Rohacell-A

9.1 Introduction

Composite sandwich structures have been receiving considerable amount of interest because of their superior stiffness-to-weight ratio, strength-to-weight ratio, resistance to corrosion and other properties such as thermal and acoustic insulations. Core material type has major impact on the overall properties of sandwich structure. It controls important mechanical properties of the structure like fatigue and shear characterization; bending stiffness; and energy absorption, the most important property. It determines the reliability of the structure for energy absorption applications like shock absorption, blast mitigation and others. Therefore, to extend the scope of any core material usage in different applications, its energy absorption capability needs to be studied. In real applications core is subjected to multiaxial stress state as shown in Fig. 9.1. When an axial force is applied on a sandwich structure, the core under that force tends to deform axially. Also, it tends to deform laterally due to Poisson effect. The rest of the core material constrains the lateral expansion that develops a lateral stress (q). Thereby, the core is under multiaxial stress state even when the applied stress is uniaxial. To simulate the multiaxial conditions on specimen, it has to be confined to develop the lateral stress in addition to the axial stress. The confinement approach by the mean of encasing the specimen inside sleeve was used in several dynamic and static studies before as in [1–4].

The objective of this study is to determine the dynamic energy absorption capability of Eco-Core and other core materials like PVC foam, Balsa wood and Rohacell-A and compare them to each other's. The approach of this work is to develop a test fixture to apply axial and lateral stresses on the specimen during dynamic tests, use the test fixture with Split Hopkinson Pressure Bar (SHPB) apparatus to conduct dynamic tests at high strain rates (3000/s–3500/s), determine the stress strain response for each material and calculate the energy absorptions form the areas under the stress strain curves.

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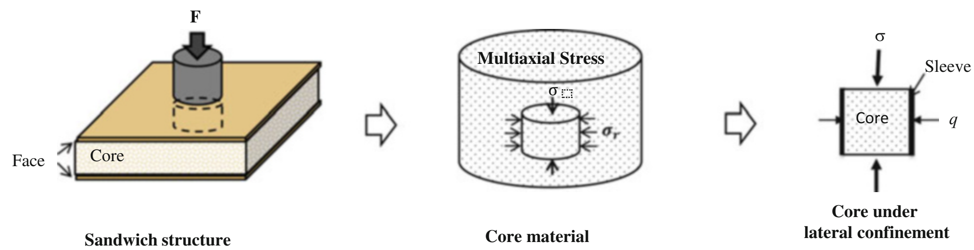
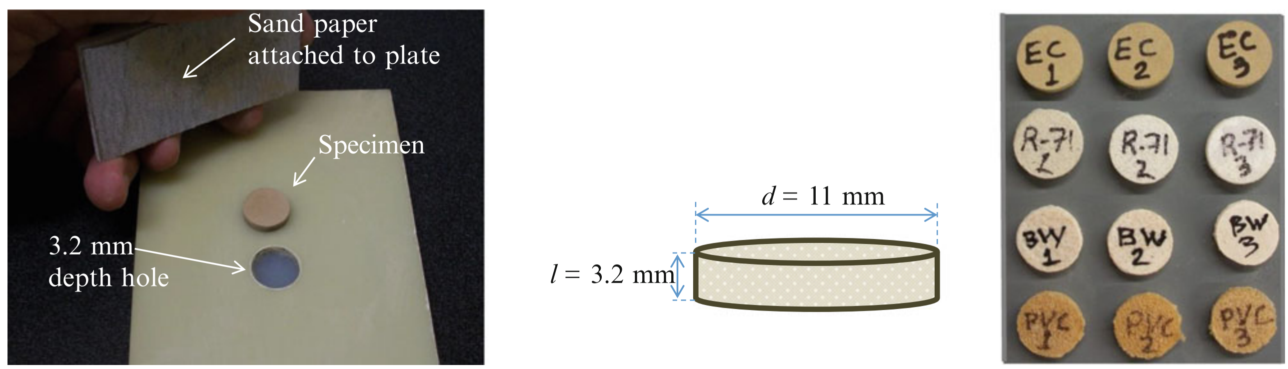


