

**MODULAR COMPOSITE SANDWICH STRUCTURES FOR THERMAL AND
STRUCTURAL RETROFITTING OF EXISTING BUILDINGS**

**A Thesis Presented for the
Master of Science
Degree
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ABSTRACT

Around 40% of global energy consumption and 30% of worldwide carbon dioxide (CO₂) emissions are attributed to buildings. Most of this consumption is dedicated to ensuring thermal comfort. The goal of this research was to develop and field validate retrofit solutions to improve the energy efficiency of buildings. Exterior cladding panels were designed and tested to ensure adequate thermal and structural performance. Sandwich panels (glass fibers reinforced polymer (GFRP) skins and polymeric foam cores) were fabricated using the vacuum assisted resin transfer molding (VARTM) process. Extruded polystyrene (XPS) and polyurethane (PU) foams were compared as core materials through a series of thermal and mechanical tests. Thermal resistances of 3.62-4.66 h.ft².°F/Btu (0.64-0.82 K.m²/W) per inch were obtained for sandwich structures. XPS samples were 26% lighter, 24%-40% stronger, and 16%-28% more brittle than PU in quasi-static loading configurations. PU absorbed 11% more energy than XPS in a low-velocity impact (LVI) test. Flatwise tensile test showed that the bonding strength between XPS and GFRP was 47% higher than PU foam. Consequently, XPS was chosen as core material and further tests were conducted accordingly. Tensile testing performed on the GFRP material resulted in a 3,191 Ksi (22 GPa) elastic modulus, 42,786 psi (295 MPa) tensile strength, and 0.165 Poisson's ratio. To predict the wind loads according to the American Society of Civil Engineers (ASCE) building standard, flexural tests were conducted on a 4 x 8 ft² (121.92 x 243.84 cm²) sandwich panel. FEA simulations were also developed to accurately predict the behavior of the retrofit panels based on actual dimensions and connections. Less than 4% variation was noted between experimental and numerical data. The deflections were within the allowable limits set by the International Building Code (IBC). The panels were supposed to be used as an exterior application; therefore, it was important to understand the environmental effects. Discoloration of the GFRP skin due to

ultraviolet (UV) and moisture exposure was observed. Ceramic coating was applied to eliminate the discoloration effect. A fire simulation (ASTM E84) was conducted on a 2 x 24 ft² (60.96 x 731.52 cm²) panel to obtain surface burning characteristics.

Keywords: Retrofitting; Sandwich structures; Vacuum assisted resin transfer molding (VARTM) process; Thermal resistance (R-value); Finite element analysis (FEA).

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LIST OF ACRONYMS

- CO₂ - Carbon Dioxide
- FRP - Fiber-Reinforced Polymer
- DOE - Department of Energy
- BTO - Building Technologies Office
- ORNL - Oak Ridge National Laboratory
- UT - University of Tennessee
- FCMF - Fibers and Composites Manufacturing Facility
- IACMI - Institute for Advanced Composites Manufacturing Innovation
- KCDC - Knoxville Community Development Corporation
- PTAC - Package Terminal Air Conditioner
- RTU - Roof Top Unit
- R-value - Thermal Resistance
- US - United States
- PU - Polyurethane
- FGB - Fiberglass Batt
- EPS - Expanded Polystyrene
- XPS - Extruded Polystyrene
- CFRP - Carbon Fibers Reinforced Polymer
- GFRP - Glass Fibers Reinforced Polymer
- UV - Ultraviolet
- SEM - Scanning Electron Microscopy

- T_g - Glass Temperature
- FEA - Finite Element Analysis
- IBC - International Building Code
- TGA - Thermogravimetric Analysis
- VARTM - Vacuum Assisted Resin Transfer Molding
- LPG - Liquefied Petroleum Gas
- OH - Hydroxyl
- NCO - Isocyanate Functional Group
- MTI - Membrane Tube Infusion
- DSC - Differential Scanning Calorimetry
- LBF - Long Beam Flexure
- SBF - Short Beam Flexure
- LVI - Low-Velocity Impact
- FTT - “Flatwise” Tensile Test
- DAQ - Data Acquisition
- CMU - Concrete Masonry Units
- LFT - Long-Fiber-Reinforced Thermoplastic
- 3D - Three-Dimensional
- RC - reinforced concrete
- ASCE - American Society of Civil Engineers
- C3D4 - Linear, 3D Stress, Tetrahedron Elements
- FDS - Fire Dynamics Simulator
- NIST - National Institute of Standards and Technology

