Impact Behaviour of Sandwich Panels made of Flax Fiber-Reinforced Bio-Based Polymer Face Sheets and Foam Cores

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ABSTRACT

In this paper, the impact behaviour of sandwich panels constructed of flax fibre-reinforced polymer (FFRP) facings and closed cell polyisocyanurate foam cores is studied. A total of 27 sandwich beam specimens (1200 mm long and 150 mm wide) made of 75 mm thick foam have been fabricated. As a part of this study, three of these specimens have been tested under impact load at several energy levels. The main test parameter is the facing thickness (one, two, or three layers of FFRP). A bidirectional flax fabric (400 g/m^2) was used for the face sheets and a foam with a density of 64 kg/m^3 was used for the core. A bio-based epoxy resin, with an approximate bio-content of 30%, was used to make the FRP facings. Each specimen was tested multiple times increasing the kinetic energy until failure. The kinetic energy was increased by first increasing the drop height and then, if necessary, adding additional weight to the impactor and resetting the height to keep the increase in energy constant. The acceleration of the impactor, the drop weight velocity, and the top and bottom facing strains at mid-span will be measured. It is expected that ultimate energy absorption and strength of the specimens will increase as both the core density and facing thickness increase. The aim of this paper is to provide data to the field of study, provide insight into the structural behavior of these types of structures and show their viability for use in infrastructure. With further research, there is the potential that these types of structures could be included in structural building codes. This research is part of a larger on-going study and more results will be available at the time of the conference.

INTRODUCTION

To accommodate the increasing interest in sustainability, new infrastructure should incorporate environmentally friendly materials. Using natural materials to make sandwich panels for building cladding and roof slabs is one way to do this. An example of using natural materials in structures is the use of flax fibers to make fiber-reinforced polymers (FRPs) for use as face sheets for structural sandwich panels. Flax fibers are commercially available, are relatively strong and stiff when compared with other plant fibers and have a lower embodied energy than traditional fibers,

such as glass and carbon (Cicala et al. 2010). Sandwich panels with flax FRP (FFRP) faces have been studied recently under flexural loading (Betts et al. 2017; Fam et al. 2016; Mak et al. 2015; Sadeghian et al. 2016) and under axial loading (Codyre et al. 2016).

One potential application of these sandwich structures is building cladding systems which can be subjected to impacts from flying debris during a storm event. There have been studies on the impact behavior of sandwich structures with synthetic FRP faces (Atas and Potoglu 2016; Schubel et al. 2005; Torre and Kenny 2000), but there are no studies into the behavior of sandwich structures with FFRP faces under impact. Therefore, the aim of the current study is to provide an understanding of the behavior of sandwich structures with FFRP faces under impact loading.

EXPERIMENTAL PROGRAM

Test Matrix

As a part of this study, three test specimens were tested under impact with a 10.413 kg drop weight until ultimate failure. Each specimen was tested multiple times, increasing the energy of each subsequent impact. The energy was increased by increasing the initial height of the drop weight. The test parameter was the effect of facing thickness on energy absorption and mechanical properties under impact loading. The test matrix is shown in Table 1.

Table 1. Test Matrix

No.	Specimen I.D.	Number of Layers	Core Density (kg/m^3)
1	1FL-P400	1	64
2	2FL-P400	2	64
3	3FL-P400	3	64
Note: FL = Flax Layers, P400 = 64 kg/m^3 core density			

The first specimen tested was 2FL-P400. In this test the drop height started at 300 mm and was increased in increments of 300 mm until failure. Upon examination of the data, it was determined that in order to capture the damage initiation and to get a more accurate ultimate energy level, a smaller drop height increment was required. Therefore, specimens 1FL-P400 and 3FL-P400 were tested with drop height increments of 100 mm.

