Thermal Fatigue of Adhesive Bonding in Modular Additively Manufactured Fiber-Reinforced Composite Tooling

Lucas E. Rodrigues [1], Meghana Kumar [2], Paul Kyu-Hwan Park [3], Prof. Garam Kim [3], Prof. Eduardo Barocio Vaca [1]

[1] Purdue University School of Mechanical Engineering, [2] Purdue University School of Aeronautics and Astronautics, [3] Purdue University School of Aviation and Transportation Technology

RAL-BECK Advanced Composites Laboratory
CM-SC Composites Manufacturing & Simulation Center
ENGINEERING UNDERGRADUATE RESEARCH OFFICE
EURO FTR FELLOW

INTRODUCTION

Additive manufacturing of fiber-reinforced tooling reduces cost and lead time but is limited by printer size. Larger tools are built in bonded sections using high-temp. adhesives that must hold a vacuum during part curing (up to 180°C).

Figure 1. Example 3D printed tooling (left) and mold usage in industry (right)

Repeated cure cycles degrade adhesive joints due to mismatches in thermal expansion, compromising vacuum integrity and structural reliability. This study investigates how the anisotropic behavior of 3D printed materials affects joint performance. Because parts expand differently by direction, bond orientation may influence adhesive degradation. Vacuum decay testing evaluates joint air leakage, while thermogravimetric analysis (TGA) assesses adhesive thermal stability.

METHODOLOGY

Materials

Samples are Polyethersulfone (PES) reinforced with 25wt% carbon fiber, bonded with a high temp. epoxy (Parker LORD® 320/322) on their 1-2, 1-3, or 2-3 face.

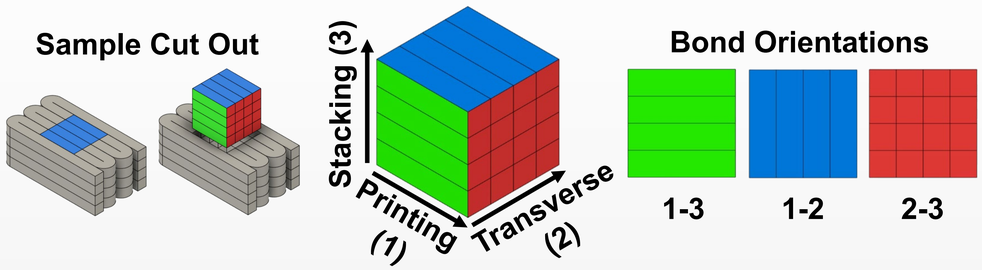


Figure 2. Defining of the 1-2, 1-3, and 2-3 Bonding Plane Orientations

Surface Preparation

- Bonding surfaces are sand blasted and cleaned to ensure maximum adhesion
- Top and bottom surfaces were sanded, cleaned, and top is coated with sealant.

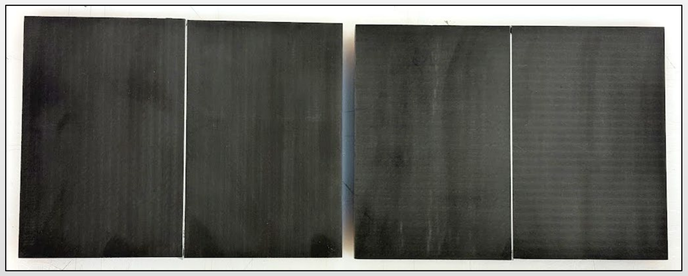


Figure 3. Vacuum Samples With 1-2 (Left) and 2-3 (Right) Bonding Orientations.

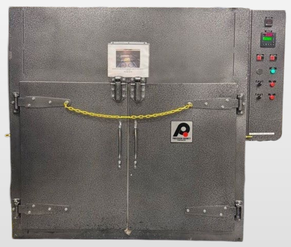


Figure 4. Oven Used for Thermal Cycles

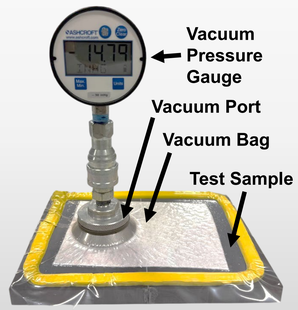
METHODOLOGY

Test Procedure

Samples are thermally cycled (heated to 350°F, held for 2 hours, cooled to ambient) in an oven to mimic repeated usage of tooling in industry for composite curing.

