Cumulative Impact Energy Absorption of Sandwich Panels with Foam Cores and Flax FRP Facings

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Abstract. In this paper, the cumulative energy absorption of sandwich panels constructed of foam cores and flax fiber-reinforced bio-based polymer (FFRP) faces is studied. Nine sandwich panels were constructed and tested under varying amounts of impact energy using a drop weight test. The parameters of the study were facing thickness and foam core density. Three different facing thicknesses (one, two, and three layers of a bidirectional flax fabric with a nominal unit weight of 400 kg/m^2) and three different core densities (32 kg/m^3, 64 kg/m^3, and 96 kg/m^3) were used. An accelerometer was placed on the bottom face of each specimen and on the drop weight. The data from the accelerometers is used to determine each specimen's fundamental frequency after each impact to determine the amount of damage in the specimen. To calculate curvature, strain gauges were placed at the center of the top and bottom face at mid-span. The information obtained is used to determine the ability of these panels to absorb the energy from multiple impact events. It also helps to establish a fundamental understanding of the behavior of the panels under impact for future research. To date all specimens have been fabricated and one of the specimens has been tested. Based on the results, the specimen was not visibly damaged after impact events of up to 122 N-m, but it failed at an impact energy of 153 N-m. The specimen deflection and facing strains increased with impact energy.

Introduction

Where lightweight and insulation efficiencies are required, sandwich panels are a popular choice of building material. Sandwich panels are typically constructed of two structural faces separated by a lightweight core with high insulative properties. The separation of the faces provides a large moment of inertia to resist bending [1]. A common choice for facing materials are fiber-reinforced polymers (FRPs) because of their high specific strength. Because failure of sandwich panels is often initiated in the weaker core material [2,3], there is an option to use lower strength, yet environmentally friendly facing materials, such as FRPs made with renewable constituents, such as flax fibers and bio-based resins.

Sandwich panels constructed with synthetic faces and foam cores have been studied under impact loading [4–6]. Panels constructed with FFRP faces have been studied in flexural applications [2,3,7,8] and axial loading applications [9]. However, there is a gap in the available research which is the behavior of sandwich panels with FFRP faces under impact loading. In this study, the cumulative energy absorption of sandwich panels with FFRP faces and foam cores is examined. The research in this paper will serve as a starting point to further investigations on this topic.

Experimental Program

Test Matrix

Nine sandwich beam specimens were fabricated for testing under a drop weight impact with increasing energy until failure. The parameters of the tests were facing thickness (1, 2 and 3 layers of bidirectional flax fabric) and core density (32, 64 and 96 kg/m^3). The test matrix is shown in Table 1. In this paper, the behavior of specimen 2FL-P400 is examined.

Table 1: Test matrix

No.	Specimen I.D.	Number of Layers	Core Density [kg/m^3]
1	1FL-P200	1	32
2	2FL-P200	2	32
3	3FL-P200	3	32
4	1FL-P400	1	64
5	2FL-P400	2	64
6	3FL-P400	3	64
7	1FL-P600	1	96
8	2FL-P600	2	96
9	3FL-P600	3	96

Note: FL = Flax Layers, PYYY = Core Type (P200 = 32kg/m^3, P400 = 64 kg/m^3, P600 = 96 kg/m^3)

Materials and Fabrication

The specimens used in this study were fabricated as a part of a larger study including specimens used in a study on the static flexural behavior of the panels [8]. The facings were made of a bidirectional flax fabric with a nominal areal weight of 400 g/m^2 (manufacturer: Composites Evolution, Chesterfield, UK) and a bio-based epoxy resin (manufacturer: Entropy Resins, Hayward, CA, USA).