- λ - Thermal Conductivity
- c_p - Specific Heat Capacity
- E - Elastic Modulus
- DI - Ductility Index
- ν - Poisson's Ratio
- σ - Stress
- δ - Deflection
- FSI - Flame Spread Index

CHAPTER 1:

INTRODUCTION AND PROJECT DESCRIPTION

The issue of climate protection has gained great significance in our present-day society. The continuous growth of the global population and the escalating demand for energy highlights the necessity for comprehensive global changes. At the forefront of these changes is the priority to reduce energy consumption, accompanied by enhancing the efficiency of energy production and utilization. Innovative strategies are thus required across various sectors that heavily rely on energy, notably transportation, industrial processes, and buildings, where energy is predominantly used for heating and cooling systems [1]. Approximately 40% of the world's energy is consumed by buildings, a significant portion of which is dedicated to maintaining thermal comfort. Moreover, these buildings contribute to more than 30% of global carbon dioxide (CO₂) emissions [2]. Retrofitting the current building infrastructure offers significant potential for energy conservation and emission reduction. This is due to the low energy efficiency of a large portion of existing buildings, their long lifespan, and their poor turnover [3, 4]. Effective insulation materials play a significant role in minimizing thermal loads in buildings and, consequently, reducing energy consumption. The effectiveness of insulation primarily depends on thermal conductivity, which is influenced by factors like material density, porosity, and moisture content [5].

Polymers have emerged as a crucial component in materials engineering, primarily due to their unique technical properties, including lightweight nature, chemical stability, elasticity, and the ability to undergo flexible processing methods [6]. These characteristics have contributed to the rapid growth and adoption of polymers as valuable insulation materials. Fiber-reinforced polymer (FRP) sandwich systems have proven to be effective and cost-efficient in their applications in civil infrastructure, covering multiple fields such as housing and construction [7-9], bridges [10-12],

and railway sleepers [13, 14]. In addition to their lightweight design and impressive load-carrying capabilities, FRP composite sandwich panels could be manufactured with an effective insulation material, like a polymer-based foam, in order to obtain an overall system having desirable thermal and structural properties.

1.1 Project Overview

The goal of this research is to develop and field validate integrated retrofit solutions that are applicable to residential and mid-size commercial buildings at first, then implemented in a wider variety of building types. The Department of Energy's (DOE) Building Technologies Office (BTO) has joined forces with Oak Ridge National Laboratory (ORNL), the University of Tennessee's (UT) Fibers and Composites Manufacturing Facility (FCMF), and the Institute for Advanced Composites Manufacturing Innovation (IACMI) to develop and produce modular cladding panels. DB Technologies was chosen as manufacturer. These panels should be designed for thermal and structural applications, allowing for swift installation and integration. The buildings requiring retrofitting are under the ownership and management of the Knoxville Community Development Corporation (KCDC), which serves as the housing authority for Knoxville, TN. Specifically, these buildings comprise several duplexes and a Boys and Girls Club. The retrofits are aimed at achieving the following objectives/conditions:

1. Minimizing disruption to occupants and retrofit time by creating over-clad composite panels off-site and utilizing easy-to-install panel connections.
2. The over-clad panels should be versatile and suitable for various building types and climates.
3. Reducing thermal loads by at least 75%.

4. Panels should ensure replicability, scalability, and cost-effectiveness to fit the geometry and measurements of different duplexes and mid-sized institutional buildings.
5. Ensure occupants and building owners' satisfaction with aesthetics.

1.2 Buildings description

1.2.1 Duplexes at Western Heights, Knoxville, TN

There are 4 duplexes that were built during the 1940s and have an approximate footprint of 27 x 63 ft² (8.23 x 19.2 m²) (Figure 1). They have load bearing masonry walls as the primary structural system and their walls and attic have no insulation. They also contain 15 years old double pane windows without low-E coating, package terminal air conditioners (PTACs), and 30 gallons (113.56 L) electric water heaters. All these features make these buildings an excellent retrofit opportunity.

