Two-Way Flexural Behavior of Sandwich Panels with Flax FRP Faces and Foam Cores Under Monotonic Loads

Dillon Betts, Pedram Sadeghian, and Amir Fam

1 Introduction

Sandwich panels are structural elements comprised of two main materials: strong, stiff faces and a light-weight core often made of foam. These structures can be used for light-weight applications or where their insulative properties are beneficial, such as in building cladding systems. Research on sandwich panels is often focused on the use of fiber-reinforced polymers (FRPs) as facing materials (Fam et al. 2016; Feng and Aymerich 2013; Petras and Sutcliffe 1999). This is due to the high specific strength and stiffness of traditional FRP materials, such as glass or carbon FRPs. In sandwich panels, the full strength of the faces is not regularly utilized as failure often occurs in the weaker core material (Betts et al. 2018b; Sadeghian et al. 2018). This means that it is possible to use weaker, but more environmentally friendly materials for sandwich panel faces, such as natural FRPs, like flax FRPs (FFRPs).

Recent studies have focused on using FFRPs for faces in one-way sandwich beams under various loading conditions, such as axial loading (Codyre et al. 2016), flexural loading (Betts et al. 2018b; Mak et al. 2015), and impact loads (Betts et al. 2018a). However, thus far the research remains limited on the flexural behavior of two-way

D. Betts (✉) · P. Sadeghian
Department of Civil and Resource Engineering, Dalhousie University, 5268 DaCosta Row, Halifax, NS B3H 4R2, Canada
e-mail: dillonbetts@dal.ca

P. Sadeghian
e-mail: pedram.sadeghian@dal.ca

A. Fam
Department of Civil Engineering, Queen's University, 58 University Ave, Kingston, ON K7L 3N6, Canada
e-mail: amir.fam@queensu.ca

B. Benmokrane et al. (eds.), *8th International Conference on Advanced Composite Materials in Bridges and Structures*, Lecture Notes in Civil Engineering 278,
https://doi.org/10.1007/978-3-031-09632-7_6

Table 1 Test matrix

Specimen ID	Number of FFRP layers	Approximate face thickness, mm	Core density, kg/m^3	Status
1FL-C96	1	1.5	96	Tested
2FL-C96	2	2.5	96	Tested
3FL-C96	3	3.5	96	Fabricated

sandwich panels with FFRP faces. In this study, the results of two large-scale two-way sandwich panel flexural tests are presented and discussed.

2 Experimental Program

2.1 Test Matrix

The test matrix is presented in Table 1. As shown in Table 1, three-panel types were chosen to test, however 3FL-C96 has not yet been tested. The main parameter of the tests is the number of FFRP layers on each face: one, two, or three. The naming convention is as follows: XFL-C96, where X is the number of FFRP layers on each face and C96 represents the fact that a 96 kg/m^3 foam was used for the panel cores.

2.2 Specimen Fabrication

Figure 1 shows the specimen fabrication procedure. The foams were provided by the manufacturer in 1220 mm × 2440 mm pieces. The dry flax fabric was provided in rolls with a width of 1220 mm. The bio-based epoxy was a two-part epoxy with an approximate bio-content of 30%.

First, each section of foam was cut in half to the size of the final specimen: 1220 mm × 1220 mm. The fabric was cut to size and the foams were cleaned of any debris and the fabrication area was prepared as shown in Fig. 1a. A bio-based epoxy was mixed and applied to the surface of the foam using plastic scrapers as shown in Fig. 1b. Once the epoxy covered the entire surface of the foam, the flax fabric was placed as shown in Fig. 1c. The fabric was gently pressed into the layer of the epoxy below using the scrapers. Epoxy was applied to the surface as shown in Fig. 1d. The steps shown in Fig. 1c, d were repeated as needed for one, two, or three layers of FFRP. When the final layer of flax and epoxy was placed, parchment paper was applied to the surface and an aluminum roller was used to remove excess resin and air as shown in Fig. 1e. Then, a weighted board was placed on the top of the specimen and the faces were allowed to cure for at least 48 h. It should be noted that no parchment paper or weighted board was used for specimen 1FL-C96; the faces

