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# CO-CONSOLIDATION ROBOTIC 3D PRINTING: A NOVEL APPROACH FOR MANUFACTURING THERMOPLASTIC SANDWICH PANELS

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## ABSTRACT

Sandwich panel composites are efficient structures in various applications, especially when bending is the predominant load, due to their low weight and high flexural stiffness. This study explores a novel manufacturing method for thermoplastic sandwich panels that removes the need for adhesive by employing in-situ face-to-core co-consolidation robotic 3D printing. It involves passing a hot nozzle which deposits a continuous carbon fiber prepreg tape over a 3D-printed core. This way, the polymer chains diffuse across the facesheet and the core interface, resulting in a homogeneous unitized polymer structure. This study investigates specimens made with a 3D printed poly lactic acid (PLA) core and continuous carbon fiber (CCF) low-melt poly-aryl-ether-ketone (LM PAEK) facesheets. Specimens were fabricated according to ASTM D1781 with a modified width. Results showed an average peeling force of 149.4 N and an average peeling torque of 99.7 N.cm/cm with 100% adhesive failure. This novel manufacturing technique can reduce the cost and time associated with thermoplastic sandwich panels, increase recyclability, and improve face-to-core bond strength.

## 1 INTRODUCTION

Sandwich core composite materials are efficacious constructions in applications requiring weight saving and high flexural stiffness. They consist of two facesheets—one on the bottom and top—sandwiching a lightweight core structure. Traditionally, facesheets are bonded to the core by using film adhesives between them. Material selection, fiber orientation, fiber volume fraction, ply thickness, number of plies, and core geometry are significant parameters which determine the mechanical behavior of the sandwich panel composite. The wide array of customization options and the potential to increase specific stiffness and strength make sandwich composites desirable to replace conventional materials.

Thermoplastic sandwich panel composites are known to be expensive; making them more cost effective yet just as performant may be done by thermoplastic co-consolidation to bond the facesheets to the core. Co-consolidation involves bonding two thermoplastics through heat and pressure to allow polymer interdiffusion. Ageorges et al. [1], express co-consolidation as an "ideal joining method as no weight is added to the final structure, no foreign material is introduced at the bondline, essentially no surface preparation is required and the bond strength is potentially equal to that of the parent laminate." Nevertheless, co-consolidation is difficult to execute since it requires specific tooling to maintain desired temperature and pressure curves [1]. In the past, researchers have been able to explore individual aspects pertaining to the success of the novel method described. Testing and evaluating sandwich panels composites constructed by unidirectional composite facesheets bonded using film adhesive onto 3D printed sandwich panel composite cores of various geometries has been performed extensively in literature. Lu et al. [2], for example, manufactured and evaluated four glue-adhered-carbon-fiber/epoxy-facesheet sandwich panel composite specimens of different PLA core geometries—namely bi-grid, tri-grid, quadri-grid, and Kagome-grid—against the traditional Nomex honeycomb matrix according to an in-house three-point bend test. Results imply that higher density PLA cores failed at higher loads and that interfacial debonding occurred when the core was flexible enough to allow it before failing due to shear. Alshaer and Harland [3] performed a similar study but with seven different cores. Their results suggest traditionally made sandwich panel composite yield flexural strength, based solely on core geometry, depends more on core-to-facesheet bond strength than on core density. Unlike the previous studies, Sugiyama et al. [4] employed continuous carbon fiber (CCF) 3D printing as a means of generating unibody sandwich panel composites of various core geometries. It eliminated the need for adhesive by laying the CCF filament and allowing co-consolidation as the filament cooled. For the facesheets, each filament containing CCF was 3D printed longitudinally. Evaluating three-point bend test results revealed no peeling failure on the adhesive surface between the facesheet and core. In a separate study not specifically discussing sandwich panel composites, Weber and Schlimbach [5] dissected the co-consolidation process into five sequential stages and used these to develop an apparatus capable of co-consolidating carbon fiber (CF) poly-ether-ether-ketone (PEEK) tape pre-forms and CF-PEEK organo sheets to manufacture reinforcements in a stamp-forming process.