1.2.2 Boys and Girls Club, Knoxville, TN

After retrofitting the duplexes, the technologies demonstrated at Western Heights could be tested by implementing the developed procedure on more complex building types, where the façade is non-planar and different spaces and occupancy types are present. The boys and girls club building was built in 1967 and covers an approximate area of 12,000 ft² (1,115 m²) (Figure 2). Load bearing masonry walls with no wall insulation constitute the primary structural system. The club also contains single pane windows with aluminum frames, PTAC units in offices, roof top unit (RTU) at meeting areas and gym, and an electric water heater.

1.3 General requirements

There were several key parameters that needed to be taken into consideration while selecting the materials for retrofitting the buildings.



Figure 1. Duplex building at Western Heights, Knoxville, TN to be retrofitted with composite cladding panels as a first phase.



Figure 2. Boys and Girls Club, Knoxville, TN to be retrofitted with composite cladding panels as a second phase.

The most important requirements were:

- Higher thermal resistance (R-value) for improved insulation.
- Superior structural stiffness.
- Fire and impact resistances.
- Better aesthetics of the building.
- Drainage and ventilation plane between the envelope and existing walls.
- Low maintenance.

These parameters were also considered for the panel-to-panel, panel-to-wall, and panel-to-window connections. Additionally, it was essential to ensure alignment of the window frame between the retrofit and existing structure.

This research focuses on the retrofitting of the duplexes at Western Heights in Knoxville, TN. Their double brick exterior walls with an integrated air cavity have an approximate R-value of 4 hr.ft².°F/Btu (0.7 K.m²/W) [15]. The United States (US) DOE recommend a minimal value of R = 20 hr.ft².°F/Btu (3.52 K.m²/W) for external building walls in Knoxville, TN [16]. Most importantly, low cost and panel thickness are important parameters to achieve an economical solution.

CHAPTER 2: LITERATURE REVIEW

2.1 Retrofitting

In order to address the susceptibility and high heat transfer characteristics of vertical building envelope components (such as infill walls or structural masonry), significant attention is devoted to enhancing external walls by incorporating thermal insulation. Conventional thermal retrofits commonly employ mineral wool, polyurethane (PU), or polystyrene as insulation materials, which exhibit thermal conductivity values of around 0.02 BTU/h.ft.°F (0.035 W/m.K) [17]. More advanced options, such as vacuum insulation panels or aerogel-incorporated plasters, offer significantly lower thermal conductivity values ranging from 0.002 to 0.0046 BTU/h.ft.°F (0.0035 to 0.008 W/m.K) [18]. However, their thermal resistance per unit price is considerably lower compared to conventional materials. Based on the US DOE data, fiberglass batts (FGBs), expanded polystyrene (EPS) foam boards, and extruded polystyrene (XPS) foam boards have the cheapest combinations of material and labor costs [19]. However, FGBs and EPS require 2 and 1.3 times the thickness of XPS to obtain the same thermal insulation, respectively. Combined with FRP composite materials and low-cost manufacturing techniques, commercially available foam boards have the potential to meet all the requirements of this project.

Most reviews related to retrofitting covered the architectural, structural, and fire resistance advantages of FRP panels. Petrovčič and Kilar [20] researched externally bonded carbon fibers reinforced polymer (CFRP) and glass fibers reinforced polymer (GFRP) systems to retrofit existing masonry structures. By assessing the efficiency of the FRP laminates on the overall seismic response, the authors concluded that FRP retrofitting systems offered structural safety that met the requirements specified in the European building codes (Eurocode 8 and CNR-DT 200

R1/2013). Furthermore, Bedon [21] highlighted the applications of FRP retrofits in the San Francisco Museum of Modern Art expansion for architectural purposes. In addition, the panels were able to pass the USA fire-regulation tests for their use above the fourth story. Another example is a study by Majumder et al. [22], who covered the use of FRP masonry retrofitting solutions with different types of fibers (glass, carbon, basalt). The enhancement of thermal properties of structures after employing FRP retrofits was not mentioned due to the lack of insulation materials. Thus, to obtain the desirable structural integrity as well as good thermal properties, sandwich structures having good insulation properties should be taken into consideration.

This section covers studies related to different factors (environmental, structural, fire resistance) that needed to be taken into consideration during the process of designing the cladding panels. More literature was then reviewed in *Section 2.2* regarding the different materials that should be used in sandwich structures to obtain the desired properties.