Fig. 9.1 Schematic of multiaxial stress state of sandwich structure core material



a) Specimen fabrication fixture b) Specimen's schematic c) Specimens' photograph

Fig. 9.2 Fabrication process, schematic and photograph of specimens

9.2 Materials and Specimens

Four core materials were used in this test, Eco-Core (500 kg/m^3), PVC foam (100 kg/m^3), Balsa wood (202 kg/m^3) and Rohacell-A (75 kg/m^3) . Eco-Core panels were fabricated from fly ash known as Cenosphere and small percentage of high char yield resin known as (Phenol-formaldehyde resole resin). More details about the fabrication process are available in reference [5]. The rest of the core material were provided in the form of panels by McMaster-Carr [6]. Rectangular panels of 100×100 mm^2 dimensions were prepared to fit in the vise of the drill machine. Cylindrical specimens of 11 mm diameter were cut from the panels using an 11 mm inner diameter core cutter. Specimens were at different lengths according to the different thicknesses of the used panels. 5 mm length specimens were cut from the different length specimens. At this stage the specimens' length was 30–40 % longer than final desired length. Each specimen was sanded down by 400-grit sand paper to 3.2 mm length within 25 μm variation using the fixture appears in Fig. 9.2a. This process insured that the two faces of the specimen were perfectly parallel to minimize the misalignment with the test fixture. The final dimensions of all specimens were $d = 11$ mm and $l = 3.2$ mm as appear in Fig. 9.2b. These dimensions were selected after many trails and according to many specimen design considerations. The aspect ratio of the specimen (l/d) was 2.9, which was within the recommended range for testing soft material [7]. Photographs of all specimens appear in Fig. 9.2c.

9.3 High Strain Rate Confined Compression Testing

High strain rate confined compression tests for core materials were conducted using SHPB test apparatus and using a specially designed test fixture. Before modifying SHPB to conduct confined tests, it was independently validated by data in the literature. Solid specimens of polycarbonate and nylon 6/6 were tested at 1200/s and 1250/s strain rates, respectively. Measured responses were compared to and validated by results of Salisbury [8] and Chou et al [9]. More details about the used SHPB for this test and the validation process are available in reference [5]. The validated SHPB apparatus along with the specially designed test fixture were used to test core materials.

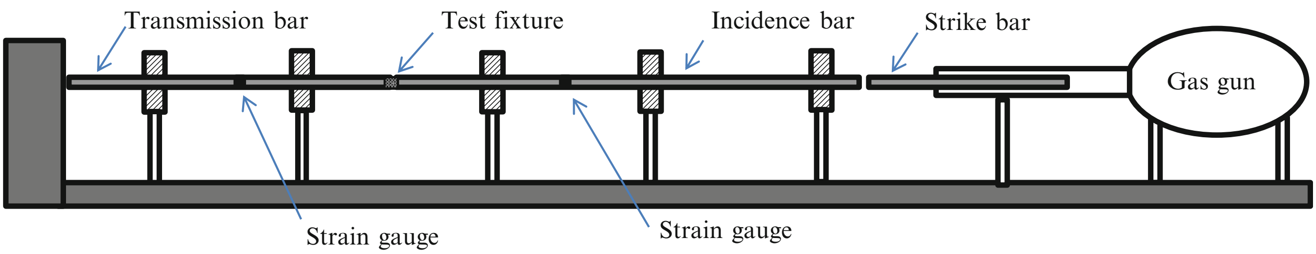


Fig. 9.3 Schematic of SHPB apparatus

9.3.1 SHPB Apparatus and Analysis

SHPB apparatus appears in Fig. 9.3 consists of two bars known as incidence bar and transmission bar and a third projectile bar driven by the pressure of a gas gun, known as strike bar. When testing with SHPB a test specimen is sandwiched between incidence bar and transmission bar. A stress/strain compression wave is generated by the impact of the strike bar on the impact end of the incidence bar. The stress/strain pulse propagates through the incidence bar toward the specimen, called incident pulse, $\varepsilon_i(t)$. When the pulse reaches the specimen-incidence bar interference, part of the pulse passes through the specimen to the transmission bar, called transmitted pulse, $\varepsilon_t(t)$. The other part of the incident pulse reflects back to the incidence bar as a tensile pulse, called reflected pulse, $\varepsilon_r(t)$. Pulse reflection occurs because of the difference in the material impedance of specimen and bar. The incident and reflected pulses are measured by a strain gauge installed on the incidence bar and the transmitted pulse is measured by a strain gauge installed on the transmission bar. The two gauges are at the same distance from the specimen (0.9 m). During the test, the specimen undergoes deformation until it reaches its dynamic limit.