Vacuum Bag Leak Test (ASTM F2338-09(2020))

- **Purpose:** To find how air leakage through the joint changes over multiple cycles
- Top surface is sealed in a vacuum bag, with a vacuum port
- Vacuum is pulled using the port
- A vacuum pressure gauge is used to record pressure every 30 sec. for 5 mins.

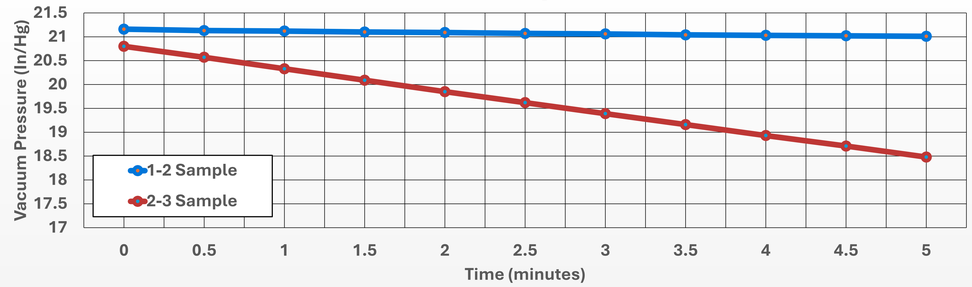


TGA Test (ASTM E1131-20)

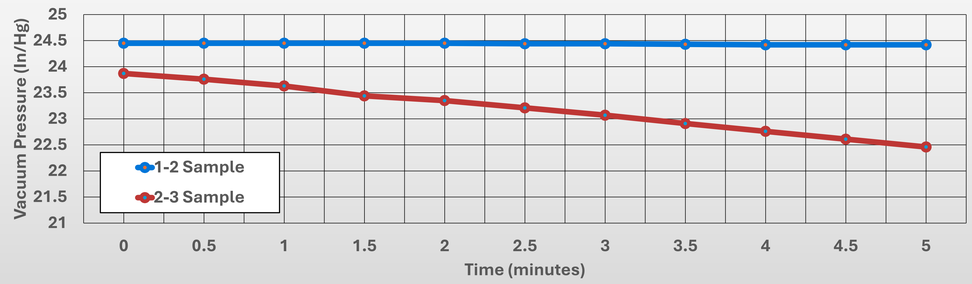
- **Purpose:** To measure adhesive decomposition from thermal cycling
- TGA Sample is placed into crucible and heated to 1000°C
- Weight is recorded as a function of temp. and time

RESULTS

Vacuum Leak Test Results for 0 Thermal Cycles



Vacuum Leak Test Results for 1 Thermal Cycle



0 Thermal Cycle Results

- Establish a control for future readings & understand differences between each sample's setup
- Average change in 30 sec. for 2-3 is .232 In/Hg
- Average change in 30 sec. for 1-2 is 0.015 In/Hg

1 Thermal Cycle Results

- Average change in 30 sec. for 1-2 is now 0.003 In/Hg (80% improvement)
- Average change in 30 sec. for 2-3 is now .141 In/Hg (39% improvement)
- Possibly due to adhesive fully setting during the first cure

CONCLUSION & FUTURE WORK

From test results gathered so far, the 1-2 sample improved more than the 2-3 sample after 1 thermal cycle suggesting that the 1-2 direction may be the best in terms of tooling lifespan. The improvement is likely due to the adhesive fully setting during the first cure cycle. Looking forward, testing will be expanded to analyze 5 and 10 thermal cycles to better understand long term joint performance as well as to TGA to understand the effects of just heat on adhesive degradation.

ACKNOWLEDGMENTS

We would like to thank the FTR program for its sponsorship and continued support of undergraduate research.

Scan QR for full reference list, including technical data sheets, testing standards, and image attributions →