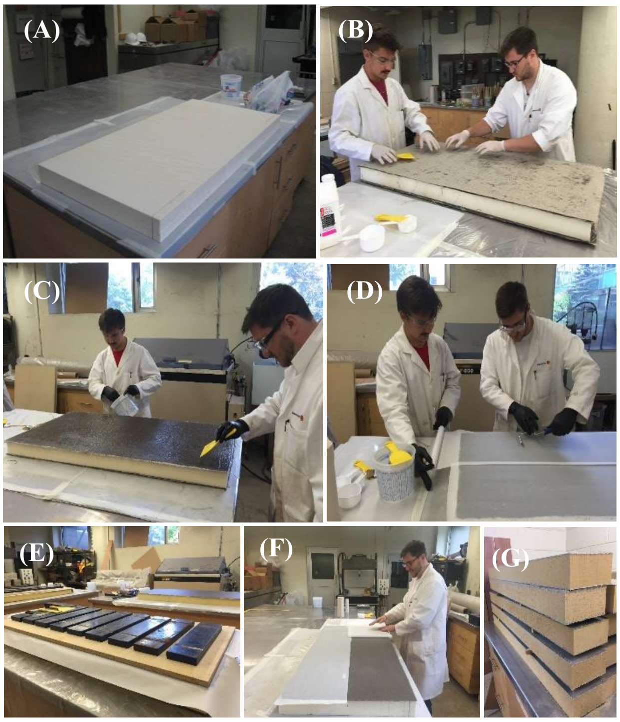

Fig. 1: Specimen fabrication: (a) plain foam section, (b) application of flax layer, (c) application of bio-based epoxy, (d) application of parchment paper, (e) curing, (f) removal of parchment paper, (g) finished samples

The cores used were closed cell polyisocyanurate foams (manufacturer: Elliott Company, Indianapolis, IN, USA). Fig. 1 shows the typical procedure for manufacturing each sandwich panel. The panels were made in 610 mm (weft fabric direction) by 1220 mm (warp fabric direction) sections and were cut down to the specimen size of 150 mm by 1200 mm after curing. A more detailed description of the materials and fabrication is available in the former study by Betts et al. [8], where similar specimens were tested under monotonic loading.

Test Setup and Instrumentation

Each specimen was tested using a drop weight with a mass of 10.413 kg at increasing heights until failure. The test set-up is shown in Fig. 2. The span length of each test specimen was 1117 mm. Strain gauges were installed at mid-width of the specimen, at mid-span, on both the top and bottom faces. Two string-type displacement sensors were located beneath the specimen at mid-span, 20 mm in from each edge of the specimen. The average result from the two displacement sensors was taken as the total displacement of the specimen throughout the impact event. An accelerometer was placed on the bottom of each specimen at mid-span and an additional accelerometer was placed on the drop weight.