The concept of the one dimensional stress wave propagation theory is used to calculate the strain rate in the specimen from the reflected wave signal, $\varepsilon_r(t)$ as:

$$\dot{\varepsilon}(t) = \frac{2c_b \varepsilon_r(t)}{l} \tag{9.1}$$

Where C_b is the speed of sound in the bars, l is the specimen length. The strain is calculated by integrating the strain rate (9.1) with respect to time as:

$$\varepsilon(t) = \frac{2c_b}{l} \int_0^t \varepsilon_r(t) dt \tag{9.2}$$

The axial stress in the specimen as a function of time is calculated from transmitted wave signal, $\varepsilon_t(t)$ as:

$$\sigma(t) = \frac{A_b E_b}{A_s} \varepsilon_t(t) \tag{9.3}$$

Where A_b is the cross-section area of incidence/transmission bar, A_s is the cross-section area of the specimen and E_b is the elastic modulus of bars' material. The stress strain response of the specimen is obtained by (9.2) and (9.3). This method of computation is given in number of text books and references on impact, for example [9–12].

9.3.2 Test Fixture

Test fixture consists of two plugs and sleeve. Sleeve was made of aluminum 6061/T6 with 11 mm diameter, 0.9 mm thickness and 6 mm length. Length of sleeve was selected to sufficiently encase the specimen and the ends of the two plugs. Plugs were made of aluminum 7075/T6 to match the impedance of the SHPB bars and avoid pulse dispersion. Figure 9.4a, b show schematic with dimensions and photograph of the test fixture, respectively. The left plug butts against the specimen

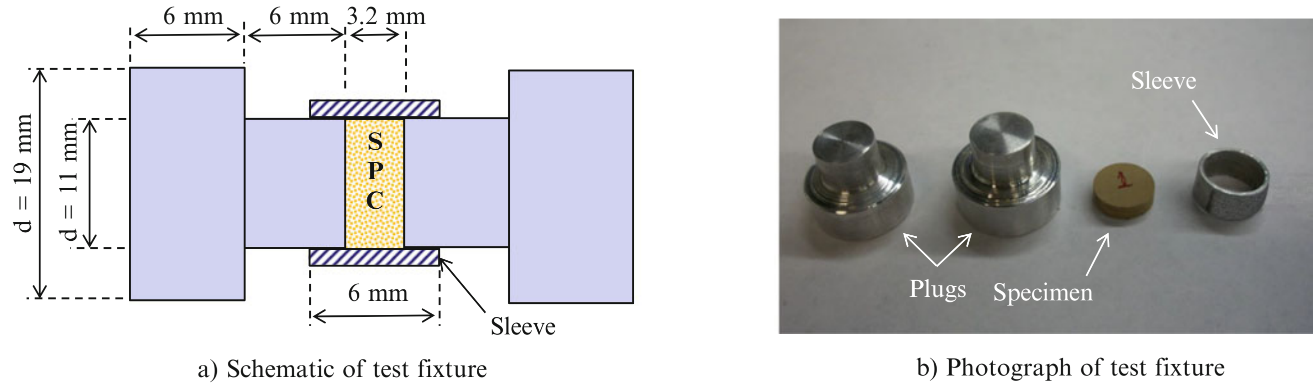


Fig. 9.4 Schematic and photograph of text fixture

and the transmission bar and the right plug butts against the specimen and the incidence bar. The specimen snug fits the sleeve within 25 μm clearance; the two plugs slide into the sleeve within 50 μm clearance.

9.3.3 Test

After SHPB apparatus was validated, confined compression tests for core materials were conducted. Starting with Eco-Core, specimen of $d = 11$ mm and $l = 3.2$ mm was inserted gently inside the aluminum sleeve. Specimen location was adjusted carefully such that it is in the mid-length of the sleeve as shown in Fig. 9.4a. The whole fixture was placed in between the incidence and transmission bars. The center of the incidence plug was aligned to the center line of the incidence bar and they were taped together without leaving any gap in between. The same process was repeated on the transmission side of the specimen. The gas gun of the apparatus was charged to 124 kPa pressure (This value was determined according to calibration process between the gas gun pressure and resulted strain rate). The trigger of the oscilloscope was turned on standby position. Then the system was fired, the strike bar impacted the incidence bar. The stress wave was generated at the impact site, traveled along the incidence bar, specimen and then to the transmission bar. The data acquisition system acquired the strain gauge signals from the incidence and transmission bars at rate of 0.5 MHz. The original waveform signals were filtered to reduce the noise by using the Xviewer software. Three specimens of Eco-Core were tested at the same gas gun pressure to insure the repeatability of the test. Also, three specimens of each of the other core materials were tested in the same manner at the same gas gun pressure. All the signals were saved to be reduced to strain rate, strain and stress.

