

# Investigation of out of plane compressive strength of 3D printed sandwich composites

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**Abstract.** In this study, the 3D printing technique was utilized to manufacture the sandwich composites. Composite filament fabrication based 3D printer was used to print the face-sheet, and inkjet 3D printer was used to print the sandwich core structure. This work aims to study the compressive failure of the sandwich structure manufactured by using these two manufacturing techniques. Two different types of core structures were investigated with the same type of face-sheet configuration. The core structures were printed using photopolymer, while the face-sheet was made using nylon/glass. The out-of-plane compressive strength of the 3D printed sandwich composite structure has been examined in accordance with ASTM standards C365/C365-M and presented in this paper.

## 1. Introduction

Composites sandwich structures are usually comprised of two thin stiff facesheets and a lightweight core structure [1]. Extrusion, expansion and corrugation process are main conventional techniques of manufacturing honeycomb core [2]. However, few new core manufacturing techniques are also available but all are limited to specific simple core design, so complex core manufacturing is not possible by these conventional techniques [3-5].

3D printing is gaining attention of researcher to explore new sandwich structure owing to its design flexibility [6-9]. Composite printing is the emerging technology to revolutionize the composite manufacturing and researchers have become interested to analyse the material behavior of such composite [9]. Due to the high flexural stiffness with overall low core density of composite sandwich structures, it is used by many industries like fashion, automotive, aerospace, marine and etc [6-8].

Many researchers have tested different types of new core design to improve the performance of the core structure, like kagome, kirigami, corrugated or spider web [10-15]. The two new core structures, vertical pillared sine wave corrugated (VPSC) structures and vertical pillared trapezoidal corrugated (VPTC) structures are designed. These types of corrugated structures are known to have high compressive strength due to its specific corrugated design [16, 17]. The 3D inkjet printing technique was selected to fabricate these corrugated core structures because of the high capability of inkjet printing to fabricate accurate features [18]. In the present study the research is focused on compressive behavior of 3D composite sandwich structure having 1.5 mm Kevlar-nylon facesheet and ABS-rubber core.

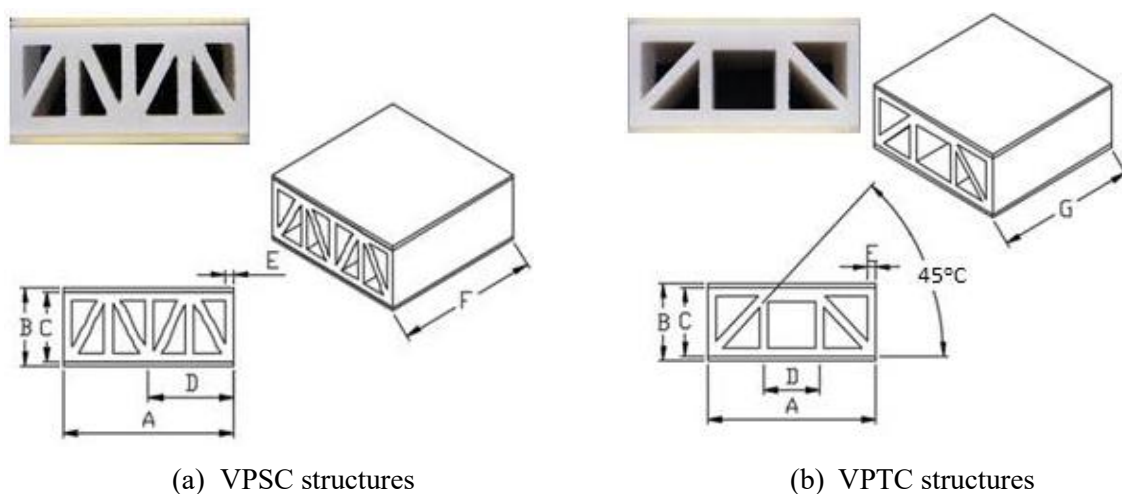


## 2. 3D printed sandwich composites and out of the plane compressive test

In this study, the focus area is to use two different 3D printing technique to print composite sandwich structure. The corrugated structures were produced by the polymer inkjet printing and the composite face sheet was produced by the composite filament fabrication technique.