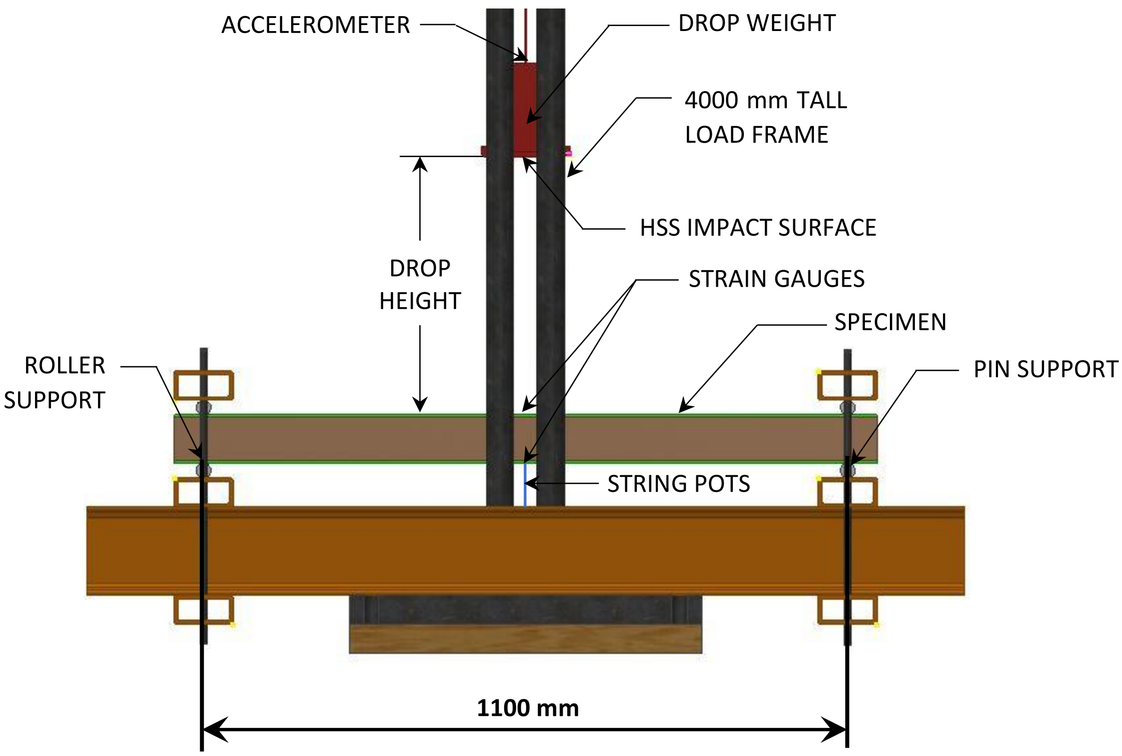

Fig. 2: Test Set-up

Results and Discussions

The specimen 2FL-P400 was subjected to impacts from heights of 300 mm, 600 mm, 900 mm, 1200 mm and 1500 mm by a drop weight with a total mass of 10.413 kg. Fig. 3 shows the impact event captured by a high-speed camera in three stages: before impact, maximum deflection and after impact.

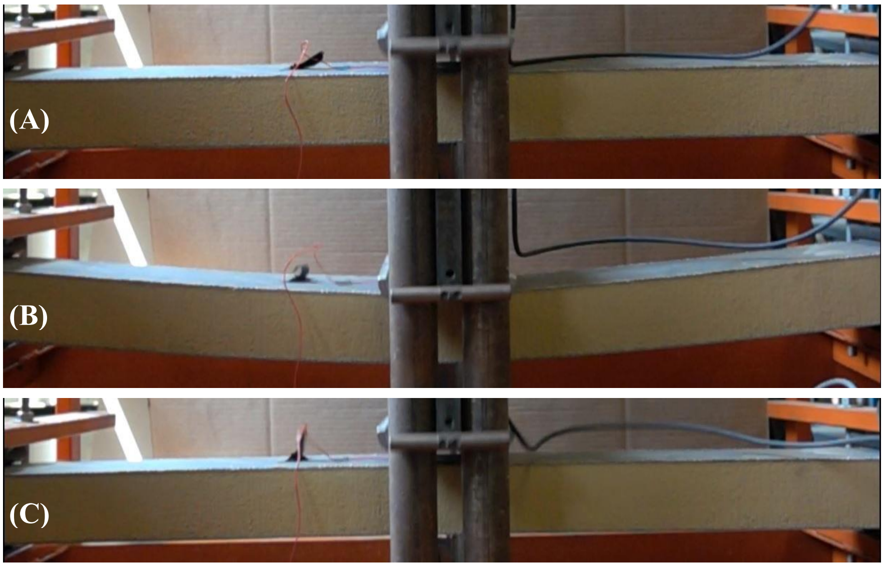

Fig. 3: Impact event from a drop height of 1200 mm: (a) before impact, (b) maximum deflection, (c) after impact

Fig. 4 shows the measured deflection after a moving average filter was applied to the data. The moving average filter was used to eliminate signal noise. After completing the moving average, the filtered data was plotted alongside the raw data to verify that the average did not affect the actual deflection data. The filtered deflection data was used to determine the specimen stiffness, damped period and damping coefficient.