9.4 Test Results

9.4.1 Basic Results

A typical time history of strain pulse signals for dynamic confined compression test of Eco-Core is shown in Fig. 9.5a. The figure shows the three strain/stress pulses of the bars (incident, transmitted and reflected pulses). The duration of the incident pulse ($T/2$) was about 415 μs (1135−720 μs) and the frequency ($f = 1/T$) was 1.2 kHz. Calculation of pulse frequency helped to select the suitable sampling rate of the data acquisition system (Oscilloscope), which was 0.5 MHz in this present case. Note that selecting higher sampling rate results in oscillatory data due to high frequency noise. On the other hand, lower sampling rate results in missing important phenomenons like peak strains/stress. The dynamic equilibrium of the specimen during the entire test period was verified by comparing the incident pulse to the sum of transmitted and reflected pulses. The pulses time history in Fig. 9.5b shows that the two values were close to each other's. It indicates that the strains of the bars on both sides of the specimen were almost equal. Since the bars have the same area and modulus of elasticity, then the stresses on both sides of the specimen were equal as well. That verified the dynamic equilibrium of the confined specimen over the entire test period and confirmed the right selection of specimen's dimensions.

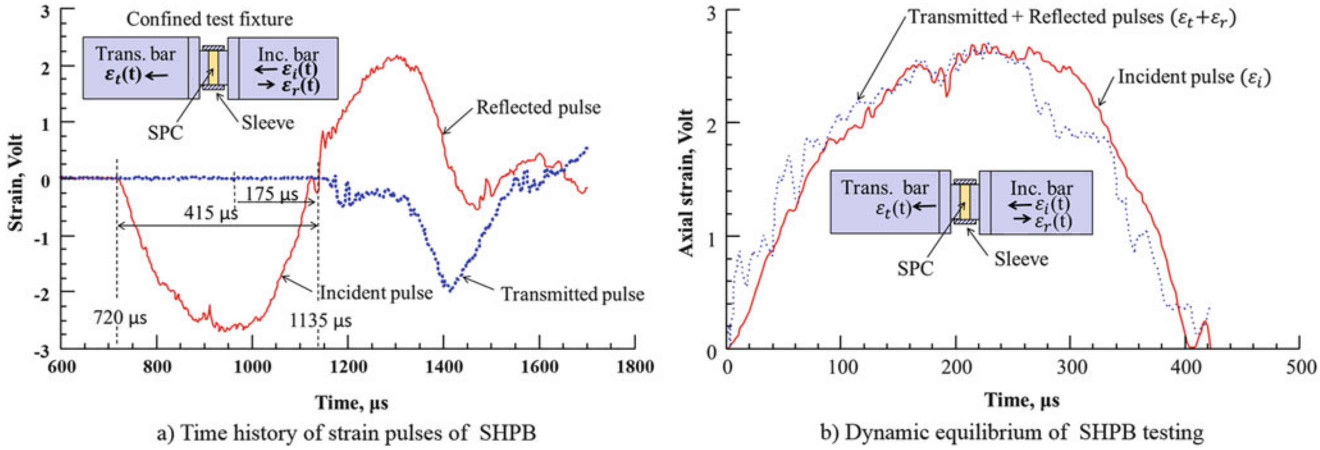


Fig. 9.5 Time history of strain pulses and dynamic equilibrium of confined compression test of Eco-Core at 3120/s