The current study aims to explore the process of co-consolidating CCF low-melt poly-aryl-ether-ketone (LM PAEK) prepreg tapes onto separately 3D printed PLA cores and evaluate the bond performance of the specimens made via this novel method. Bond strength, according to the implications of results found in [2] and [3], is a major determinant of sandwich panel composite performance; hence ASTM D1781 was chosen as the evaluation standard. Unlike the aforementioned studies, this study investigates the performance of a novel in-situ co-consolidation robotic 3D printing manufacturing technique for thermoplastic sandwich panels which not only obviates the film adhesive, but also allows co-consolidation for various core geometries and between differing thermoplastic materials.

In this study, thermoplastic sandwich specimens are manufactured using a novel co-consolidation robotic 3D printing. Visual inspection of the specimens is completed and bond strength results for one specimen per ASTM D1781 with a modified width are discussed. The structure of the paper is as follows: Section 2 describes the materials and methodology used in this work. Section 3 discusses the visual observances of preliminary co-consolidated specimens and the quantitative results from drum peel for bond strength testing. Section 4 concludes the research with major findings and directions for future work.

# 2 MATERIALS AND METHODOLOGY

## *2.1 Materials and Manufacturing Process*

Teijin Ltd. makes the prepreg tapes by combining the HTS 45 carbon fiber and the polymer. The matrix weight fraction of the composite facesheet material is 34.2% [6]. Co-consolidation robotic 3D printing of the CCF LM PAEK onto PLA involves passing a hot (380 °C) nozzle depositing 6.35 mm (1/4 in.) prepreg tapes onto the flat core. The nozzle also softens the PLA as it passes over the core allowing for interdiffusion of both thermoplastics and unification at the interface. Note that PLA has a much lower glass transition temperature ($T_g$) of 60 °C than LM PAEK of 155 °C [7], [8].

The manufacturing set-up used to fabricate the thermoplastic sandwich specimens is an ABB IRB 1200 5 kg/0.9 m robotic arm with a custom-built 3D printing head for processing prepreg tapes.

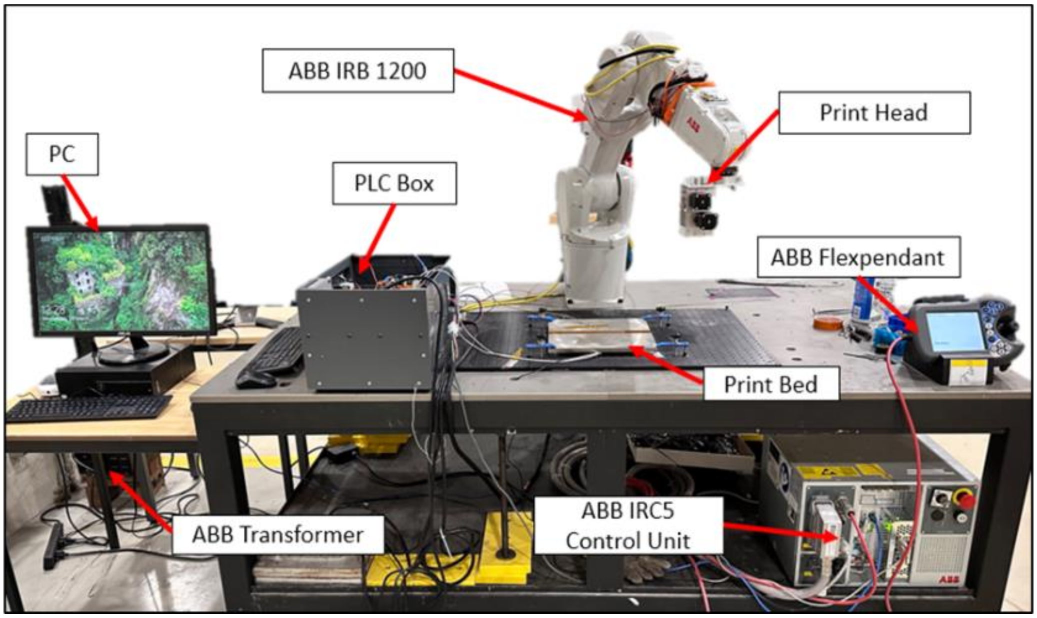


Figure 1. The robotic 3D printing set-up.