Specimen Fabrication

The specimens were fabricated as a part of a larger study and the specimen fabrication process is discussed extensively in the former studies by (Betts et al. 2017). The closed-cell polyisocyanurate foam cores were supplied in 1200 mm by 2400 mm boards (manufacturer: Elliott Company, Indianapolis, IN, USA). To make the specimens, the foam boards were cut down to a size of 600 mm by 1200 mm and the top and bottom surfaces were cleaned and prepared for fabrication. A layer of the bio-based epoxy (manufacturer: Entropy Resins, Hayward, CA, USA) was then applied followed by a layer of bidirectional flax fabric with a nominal areal mass of 400 g/m^2 (manufacturer: Composites Evolution, Chesterfield, UK). Additional epoxy was applied to the flax fabric until saturation and additional layers of flax fabric were placed as required. In order to provide a flat finish, a layer of parchment paper was applied to the surface and extra resin and air

was removed with a roller. The specimens were allowed to cure for seven days at which point the process was repeated for the opposite surface. After both faces had cured, the specimens were cut down to their final size of 1200 mm long by 150 mm wide using a band saw. The fabrication process is presented in Figure 1.
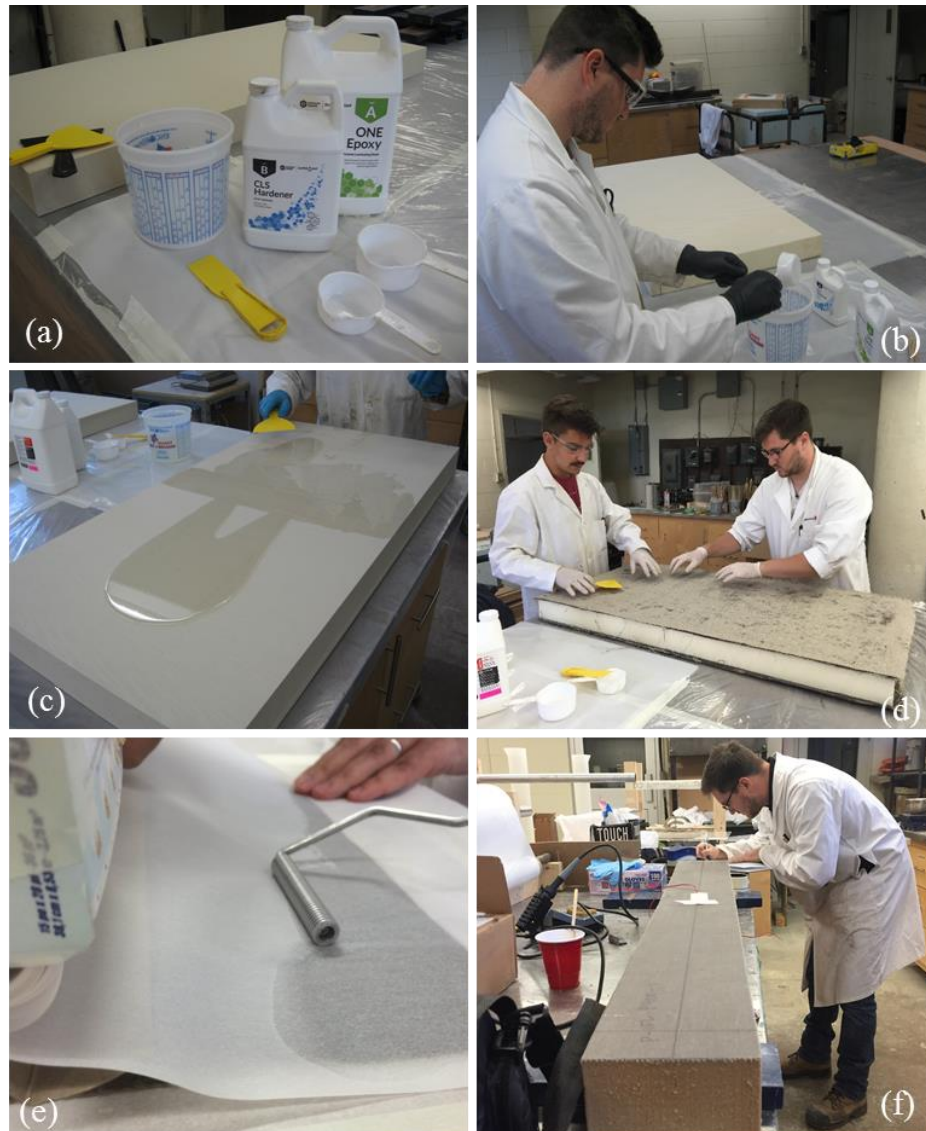

Figure 1. Specimen Fabrication (a) Cleaned Foam and Epoxy (d) Epoxy Preparation (c) Application of Epoxy (d) Application of Flax Fabric (e) Application of Parchment Paper (f) Application of Strain Gauges – Courtesy of Dillon Betts and Pedram Sadeghian