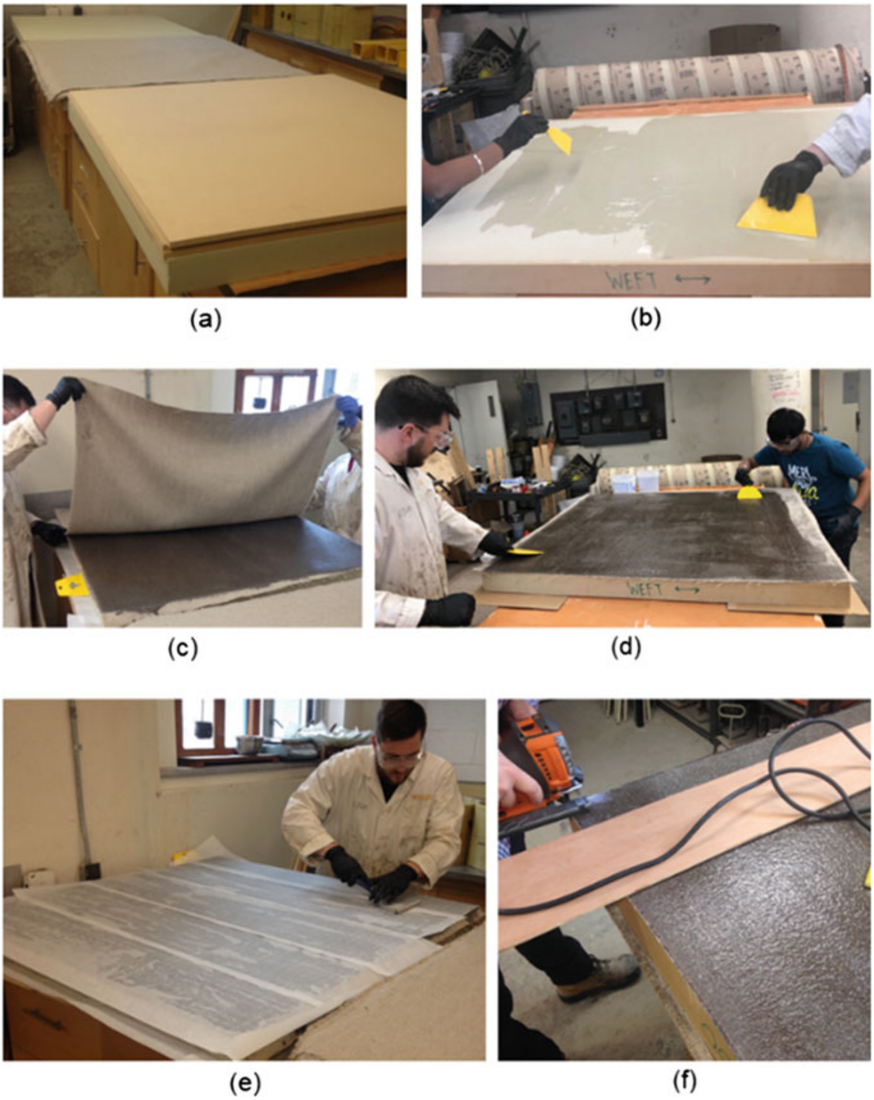

Fig. 1 Specimen fabrication **a** Fabrication set-up; **b** Application of epoxy on foam surface; **c** Placement of flax fabric; **d** Application of epoxy on flax fabric; **e** Placement of parchment paper and rolling [Not performed for specimen 1FL-C96] and; **f** Cutting face edges

of this specimen were allowed to cure open to the air. The last step of the specimen preparation was to cut the excess FFRP away from the edges using a jigsaw with a fine-tooth blade as shown in Fig. 1f.

FFRP coupons were tested in compression in the warp and weft direction. In the warp direction, the FFRPs were found to have an ultimate tensile strength and ultimate tensile strain of 70.0 ± 3.4 MPa and 0.0202 ± 0.0022 mm/mm, respectively. In the weft direction, the FFRPs were found to have an ultimate tensile strength and ultimate tensile strain of 51.3 ± 1.4 MPa and 0.0204 ± 0.0024 mm/mm, respectively.