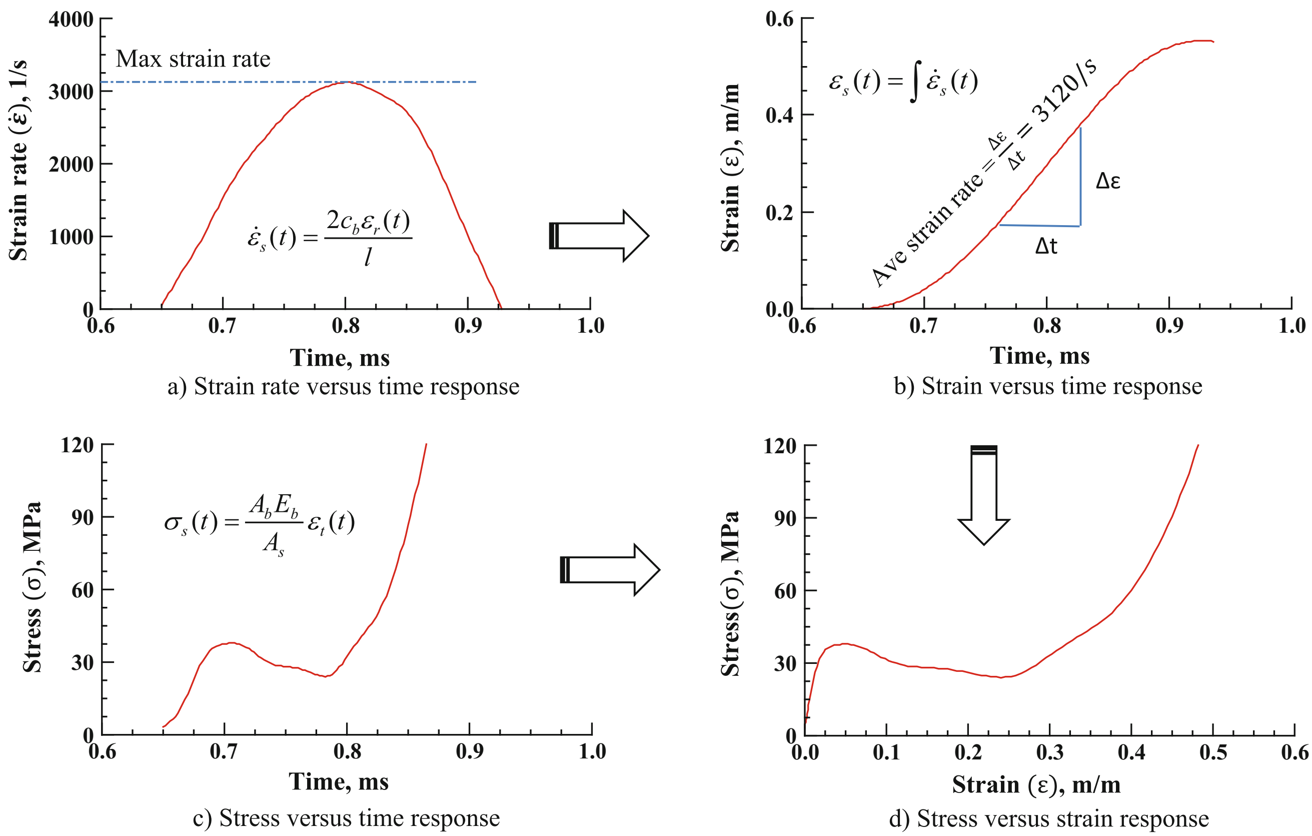


Fig. 9.6 Strain rate, strain and stress versus time responses and stress strain response of Eco-Core at 3120/s strain rate

Basic strain rate, strain and stress results were derived from the reflected and transmitted pulses time history. They were calculated by applying (9.1), (9.2) and (9.3), respectively. The parameters used with the equations were: $A_b = 285\ \text{mm}^2$, $A_s = 95\ \text{mm}^2$, $E_b = 71.7$ GPa, $C_b = 5051$ m/s and $l = 3.2$ mm. Results were reduced to stress versus strain response. Figure 9.6a–d show respectively the basic strain rate, strain, stress versus time responses and the derived stress versus strain response of Eco-Core at 3120/s. Stress strain responses for three specimens of each core materials were determined. In all cases the three responses agreed very well with each other's to indicate good repeatability of the test. The middle response out of the three responses of each material was used with its associated strain rate for further comparison and analysis.