RobotStudio2023 was the software used to program the robot to perform the motion required for tape laying. For all specimens, prepreg tape was deposited over PLA cores less than 0.100 mm away from the core. Since there was no feeding and cutting of the feedstock, manual manipulation was required to feed and arrest the tapes whenever the tool tip direction reversed.

Cores were manufactured using the AnyCubic Chiron® 3D printer from a 1.75 mm diameter pure PLA filament. The nozzle and bed temperatures were set to 210 °C and 70 °C, respectively. The relative humidity while printing the cores was measured to be 27% and the environmental temperature was approximately 20 °C. All cores were designed using Fusion 360® and sliced using Ultimaker Cura® to have the desired infill type and density.

## *2.2 Testing and Specimen Design*

Standard test method for climbing drum peel for adhesives (ASTM D1781) [9] was used to determine the bond strength between the 3D printed PLA core and CCF LM PAEK facesheets. An Instron 5900R machine with a constant crosshead speed of 1 in./min was used for testing. Load versus head movement was recorded.

ASTM D1781 specifies specimens at least 76 mm wide and 305 mm long. In addition, it calls for 15 mm overhangs on one facing at each end of the specimen to allow clamping. Since the tape widths are 6.35 mm (1/4 in.) and they were to be laid with a raster offset of 6 mm, 13 tapes would give a specimen width of 78 mm. Nevertheless, due to limited feedstock availability, ASTM D1781 specimen dimensions were modified to have three tapes in width (18 mm). The overall sandwich panel construction included a nominal 5 mm PLA core and two facesheets, each with two layers of CCF LM PAEK with a nominal thickness of 0.14 mm. The overall nominal thickness of the specimen was 5.56 mm.

# 3 RESULTS AND DISCUSSION

## 3.1 Qualitative Observations

Initial trials to produce thermoplastic sandwich panels elucidated complications in the novel co-consolidation method that led to various inaccuracies. In the initial trials, two different core types were explored: (1) 0° oriented, 30% density, tri-hexagonal infill with 0.4 mm wall thickness; and (2) 0° oriented, 25% density, cubic infill with 0.4 mm wall thickness. These specimens are different from the drum peel test specimen described in Section 2.3.

Figure 2 shows the top/bottom views of the sandwich specimens with the core pattern impressions on the facesheet. This is indicative of the imprint of the harder PLA core on the softer CCF LM PAEK during fabrication. Misalignment was also observed and is a product of changes in feedstock width after 3D printing. The cross sections, shown in Figure 3, show both waviness and smoothness at the interface between the facesheets and core which might have implications on the facesheet to core bond strength. Thickness measurements on the second specimen on both sides and in the middle revealed an average thickness of 4.78 +/- 0.07 mm which is approximately 78 mm less than the nominal thickness. This phenomenon is due to the melting of PLA as the hot nozzle passes over the core (refer to Figure 4).

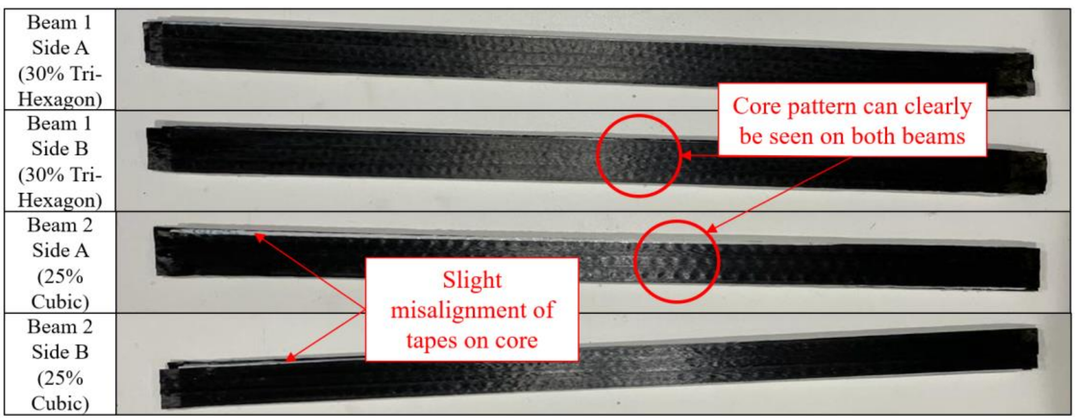


Figure 2. Co-consolidation robotic 3D printed thermoplastic sandwich specimens side observations.