2.3 Test Setup

The test setup is presented in Fig. 2. Each specimen had a span length of 1120 mm in both directions. Two of the roller supports were welded to the support frame as "pin" connections and two were allowed to roll as "roller" supports. The load was applied through a circular steel section with a diameter of 150 mm. During the first test, specimen 2FL-C96, the loading circular area caused local failure and severed the wires of the strain gauges. Therefore, for the next specimen, 1FL-C96, (and all proceeding tests) a rubber mat was placed under the loading area. This will be discussed further in the proceeding section.

The load was measured using a 250 kN load cell and the center point deflection was measured from the bottom using a string potentiometer. Each specimen was equipped with six strain gauges: three on the top and bottom. The strain gauges were placed at the specimen center; one was placed in the warp direction, one in the weft direction and one at 45° from the warp direction. All data were acquired at a rate of 10 Hz.

3 Results and Discussions

In this section of the paper the results of the tests will be presented. Firstly, the failure modes of the specimens will be discussed, followed by a discussion on the flexural behavior of the panels. Finally, the effect of FFRP face thickness will be quantified.

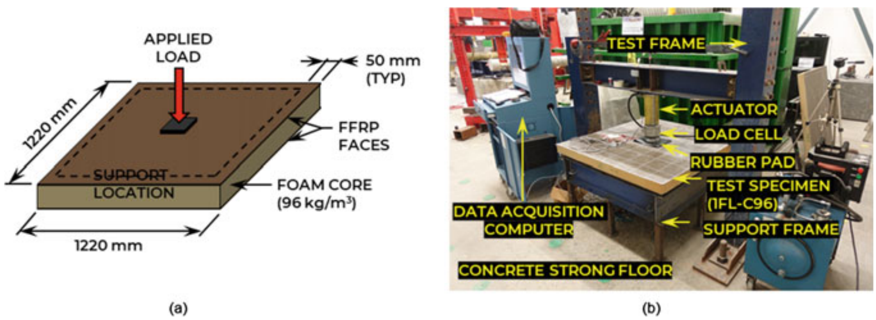

Fig. 2 Test setup **a** Simplified schematic and; **b** Photo

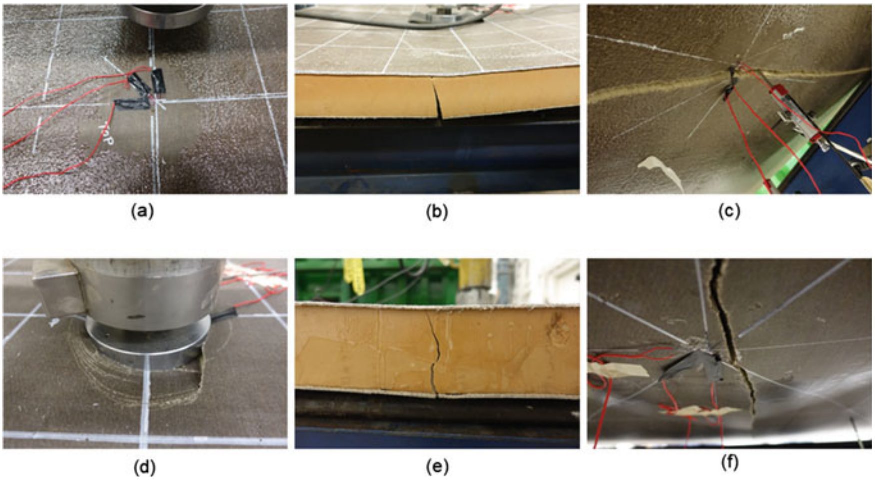

Fig. 3 Failure modes **a** 1FL-C96 loading area; **b** 1FL-C96 side view; **c** 1FL-C96 underside; **d** 2FL-C96 loading area; **e** 2FL-C96 side view and; **f** 2FL-C96 underside

All data processing and analysis were performed by a Python script written using the scientific package, Anaconda.

3.1 Failure Modes

Figure 3 shows the failure modes exhibited during testing. Figure 3a–c shows specimen 1FL-C96 and Fig. 3d–f show specimen 2FL-C96. As mentioned previously, the first specimen tested was 2FL-C96 and as no rubber mat was placed under the loading area, it experienced local failure around the loading area as shown in Fig. 3d. However, it did fail simultaneously in tensile rupture of the weft fibers in the bottom face (Fig. 3e, f). Through the use of the rubber mat under the loading area, the local failure was avoided in specimen 1FL-C96 (see Fig. 3a). As shown in Fig. 3b, c 1FL-C96 also failed due to tensile rupture of the weft fibers on the bottom face.