Test Set-up

To complete the testing, a test set-up was designed and built. This test set-up is shown in Figure 1. As shown in Figure 1, the specimen deflections were measured with a string-type displacement gauge and the top and bottom facing strains were measured with strain gauges located at midspan. A high-speed camera with a frame rate of 500 fps was used to record each impact.
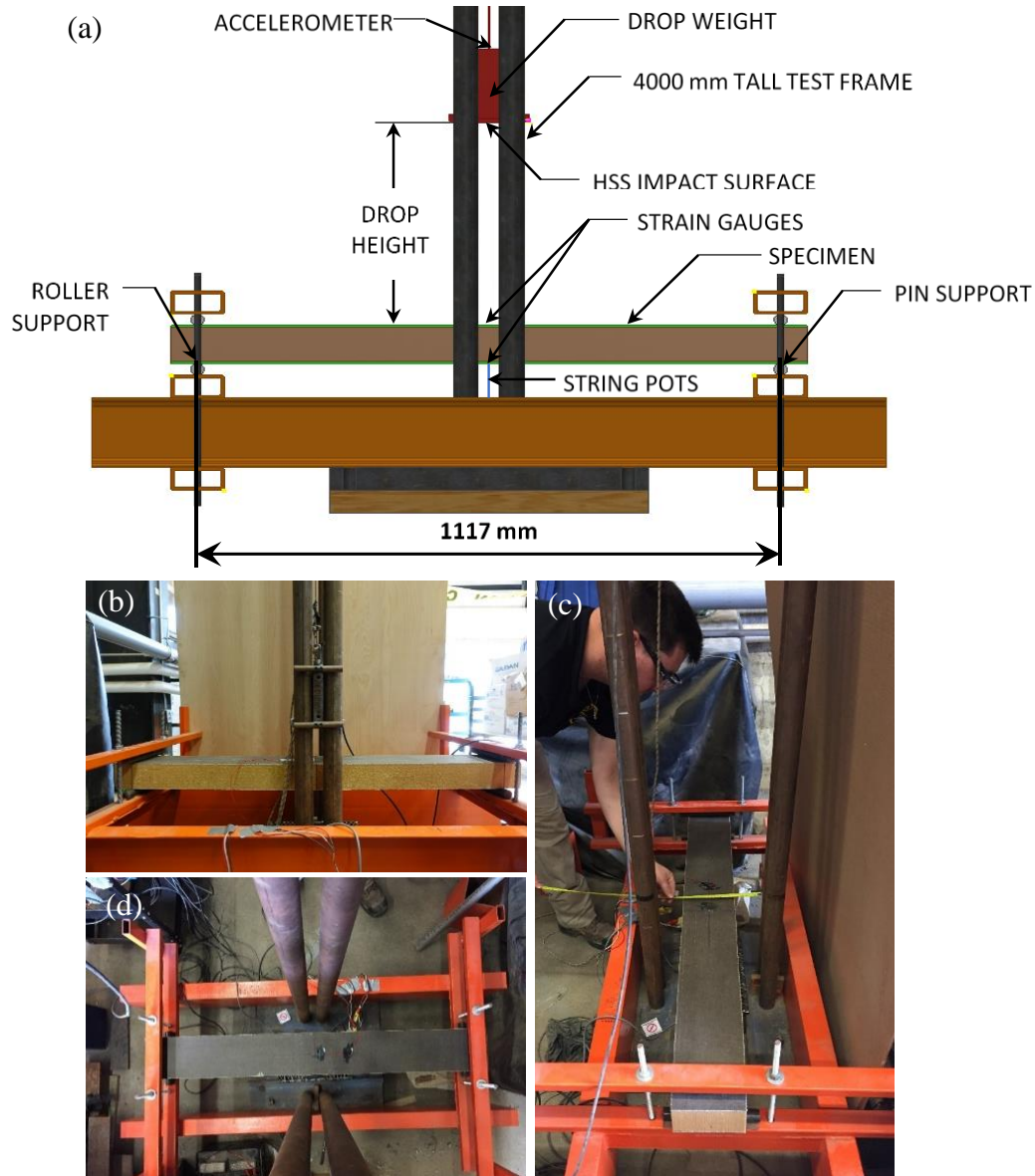
Figure 2. Test Set-up (a) Model (b) Side View (c) End View (d) Top View – Courtesy of Dillon Betts and Pedram Sadeghian

RESULTS AND DISCUSSIONS

The specimen stiffness, damping coefficient, maximum deflection, and maximum facing strains are presented against the impact energy in Figure 3. The impact energy absorption of the panels increased with facing thickness. Before failure, 1FL-P400 resisted a maximum impact of 30.6 Joules (J), 2FL-P400 resisted a maximum impact of 122.6 J, and 3FL-P400 resisted a maximum impact of 172.7 J.