9.4.2 Energy Absorption Results

Energy absorption per unit volume of each core material was calculated from the area under its stress strain response curve until the densification limit (ε_d). Approximated densification limit for each material was determined from the intersection between the tangent to the crushing phase curve and the tangent to the densification phase curve (see Fig. 9.7a). The stress strain response for each of Eco-Core, PVC foam, Balsa wood and Rohacell-A and their densification limits were determined and plotted in Figs. 9.7a–d, respectively. Area under each material response curve was determined by integrating the products of stress of small interval by the stain deference of the interval from 0 to the densification limit as:

$$A = \int_0^{\varepsilon_d} \sigma \, d\varepsilon \tag{9.4}$$

Where σ is the stress of small interval (2 μs) and $d\varepsilon$ is the strain difference during the small interval. The energy absorption per unit volume for all materials were calculated and compared to each other's in Fig. 9.8a. Since the weight of the core material curies significant importance toward its overall properties, then energy absorption per unit mass was calculated as well. It was called specific energy absorption in this study and calculated by dividing the energy absorption per unit volume by the density of the material. Specific energy absorptions for all materials were plotted in Fig. 9.8b.

Also, the energy absorption results for all materials at 3120/s–3490/s strain rates in addition to the densities and static yielding strengths were all summarized in Table 9.1. Results as appear in the last figure and table show that the energy absorption per unit volume of Eco-Core (11 MPa) is more than twice that of Balsa wood (4.4 MPa), more than five time that of PVC foam (1.9 MPa) and more than nine times that of Rohacell A (1.1 MPa). That means energy absorption per unit volume of Eco-Core is superior to other core materials. On the other hand, energy absorption per unit mass of Eco-Core

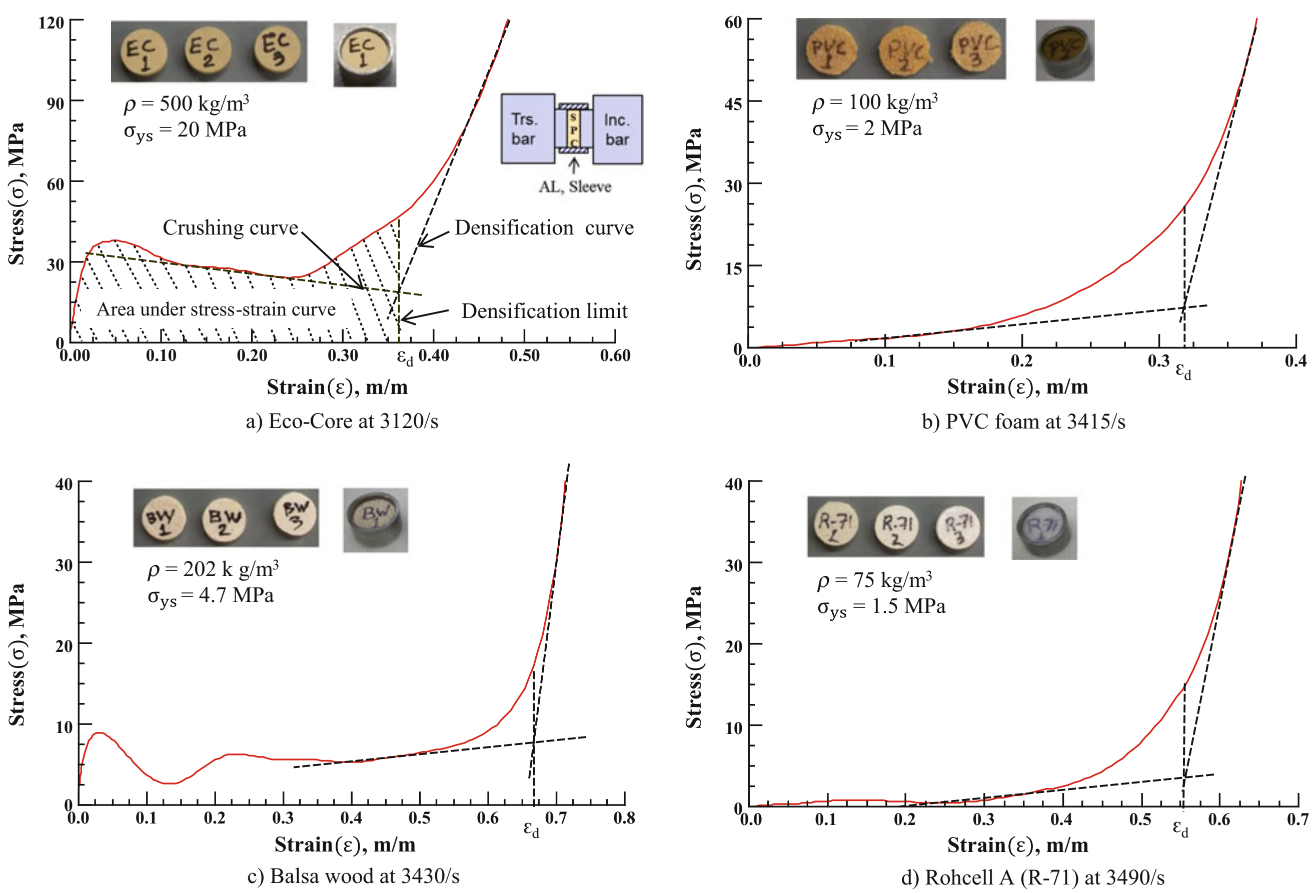


Fig. 9.7 Stress strain responses of core materials and determination of area under responses curves