3.2 Flexural Behavior

The flexural behavior of the panels is presented in Fig. 4. Looking at Fig. 4a, the specimens both presented a slightly nonlinear load–deflection behavior close to the end of the tests. Looking at Fig. 4b, there is a pronounced nonlinear load-strain behavior on the bottom face, especially close to failure. Note that due to the severing

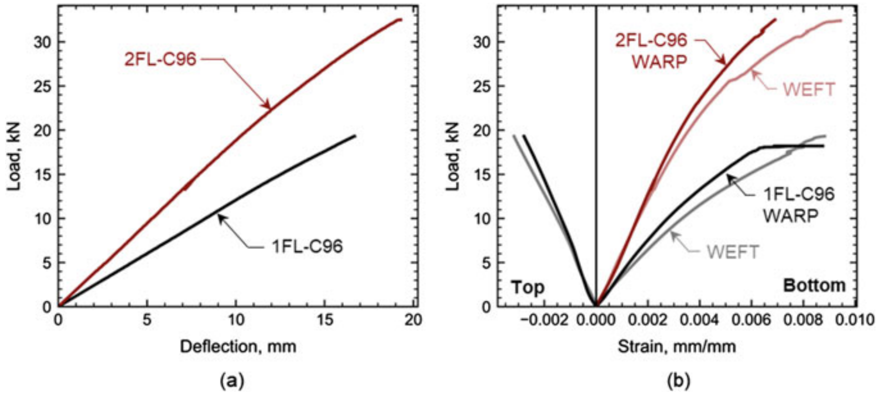

Fig. 4 Flexural behavior **a** Load–Deflection, **b** Load-Strain [Note that there was no available strain data for the top face of 2FL-C96 as strain gauge wires failed]

Table 2 Test results

Specimen ID	Stiffness, N/mm	Ultimate load, kN	Ultimate deflection, mm	Ultimate strain in weft direction on bottom face, mm/mm
1FL-C96	1209.8	19.3	17.3	0.0088
2FL-C96	1785.7	32.5	20.2	0.0094

Note Stiffness was calculated between a deflection of 0.5 mm and 2 mm

of the strain gauge wires during testing, the top face compression strain data is not presented for 2FL-C96.

Table 2 presents the stiffness and ultimate conditions observed during the tests. Increasing the face thickness from one layer of FFRP to two layers increased the stiffness and ultimate load and deflection. The stiffness of 2FL-C96 was found to be 48% higher than the 1FL-C96. Additionally, the ultimate load and deflection were increased by 68% and 17%, respectively, between the 1FL-C96 and 2FL-C96 specimens.

Interestingly, the ultimate strain in the weft direction on the bottom face (the failure area) was at 0.0088 mm/mm and 00.0094 mm/mm for the 1FL-C96 and 2FL-C96 specimens, respectively. These strains are approximately 45% of the ultimate strain observed during the weft coupon tensile tests. This behavior is currently being investigated further.

4 Conclusions

As a part of this study, three 1220 mm × 1220 mm sandwich panels with FFRP faces and foam cores were fabricated and, thus far, two have been tested under a concentrated load at the center. Both panels presented the same ultimate failure mode: tensile rupture of the weft fibers of the bottom face. However, specimen 2FL-C96 also exhibited a local failure under the application of the load. It was determined that using a rubber pad under the loading area mitigated the possibility of local failure occurring around the load application. Based on the test results, it was determined that the strength and stiffness of the panels increased with the number of FFRP face layers. Doubling the number of face layers increased the strength by 68% and the stiffness by 48%. Further research in this study includes the testing of the three FFRP layer specimen, 3FL-C96, as well as the development of a model to predict the flexural behavior of these panels.

Acknowledgements The authors would like to thank Jordan Maerz, Anurag Mishra, Lucas Marques, and Eric Tynski for their assistance in the lab. The authors would also like to acknowledge and thank the Natural Sciences and Engineering Research Council of Canada (NSERC), Queen's University, and Dalhousie University for their financial support and in-kind contribution.

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