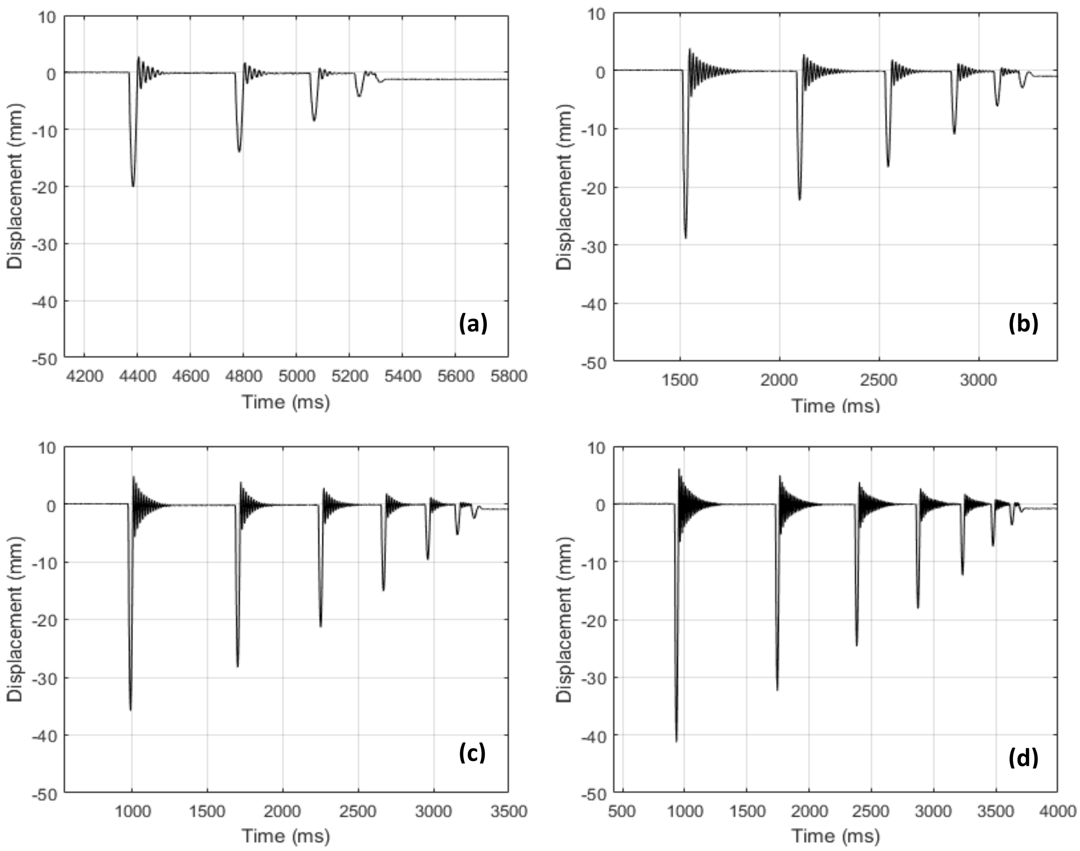

Fig. 4: Deflection vs. time: (a) 300 mm drop, (b) 600 mm drop, (c) 900 mm drop, (d) 1200 mm drop

The damped period of the specimen was determined by finding the average time elapsed between the crests and troughs of the deflection curve while the specimen was experiencing free vibration (i.e. while the weight and specimen were not touching). The damping ratio, ξ, was also calculated using the deflection data assuming that it was less than 10%, using Eq. 1.

$$\xi = \frac{1}{2\pi p}\ln\left(\frac{u_n}{u_{n+p}}\right). \quad (1)$$

where p is the number of full periods between the peak deflections, u_n and u_{n+p}, as shown in Fig. 5.