### 2.1. Sandwich design

Before the fabrication of the sandwich, core and the facesheets, the design were modelled using computer-aided (CAD) software, SOLIDWORKS 2015, after this the models were exported into STL files to be 3D printed. figure 1a shows the CAD model of the VPSC structure, whereas figure 1b shows the VPTC structure. Table 1 shows the overall dimensions of the 3D printed corrugated sandwich structures.



**Figure 1.** Design of VPSC and VPTC structures

**Table 1.** Dimensions of cellular core segments

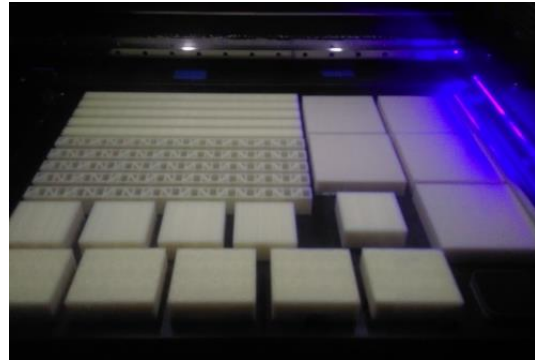
Designs	Dimensions (mm)						
	A	B	C	D	E	F	G
Vertical pillar corrugated sine wave (VPSC) structure	40	18	16	20	1.45	40	-
Vertical pillar corrugated trapezoidal (VPTC) structure	40	18	16	13	1.5	-	40

### 2.2. Inkjet core printing

Corrugated structures were fabricated using 3D SystemsProJet 5500X 3D printer, an inkjet 3D printer which is capable of printing multiple materials simultaneously. The UV curable rubbery and rigid polymers could be selectively deposited on the built tray based on the material selected during the printing process setup. RWT-FBK 100 (80% rigid-ABS, 20% flexible-Rubber) semi-rigid material was selected for core material printing. Figure 2a displays the ProJet 5500X 3D printer, whereas figure 2b shows the 3D printing of corrugated structures by ProJet 5500X 3D printer.



(a) ProJet 5500X 3D printer

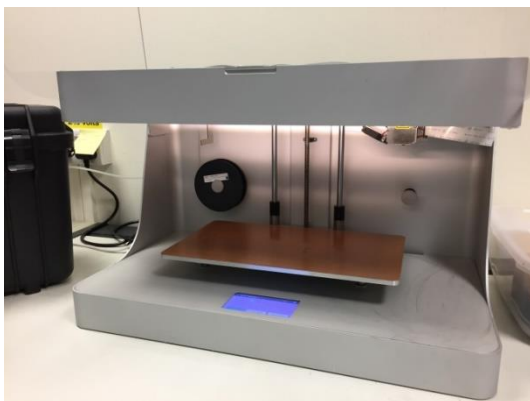


(b) Printing of corrugated structures

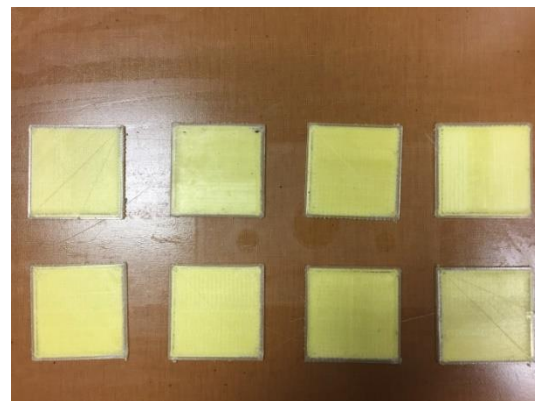
**Figure 2.** 3D inkjet printing

### 2.3. Facesheet printing by composite filament fabrication

The facesheet was fabricated using Mark Forged Mark One 3D printer. The Mark One is a fused deposition modeling technique based 3D printer which has dual nozzles to extrude both the fiber composite filament and pure Nylon filaments to 3D print fibre reinforced composite structures. Kevlar-nylon filament were selected for facesheet fabrication. The printed facesheet thickness is 1.5 mm with 0/90 fiber orientation. Figure 3a shows the Mark One 3D printer, whereas figure 3b shows the 3D printed facesheet.