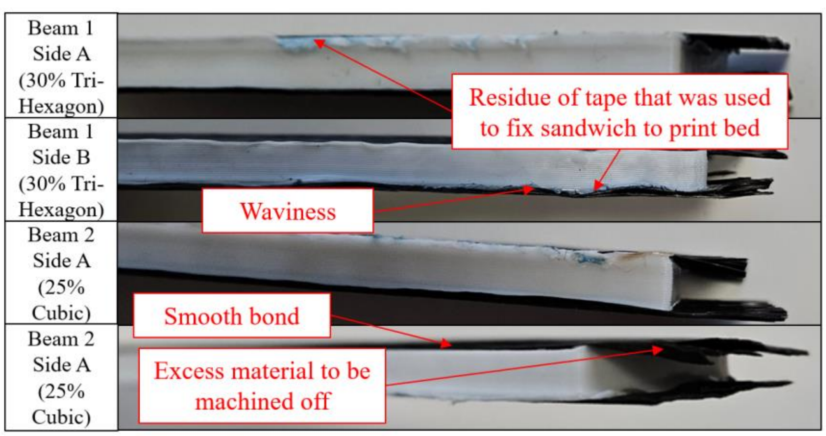


Figure 3. Co-consolidation robotic 3D printed thermoplastic sandwich specimens cross section observations.

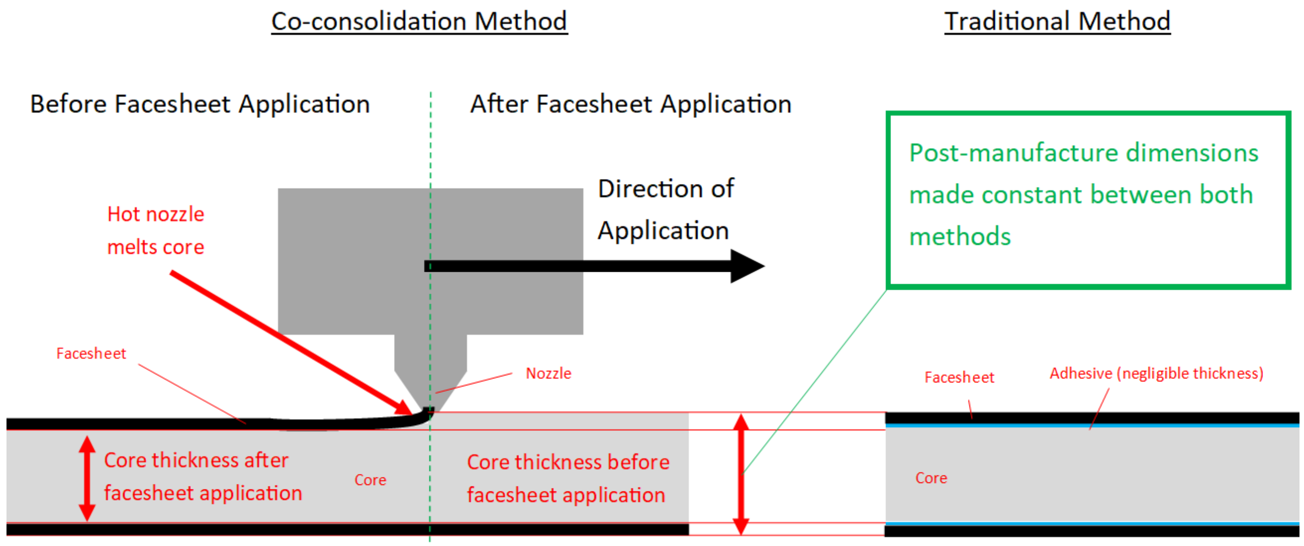


Figure 4. Co-consolidation versus traditional method core thicknesses considerations.