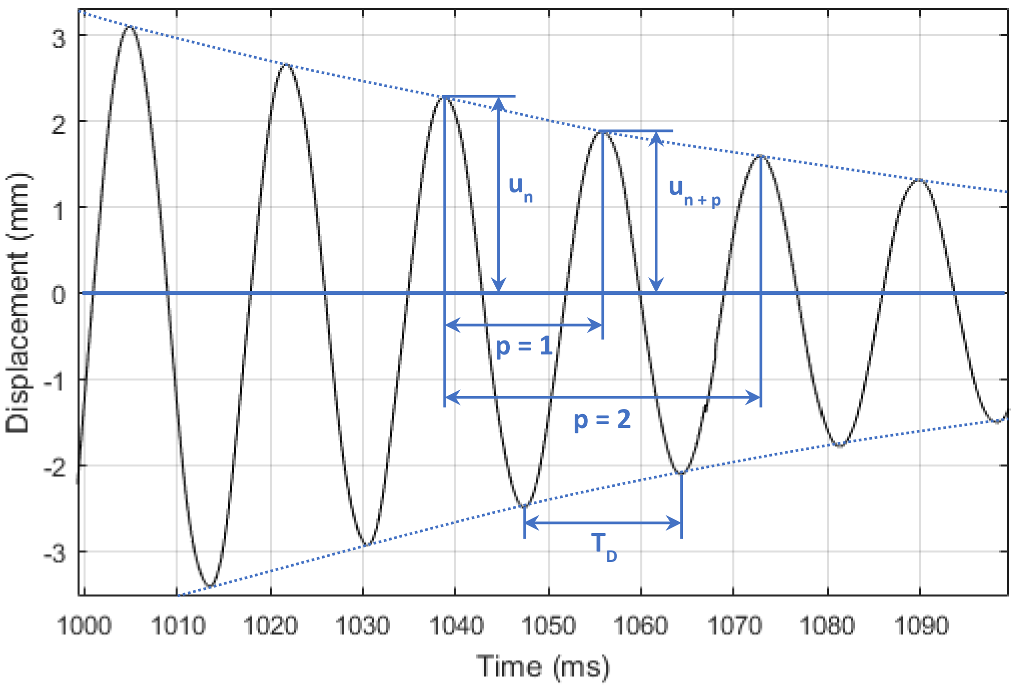

Fig. 5: Damping of sandwich panel under free vibration

The natural angular frequency, ω_n, could then be calculated by Eq. 2 assuming the damped and undamped periods are the same (i.e. $T_n = T_D$), which is valid if $\xi < 10\%$.

$$\omega_n = \frac{2\pi}{T_n}. \quad (2)$$

The specimen stiffness, K, could then be calculated using Eq. 3 as follows:

$$K = \frac{\omega^2 mL}{2}. \quad (3)$$

where m = specimen mass / length and L = span length. Each peak deflection after the first is a rebound impact. The Fig. shows that after the drop from 300 mm, the drop weight rebounded three times. After the 600 mm drop initial impact, the drop weight rebounded four times. When dropped from the heights of 900 mm and 1200 mm, the drop weight rebounded five times.

Fig. 6 shows the strain-time plot for each impact drop height other than the 1500 mm. By comparing the maximum strains from each drop height and comparing to the load-strain diagrams from the static tests [8] of the previous study, we can determine the equivalent static load to cause the strains in this specimen. Looking at the maximum strain in the tensile (bottom) face from the plots in Fig. 6 and comparing to the previous study, the 300 mm drop is approximately equivalent to a static load of 2 kN, a 600 mm drop is equivalent to 2.5 kN, a 900 mm drop is equivalent to 3 kN, and a 1200 mm drop is equivalent to 3.2 kN. This same procedure can be completed by comparing the maximum deflections from Fig. 5 to obtain similar results. The maximum facing strain in the previous study [8] was approximately 0.009 mm/mm, which is similar to the maximum strain of 0.0091 mm/mm in the current study, as shown in Fig. 6d and Table 2. Therefore, future tests can be tailored to reach failure energy by predicting approximate specimen behavior based on the static test data. However, it should be noted that due to the different strain rates in static and impact tests, the material properties can vary. In future tests, the effect of strain rate on the material properties will be determined.