2.1.1 Environmental effects

The degradation of FRP composites over time can be attributed to various environmental factors, including temperature fluctuations, ultraviolet (UV) radiation exposure, moisture absorption, and freeze-thaw cycles. Since the cladding panels are outdoor structures, physical and chemical reactions could result in some degradation of certain mechanical, physical and chemical properties of the composite material [23]. Therefore, the effects of UV and moisture were further explained in this section.

2.1.1.1 Ultraviolet (UV) resistance

UV radiation could cause chemical degradation in FRP composites structures due to their polymeric nature. Moreover, due to sunlight exposure, the finished surface of the composite structure risks losing its desired aesthetic properties [24]. This is due to photodegradation, which is responsible for surface discoloration, yellowing and loss of surface gloss. Lu et al. [25] proposed a numerical model to simulate the damage induced by UV on sinusoidal polymer surfaces. The authors concluded that, under exposure, the irregular (sinusoidal) surface will lose its roughness due to degradation of the resin. Zhao et al. [26] investigated the effect of UV exposure on mechanical properties of vinyl ester and epoxy resins. The results showed that the tensile strength of epoxy did not change after 30 days and 90 days of exposure. However, the tensile strength of vinyl ester decreased by 57% after 30 days, and a total of 65% after 90 days of UV exposure. The epoxy resin's elastic modulus increased by 25% after an exposure of 30 days. It then decreased by 20% from the initial value after 90 days of exposure. The vinyl resin saw its elastic modulus decrease by 52% after 30 days and a total of 69% after 90 days of exposure. Although both resins experienced a reduction in their mechanical properties in this study, it was clear that epoxy performed better under UV exposure than vinyl ester. Bazli et al. [27] exposed pultruded GFRP parts having a vinyl ester resin to sequential UV radiation and water vapor cycles. Mechanical tests were then conducted, and the results indicated that the maximum reduction in strength was 34% for three-point bending tests, 23% for compressive tests, and 28% for tensile tests after 3000 hours of exposure. In both studies, the exposed samples to UV radiation experienced visible discoloration and yellowing of the surface. Scanning electron microscopy (SEM) also showed micro cracks inside the tested parts.

The GFRP/epoxy composite used in this project was therefore tested under UV exposure. The goal was to check any signs of discoloration and whether a UV stabilizer should be used. The testing also covered moisture absorption and is found in *Section 3.2.3.5*. The results are given in *Section 4.3.5*.

2.1.1.2 Moisture resistance

High moisture effects on FRP composites should be taken into consideration due to the damage that could be induced in the fibers, matrix and the fiber-matrix interface. Although glass fibers do not absorb water, their rupture could still be caused by micro cracks occurring at their surface [24]. Moisture penetration into the epoxy resin could create interfacial problems and reduce its glass temperature (T_g) [28]. Guzman and Brøndsted [29] studied the effect of moisture on GFRP composites consisting of multidirectional glass fibers having a $0^\circ/45^\circ$ configuration and an epoxy resin. The results showed that the shear elastic modulus decreased by 7% and the tensile elastic modulus decreased by 13%. The degradation was caused by the expansion of the material under moisture absorption, causing a loss of fiber/matrix bond. In another study, Eldridge and Fam [30] didn't observe any significant degradation happening in Young's modulus of the epoxy GFRP after 300 days of continuous exposure to water. However, the tensile strength of the specimens decreased by 19% for a temperature of 73.4 °F (23 °C) and 56% for a temperature of 104 °F (40 °C).

Although the panels used in this paper won't be immersed in water, they risk facing the negative effects of moisture absorption. Moisture testing was therefore conducted in parallel with UV exposure on the GFRP/epoxy system.

2.1.2 Structural performance

Apart from resisting environmental effects and providing acceptable thermal characteristics, the modular panels should also be able to withstand structural and mechanical forces. The outdoor structure will be subjected to wind loads and should therefore present admissible resistance and deflection. As mentioned in *Section 2.1*, sandwich structures were chosen for their thermal insulation properties. This section reviews their structural performance under mechanical loadings.