Figure 3a shows the effect of impact energy on the specimen stiffness which was calculated using the following equation:

$$K = \frac{\omega^2 mL}{2}$$

where K is the specimen stiffness, ω_n, is the angular frequency, m is the mass of the specimen in kg/m and L is the span length. Before failure, the specimens' stiffness remained relatively constant and as expected, the stiffness increased with facing thickness. At an impact energy of 40.9 J, the compression face of specimen 1FL-P400 failed beside the drop weight and the stiffness was reduced by approximately 27%. The specimen was tested after failure at impact energies of 51.1 J and 61.3 J. As the specimen was already damaged, the stiffness was reduced by approximately 76% at these post-failure tests.
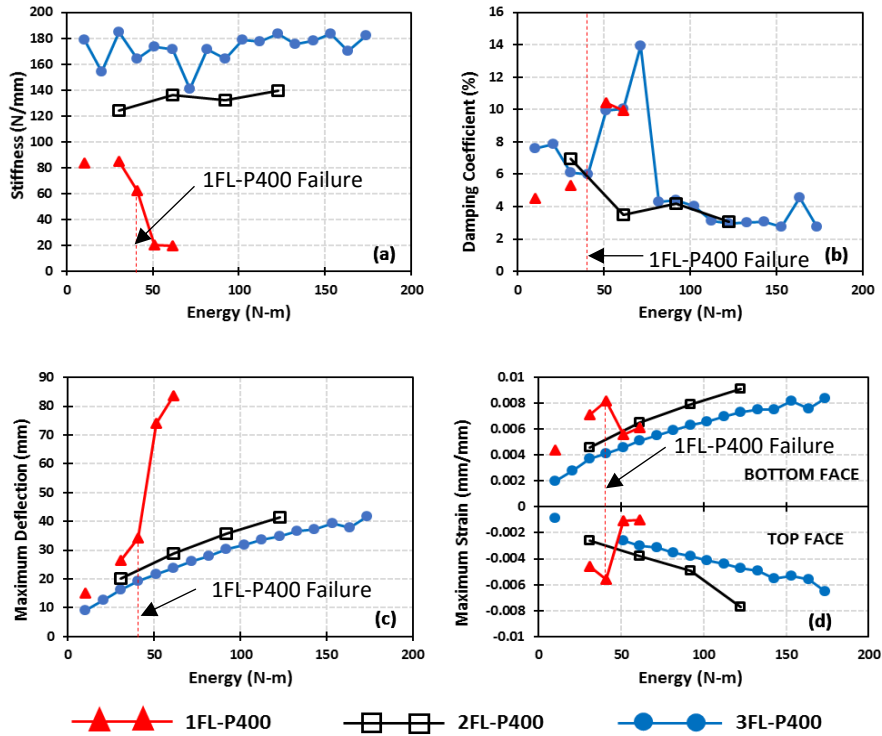

Figure 3. Test Results at Each Energy Level (a) Stiffness (b) Damping Coefficient (c) Maximum Deflection (d) Maximum Facing Strains

Figure 3b shows the damping coefficient versus the impact energy. The damping coefficient was calculated by fitting an exponential curve to the peaks of the deflection data during the free vibration after the first impact as shown in Figure 4. The equation for this curve is:

$$f_{(t)} = Ce^{-\xi\omega_n t}$$

where C is a constant, ξ is the damping coefficient, ω_n is the natural angular frequency of the specimen and t is time. After fitting the curve, the value of the exponential coefficient was determined and ξ could be calculated. Specimens 2FL-P400 and 3FL-P400 show that as the impact energy increases there is a downward trend in the damping coefficient. Specimen 1FL-P400 shows that after the failure of the top face, there was an increase in damping coefficient.