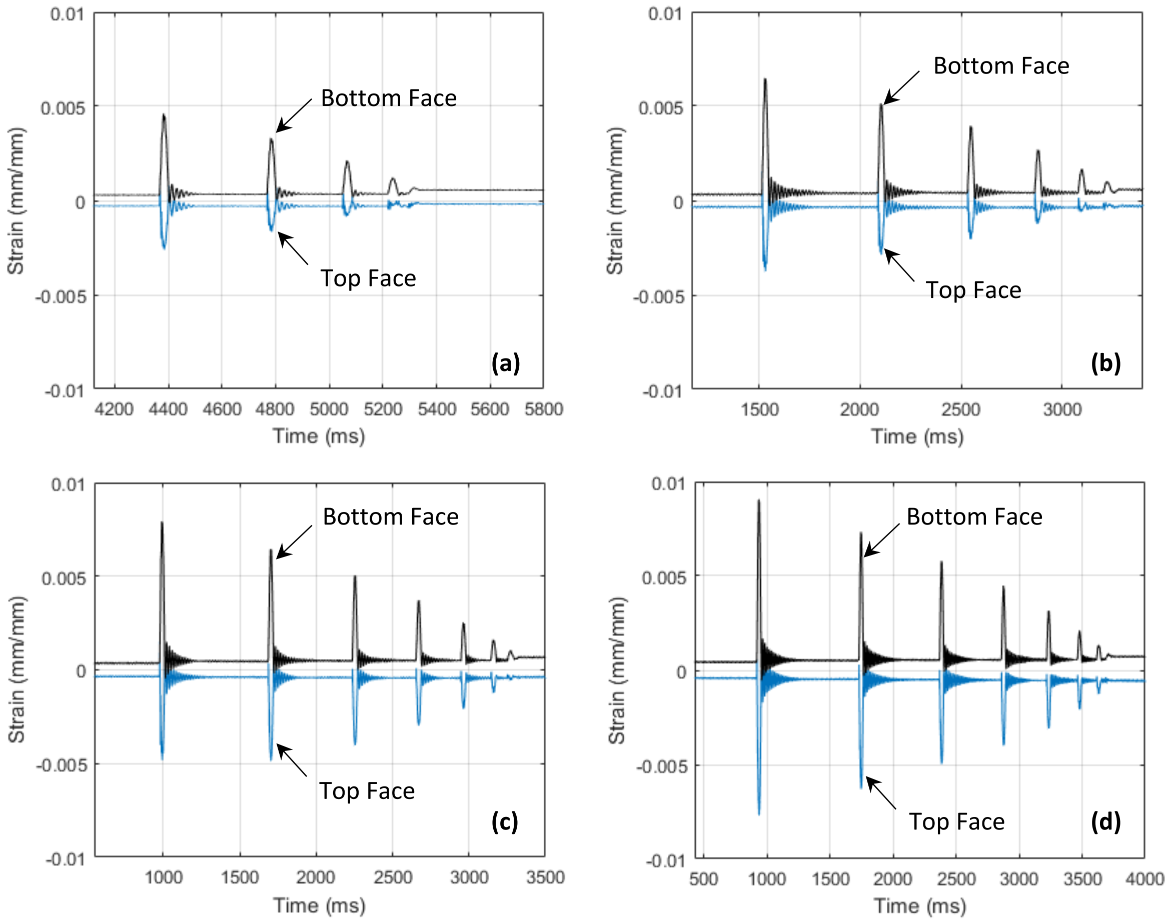

Fig. 6: Strain vs. time: (a) 300 mm drop, (b) 600 mm drop, (c) 900 mm drop, (d) 1200 mm drop

Table 2: Test results

Drop Height [mm]	V_{test} [m/s]	V_{calc} [m/s]	PE [N-m]	K [N/mm]	T_D [s]	ξ [%]	Δ [mm]	a_{DW} [m/s^2]	ε_{max} [mm/mm]	ε_{min} [mm/mm]
300	2.31	3.06	30.65	129.3	0.0175	7.1	20.1	55.6	0.0046	-0.0026
600	3.26	4.64	61.29	136.9	0.0170	3.5	28.9	64.3	0.0065	-0.0038
900	4.00	5.62	91.94	133.0	0.0173	4.2	35.8	91.4	0.0079	-0.0049
1200	4.62	6.25	122.58	140.1	0.0168	3.0	41.3	117.5	0.0091	-0.0077
1500	5.16	9.00	153.23	N/A	N/A	N/A	N/A	204.0	N/A	N/A

Note: V = velocity, PE = potential energy, K = stiffness, T_D = damped period, ξ = damping coefficient, Δ = maximum deflection, a_{DW} = acceleration of the drop weight on impact, ε = facing strain

Table 2 shows the test results of the specimen at each drop height. At a drop height of 1200 mm, the energy is 122.58 N-m. Upon examining the load-deflection curve of the static test performed by Betts et al. [8], the energy absorption of the static test specimen was found to be approximately 75 N-m . This shows that the energy absorption of the impact test was higher than that of the static test. The specimen experienced ultimate failure at an impact energy of 153 N-m (drop height of 1500 mm). This indicates that the failure energy is between 123 N-m and 153 N-m. The failure is shown in Fig. 7. The specimen failed simultaneously in tensile rupture and shear failure. The shear-type failure symmetrically about the drop weight impact as shown in Fig. 7a.