(a) Mark One 3D printer



(b) Composite facesheet

**Figure 3.** 3D composite printing

Upon completion of both types of printing, the parts were taken out of the building chamber for post-processing. Post-processing of ProJet printed parts involved melting of wax support material that surrounds the final part. On the other hand, there is no separate support material for Mark One 3D printer. A thin layer of nylon was printed as support structure, and it can be peeled off manually from the printed part. After that, the 3D printed core and the facesheet were assembled to form sandwich beams using M-bond 200 adhesive (AVPG brand).

### 2.4. Out of plane compressive test

The out of plane compression test was performed by using SHIMADZU universal testing machine with a 10 kN load cell and loading rate is selected 0.50 mm/min, in accordance with ASTM standards C365/C365M. This test was used to find out the ultimate compressive strength, compressive stress at 2 % deflection and compressive chord modulus of the 3D printed composite sandwich structures (refer

Equation 1 to 3). Figure 4a shows the test setup of out of plane compression test of corrugated structures. Figures 4b and 4c show the failed specimen of VPTC structure and VPSC structure, respectively.

$$\sigma^u = \frac{P_m}{A} \quad (1)$$

$$\sigma_{.02}^{fc} = \frac{P_{.02}}{A} \quad (2)$$

$$E^{fc} = \frac{(P_{.003} - P_{.001}) t}{(\delta_{.003} - \delta_{.001}) A} \quad (3)$$

$\sigma^u$  is the ultimate compressive strength (MPa),

$\sigma_{.02}^{fc}$  is the compressive stress at 2 % deflection (MPa),

$E^{fc}$  is compressive chord modulus (MPa),

$P_m$  is the maximum load before fracture (N),

$A$  is the cross section area of the sandwich ( $\text{mm}^2$ ),

$t$  is the thickness of the specimen,

$\delta_{.02}$  deflection value at  $\delta/t \sim 0.02$ ,

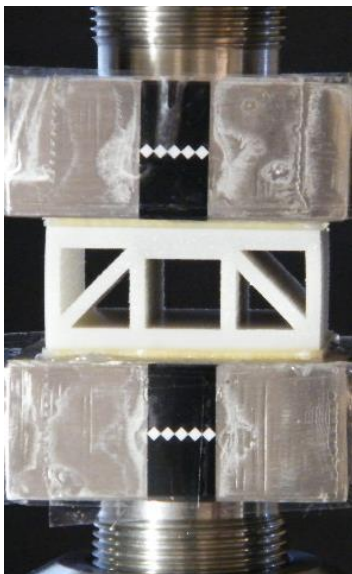
$\delta_{.001}$  deflection value at  $\delta/t \sim 0.001$ ,

$\delta_{.003}$  deflection value at  $\delta/t \sim 0.003$ ,

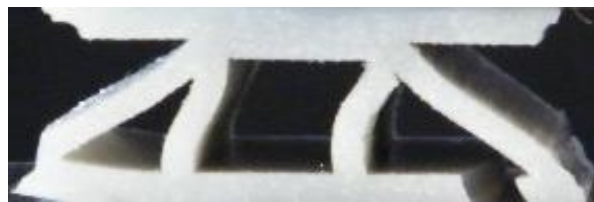
$P_{.02}$  is applied force corresponding  $\delta_{.02}$ ,

$P_{.001}$  is applied force corresponding  $\delta_{.001}$ , and

$P_{.003}$  is applied force corresponding  $\delta_{.003}$ .