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Figure 3c shows a plot of the measured maximum deflection versus the impact energy. For each specimen, the deflection increased with impact energy. After initial failure, the deflection of specimen 1Fl-P400 increased drastically.
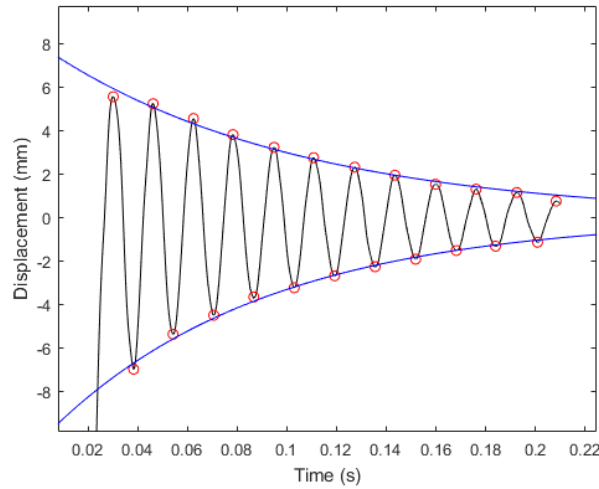

Figure 4. Calculation of Damping Coefficient

As shown in Figure 3d, the facing strains of specimens 2FL-P400 and 3FL-P400 increase as the impact energy increases. After initial failure, the facing strains in specimen 1FL-P400 decreased in the next impact and then began to increase again in subsequent impacts.

Failure Modes

Identical specimens have been tested under static loading by Betts et al. (2017a). Figure 5 shows a comparison of the dynamic failure modes compared to the failure modes of the static tests. Specimens 1FL-P400 and 3FL-P400 show similar failure patterns as their static counterparts, but specimen 2FL-P400 exhibits a different failure mode: tensile rupture and core shear. The static test specimen failed by compression face wrinkling.
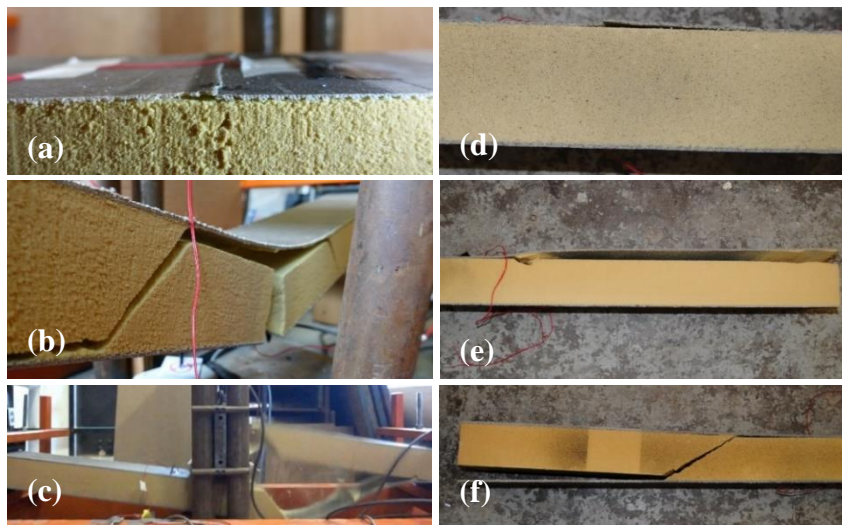

Figure 5. Failure Modes (a Dynamic 1FL-P400 (b) Dynamic 2FL-P400 (c) Dynamic 3FL-P400 (d) Static 1FL-P400 (e) Static 2FL-P400 (f) Static 3FL-P400 - Courtesy of Dillon Betts

CONCLUSIONS

Three specimens were tested under impact with a drop weight at increasing drop heights until failure. The impact resistance and stiffness of the panels increased with facing thickness. The stiffness of each specimen remained relatively constant under the increasing impact energies. Facing strains and maximum deflection both increased with impact energy whereas the damping coefficient decreased. After the failure of the compression face, the stiffness and facing strains of specimen 1FL-P400 decreased drastically and damping coefficient and deflection increased. Based on the test results, the following conclusions were drawn:

- specimen 1FL-P400 resisted a maximum impact of 30.6 J before failure;
- specimen 2FL-P400 resisted a maximum impact of 122.6 J before failure;
- specimen 3FL-P400 resisted a maximum impact of 172.7 J before failure;
- the failure modes of 1FL-P400 and 3FL-P400 matched those observed during static testing;
- the failure mode of 2FL-P400 was different than that observed during static testing.

ACKNOWLEDGEMENTS

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