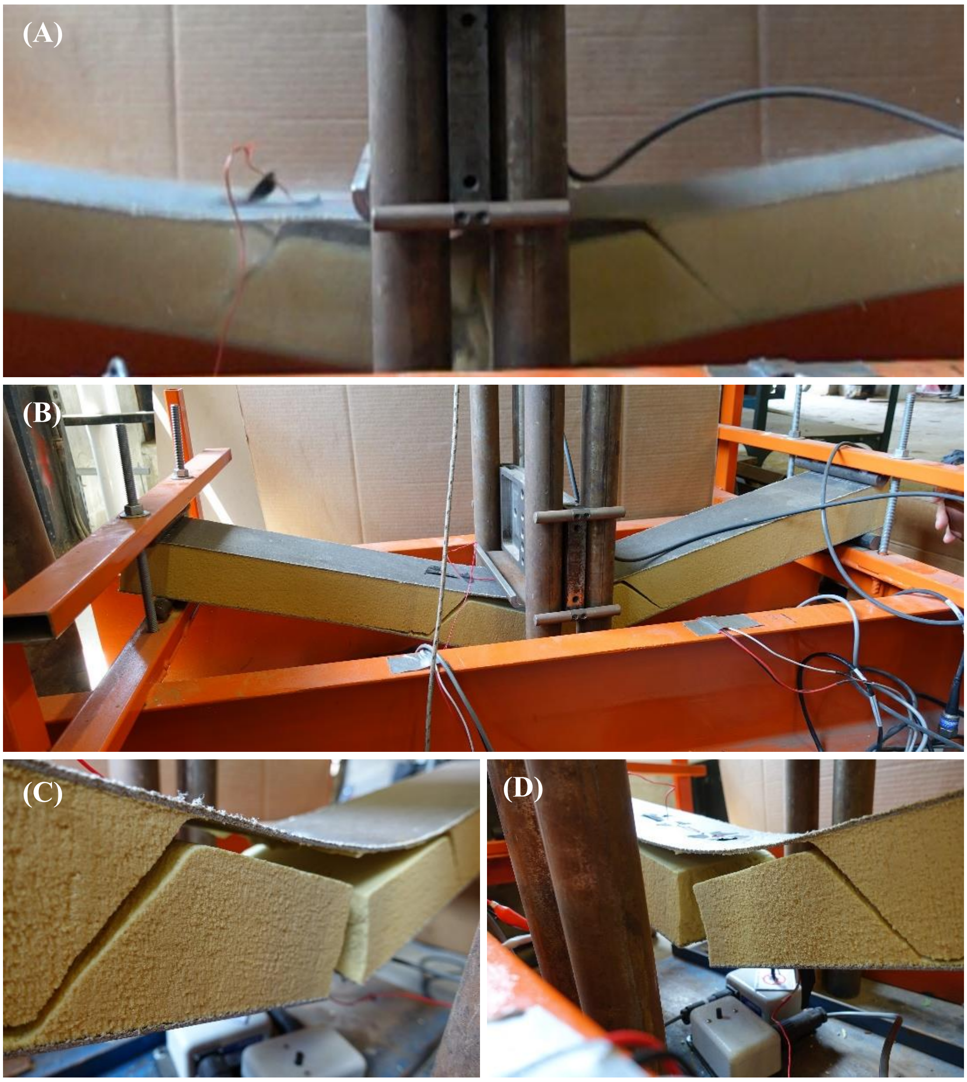

Fig. 7: Specimen failure at drop height of 1500 mm: (a) during impact, (b) after impact, (c) detail, (d) detail

Fig. 8a shows the effect of impact energy on the calculated stiffness of the specimen. It shows that the stiffness is relatively constant until the 1500 mm drop which caused failure. This is indicative that there was no damage in the specimen before the final loading. This agrees with the test observations as no visible damaged was seen during the testing before failure. If damage were present in the specimen after an impact event, it would be expected that the stiffness of the member would decrease. Fig. 8b shows the damping ratio as calculated from the free vibration of the first impact from each energy level. It shows that after the first hit there is a reduction in the damping ratio of approximately 50%, after which the damping ratio stays within 3 to 4 %. As the damping ratio is always under 10%, it verifies the earlier assumption that the natural period can be approximated as the damped period, T_D.

As expected, Fig. 8c, shows that as the impact energy increases, the maximum deflection also increases. Fig. 8d similarly shows the increase in the strain on the top and bottom faces. Fig. 8d also shows that the bottom face strain is approximately 0.002 mm/mm larger than the top face strain. However, as shown by Betts et al. (2017), the neutral axis of the specimens is located close to the midplane [8] and the strains should be opposite but approximately equal in magnitude. It is hypothesized that this difference is caused by the HSS impact surface shown in Fig. 2. As there is a strain gauge in the center of the top face, a 25 mm diameter hole was placed in the middle of the HSS impact surface, to avoid damage to the strain gauge. This could have potentially caused local tension in this area of the face, thereby reducing the strain gauge reading of the bending strain in the face.