Tabatabaiefar et al. [31] conducted 3-point and 4-point bending tests on sandwich structures having polystyrene/cement cores and cement facings. The results showed that the primary factor in determining the overall strength of the sandwich panels was the resistance of their tension face. Since the core was rigid, the failure was brittle and occurred in the bottom cement facesheet (tension side). Höwer et al. [32] tested the strength of the facesheet/core interface in sandwich structures having 8-ply carbon prepreg facers and an aluminum honeycomb core. Although the test results only served as a comparison tool with numerical simulation, the authors showed the importance of studying the interface: in most loading situations, delamination between facesheets and core is a commonly observed failure mode. Other studies researched sandwich structures with flexible foam cores. Sharaf et al. [33] conducted flexural tests with uniformly distributed loads on sandwich structures with GFRP/epoxy skins and PU foam cores. 2 types of cores were used: the “soft” PU foam had a density of 0.045 psi (0.31 kPa), while the “hard” PU foam had a density of 0.091 psi (0.63 kPa). Although the total deflection at failure was similar for both core types, the “soft” PU foam exhibited a more ductile behavior. The flexural strength of the sandwich structure with the “hard” core was 157% higher than the other type. The difference in behavior was attributed to different load transfer mechanisms inside the foam due to their densities. In a similar study, Tuwair et al. [34] tested GFRP/PU sandwich structures with 2 core densities

“high” and “low”. In a 3-point bending test, the “high” density panel failed by crushing of the core while the “low” density panel failed by wrinkling of the facesheet. However, the strength and modulus values were hard to compare because the sandwich structures had different geometries.

Several mechanical tests including flexural, tensile, and impact were conducted on the sandwich panels to check their structural integrity and failure modes. 2 types of cores were used in lab-scale tests (*Section 3.2.2*), and similar designs and dimensions were used for comparison purposes. In addition, finite element analysis (FEA) simulations served as a comparison tool between experimental and numerical results of large-scale tests (*Section 3.2.3.2*).

2.1.3 Fire resistance

During the past 2 decades, there have been numerous fire-related incidents linked to flammable cladding materials. Some severe cases (Wooshin golden suites, Busan, Korea - Saif Belhasa building, Dubai, UAE - Lacrosse Docklands, Melbourne, Australia) have led to severe consequences, including loss of human life, significant financial setbacks, and extensive damage to buildings [35-38]. These events contributed in increasing public awareness and concerns regarding non-compliant materials, which placed pressure on governmental and commercial entities to address the risks associated with non-compliant building structures [39]. In the mentioned incidents, the fire typically escalated into an uncontrollable blaze within a span of 10 to 20 minutes after the initial ignition. The thermal properties of the cladding material used contributed to the speed at which the fire spread. Typically, the insulation melted, and burning droplets flowed downward along the surface and penetrated the building, leading to rapid downward propagation of the fire. In certain scenarios, the uncontrollable spread of the fire compromised the structural integrity of the building, resulting in the collapse of internal structures

[40]. Tran et al. [41] assessed the fire performance of GFRP in marine composite structures and concluded that it was necessary to gather some key parameters from a variety of laboratory and field experiments. The parameters included thermal degradation, combustion mechanisms, and their relationship to thermal decomposition reactions, reaction rates, toxic gases, flammable volatiles, as well as the characteristics of the polymer matrix and fibers. For building material, the International Building Code (IBC) states that flame spread and smoke characteristics are important to obtain. Berardi and Dembsey [42] mentioned that the ASTM E84 tunnel test was needed to get the desired parameters. However, due to the scale and cost of such a test, they performed a smaller scale fire test on their GFRP samples with an acrylic resin. The samples were 1.97" (50 mm) long, 1.97" (50 mm) wide, and 0.14" (3.6 mm) thick. The exposed surface reached a temperature of 1,148 °F (620 °C) in just 195 seconds. After the same time period, the unexposed surface reached a temperature of 1,022 °F (550 °C). Compared to experimental results, fire simulations gave a 20% higher temperature for the exposed face. The difference could have been caused by the small dimensions of the samples or inaccurate thermal characteristics of the materials.

Apart from thermal insulation, the cladding panels used in this project should present an adequate fire performance. Thus, they needed to be tested according to the IBC code and ASTM E84 standard to check if they met the desired requirements. The large-scale test was found appropriate for the current application of the sandwich structures. A fire simulation (*Section 3.2.3.6*) was conducted to obtain preliminary results before the actual testing. In order to get accurate thermal characteristics to use as input parameters in the numerical model, the materials were thermally tested in *Section 3.2.2.1*.