### 3.2 Bond Strength

The drum peel test specimen displayed imperfections similar to those exhibited by the preliminary specimens presented in section 3.1. Misalignment of the tapes on the core was observed which was mainly due to the change in the feedstock width. Tabs were added to the specimen as a means of fixing the specimen to the build platform. The cross section shows areas of smooth bonding and areas of waviness speculated to have poor bonding.

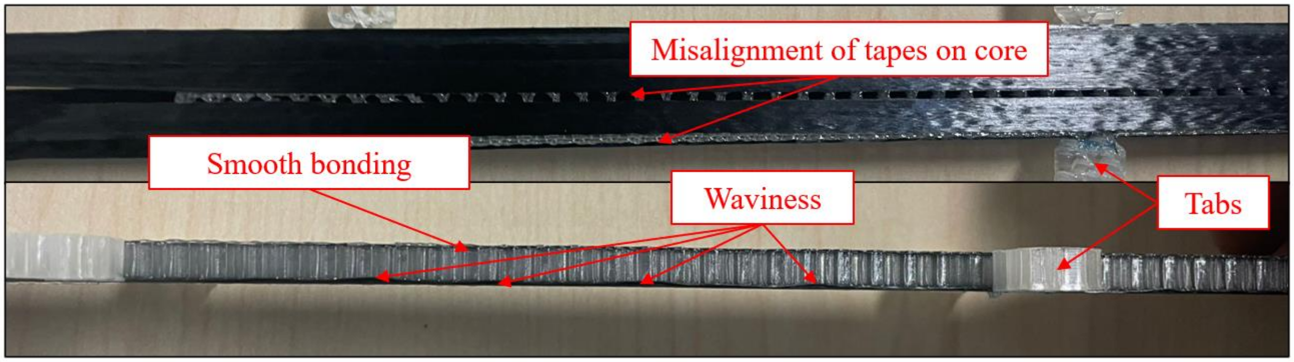


Figure 5. Visual observations of drum peel test specimen before testing.

Results from the drum peel test indicated an average peeling load of 149.4 N and peeling toruqe of 99.7 N.cm/cm required to remove the facesheet from the core. The failure mode was 100% adhesive to sandwich panel failure.

Observations of the specimen after test demonstrate a flattening of the PLA which is indicative of pressure and temperature applied during co-consolidation. Moreover, the specimen exhibits a greyish shade compared to its original transparent white color which may be CF residue.

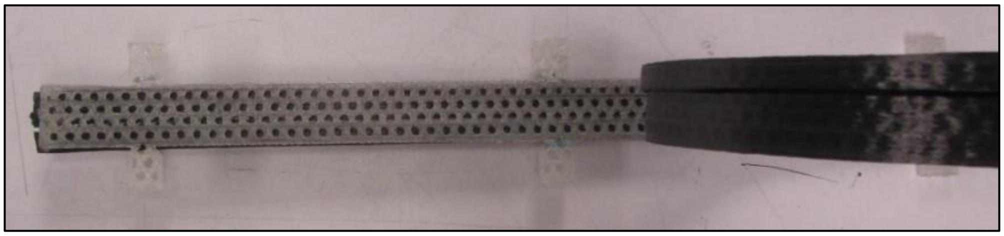

Figure 6. Specimen after test.

# 4 CONCLUSIONS

In this paper, a novel co-consolidation robotic 3D printing method was explored for its ability to fabricate thermoplastic sandwich panels. The adhesion between the CCF-LM PAEK facesheets and the PLA core was explored through the drum peel test for bond strength. Preliminary observations showed inaccuracies during manufacturing; namely: misalignment and waviness at the interface which is speculated to correlate with poor bonding. Drum peel test results demonstrated an average load of 149.4 N required to remove the facesheet from the core. Future studies should aim at evaluating the impact of process parameters on the bond strength, e.g., nozzle temperature and 3D printing speed.

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