(a) Specimen subjected to compression testing



(b) Failed VPTC structure

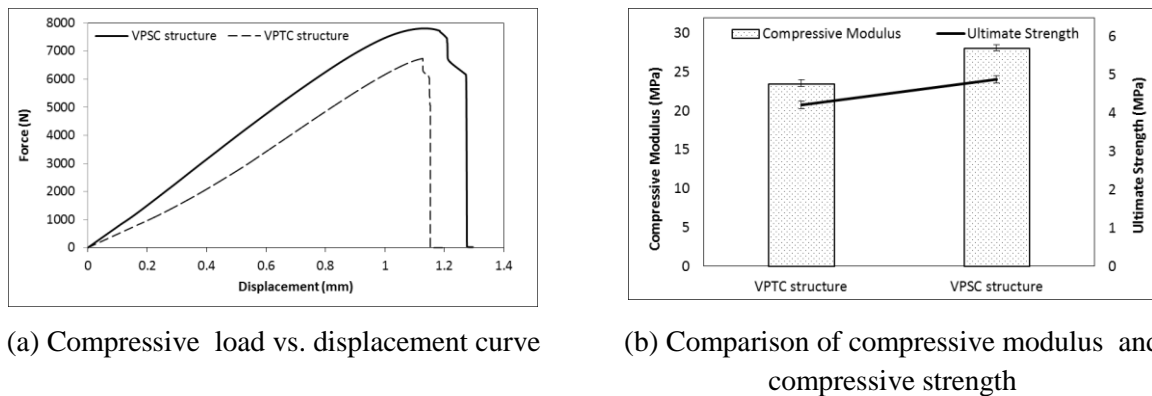


(c) Failed VPSC structure

**Figure 4.** Compression test of corrugated structures

### 3. Result and Discussion

The relative density of both type of corrugated structures was retained constant. Five specimens were tested for each type of corrugated structures. Figure 5a shows the average load vs. compressive displacement curve for both types of corrugated structures. Ultimate compressive strength, compressive stress at 2 % deflection and compressive modulus were also calculated from the Equation 1, 2 and 3, respectively. Figure 5b gives a summary of the calculated average compressive modulus, and average ultimate compressive strength for both types of corrugated structures. Table 2 gives a summary of the calculated average ultimate compressive strength, average compressive modulus and average compressive stress for both types of corrugated structures. The standard deviation of test results is also shown in figure 5 and table 2. The test results show that the VPSC structures can withstand more load than the VPTC structures. The ultimate strength of the VPSC structures was found to be 4.9 MPa which is 16.6% higher than the ultimate strength of VPTC structures.



**Figure 5.** Out-of-plane compression test results

**Table 2.** Values of ultimate strength, compressive modulus and compressive stress

Samples	Ultimate Strength $\sigma^u$ (MPa)	Compressive Modulus $E^{fc}$ (MPa)	Compressive stress $\sigma_{0.02}^{fc}$ (MPa)
Vertical pillar corrugated sine wave (VPSC) structure	4.9±0.3	28.0±2.2	1.3±0.2
Vertical pillar corrugated trapezoidal (VPTC) structure	4.2±0.2	23.4±1.7	0.8±0.1

The failure behavior of the VPSC structures is slightly different from the VPTC structures during loading as well as in breaking. Both types of specimen failed due to buckling of the sine-wave/trapezoidal walls. In both types of specimens, the initial cracks were developed in the mid cross-section area in the thickness direction, however VPTC structures also showed failure cracks at the top and bottom facesheet. During testing, the vertical walls of the VPSC structures protruded outwards and the sine-wave curve undergoes the inward bending. However, in the trapezoidal structure, both the vertical walls as well as the inclined trapezoidal cell experienced outward protrusion that eventually led to lower load bearing capacity.

#### 4. Summary

The out-of-plane compressive behaviour was studied and the ultimate strength, compressive modulus and compressive stress were also observed. The following conclusions for this research work are summarized:

- The observed results of the out-of-plane compressive tests of VPSC structures have revealed higher compressive strength and modulus as compared to VPTC structures.
- Buckling of the walls is the main failure mode.

#### Acknowledgement

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