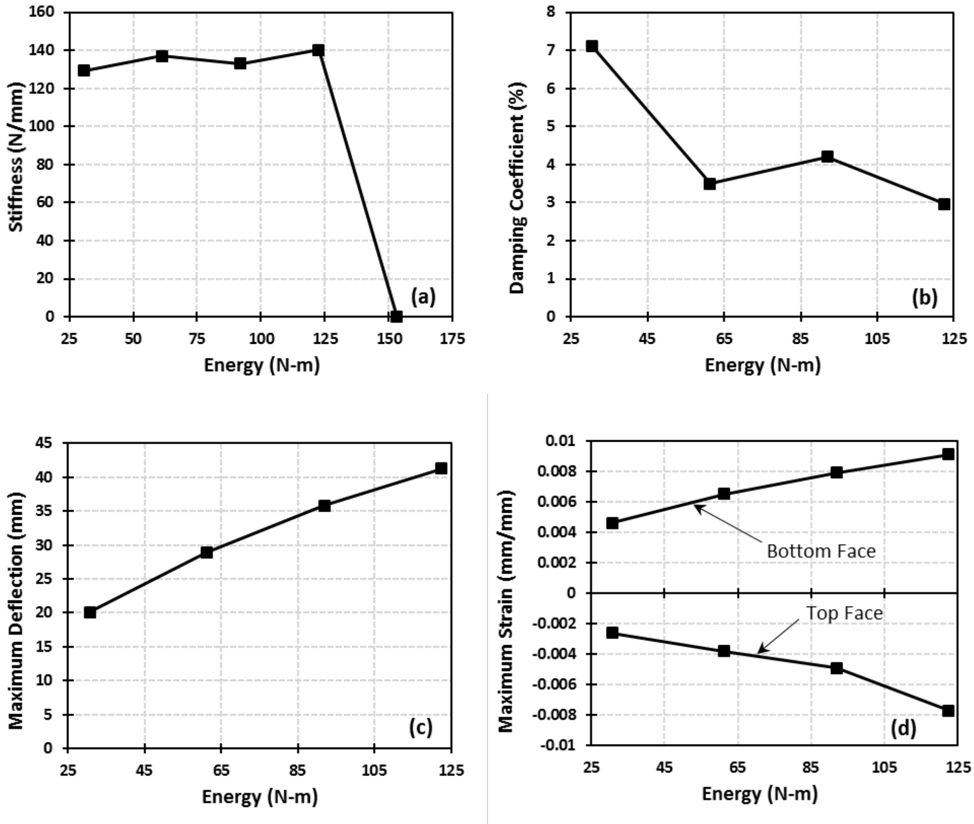

Fig. 8: Effect of input energy on specimen: (a) stiffness, (b) damping coefficient, (c) maximum displacement, (d) maximum facing strain

Conclusions

In this study, a sandwich specimen constructed of two-ply FFRP facings and a 64 kg/m^3 foam core was tested under varying impact energies. The specimen was not visibly damaged after impact events of up to 122 N-m, but it failed at an impact energy of 153 N-m. As expected, the specimen deflection and facing strains increased with impact energy. However, the stiffness was relatively constant until failure. Based on the results of the tests in this study, the following conclusions were made:

- the maximum cumulative energy absorption on of specimen 2FL-P400 is between 123 and 155 joules and failed simultaneously by tensile face rupture and shear.

- both maximum deflection and facing strain increased with impact energy;
- there was no obvious damage present before failure;
- and the sandwich panels can absorb more energy from an impact event than they can under quasi-static loading.

These tests are a part of an ongoing research and helped to provide insight into the general behavior of these structures as well as to provide an understanding of future testing requirements, such as:

- the use of smaller energy increments to capture the damage initiation energy and actual failure energy;
- testing of all specimen types to determine effect of the facing thickness and core density on energy absorption and failure mode
- development of a numerical model to predict impact behavior of sandwich specimens

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