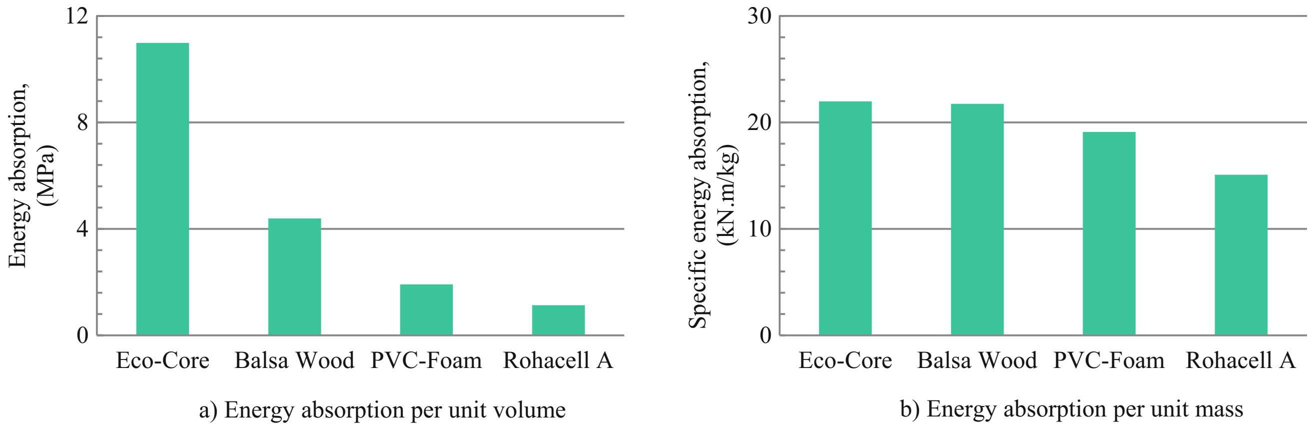


Fig. 9.8 Energy absorption per unit volume and per unit mass for core materials at 3120/s–3490/s strain rates

Table 9.1 Energy absorption per unit volume and per unit mass of core materials at 3120/s–3490/s strain rates

Material	Density, kg/m^3	Static yielding strength, MPa	Energy absorption per unit volume, MPa	Energy absorption per unit mass, kN m/kg
Eco-Core	500	20	11.0	22.0
Balsa wood	202	4.7	4.4	21.7
PVC Foam	100	2	1.9	19.1
Rohacell A (R-71)	75	1.5	1.1	15.1

(22 kN m/kg) is still better than that of other core materials (21.7, 19.1 and 15.1 kN m/kg for Balsa wood, PVC foam and Rohacell A, respectively), but, the difference is marginal. According to these results Eco-Core is highly recommended for applications with fire safety and energy absorptions requirements where weight of the structure is not an important factor like stationary applications as in bunkers. Also, it is still recommended for mobile applications like transportations, air-crafts, aerospace and naval wherever possible.

9.5 Conclusion

High strain rate (3120/s–3490/s) confined compression tests were performed on Eco-Core and other core materials (Balsa wood, PVC foam and Rohacell A). SHPB apparatus along with special test fixture to apply axial and lateral stresses on specimen were used to perform the tests. Specimens of all materials were of 11 mm diameter and 3.2 mm length. Test results showed that the energy absorption per unit volume of Eco-Core (11 MPa) is far superior to other tested commercial core materials (more than twice of Balsa wood the nearest material). The energy absorption per unit mass of Eco-Core (22 kN m/kg) is marginally better than other tested commercial core materials (As good as Balsa wood). Accordingly, Eco-core is highly recommended for stationary applications where the weight is not a significant factor as in stationary applications as in bankers and still recommended for mobile applications like transportations, air-crafts, aerospace and naval wherever possible.

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