2.2 Sandwich structures

Sandwich structures, composed of two thin and stiff face sheets bonded to a lightweight core material (Figure 3) [43], have become increasingly popular in various industries due to their high strength-to-weight ratio, stiffness, and excellent energy-absorption capabilities [44, 45]. In this project, they are used as structural components able to withstand wind and impact loads, but mainly as thermal insulators for improving the R-value of the existing buildings. The materials used for the panels in this project were reviewed in detail in this section.

2.2.1 Glass fibers

Glass fibers are widely used in a variety of applications such as aerospace, automobile, marine, medical and electronics. They are known for their corrosion, impact, and fire resistance. In addition, glass fibers exhibit high strength, good electrical and optical properties, and good sound and thermal insulation characteristics [46]. The physical and mechanical properties of E-glass fibers are shown in Table 1 [47].

Braga and Magalhaes Jr. [48] compared the mechanical and thermal properties of 2 types of FRP/epoxy samples. The first type was made of 3 layers of jute fibers while the second type contained 1 layer of jute fibers sandwiched between 2 layers of glass fibers. Their goal was to check the performance of glass fibers against one of the most widely used natural fibers. The second type (glass/jute/glass composite) gave a 92% higher tensile strength, a 2% higher flexural strength, a 46% higher flexural modulus, and a 60% higher impact energy than the first type (jute/jute/jute composite). Furthermore, a thermographic analysis (TGA) showed that the second composite experienced 10% less total weight loss compared to the first composite.

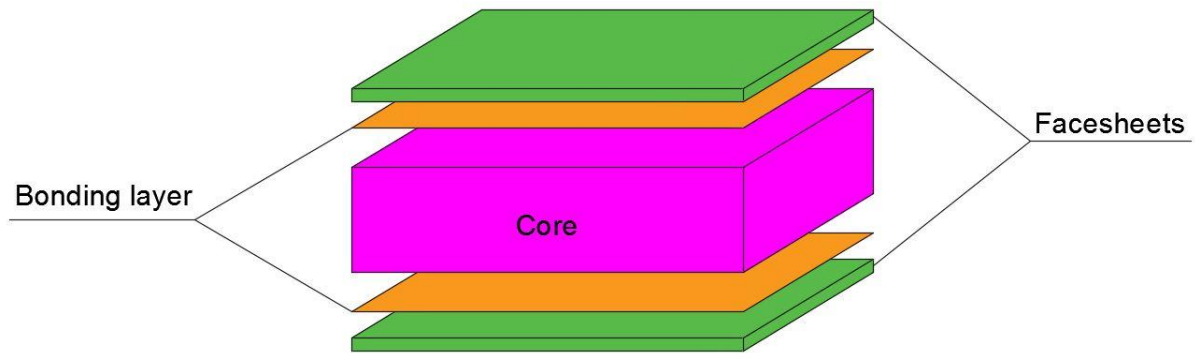


Figure 3. Different components constituting a typical sandwich structure.

Table 1. Physical and mechanical properties of E-glass fibers.

Fiber	Density - lb/in³ (g/cm³)	Tensile strength - psi (GPa)	Young's modulus - psi (GPa)	Elongation (%)	Coefficient of thermal expansion - 10⁻⁷/°F (10⁻⁷/°C)	Poisson's ratio	Refractive index
E- glass	0.093 (2.58)	499,655 (3.45)	10,486,000 (72.3)	4.8	0.56 (54)	0.2	1.558

The results gave a better understanding of the superiority of glass fibers over jute fibers in terms of mechanical and thermal performance. GFRP composites are also used in building façades. Bedon et al. [49] compared the thermal and structural properties of GFRP/glass sandwich systems with traditional non-integrated frame curtain walls. The sandwich system performed better on both ends by having a 10% better thermal resistance and 18% higher flexural modulus. Another study by McCuaig et al. [50] used GFRP wraps to repair the concrete façade of a school in Toronto, Canada. The authors implemented 2 types of reinforcement: unidirectional and bidirectional glass fabrics. The 2 types of GFRP composites were then tested under tensile loading along with the unrepaired façade. The results showed that the unrepaired façade failed by buckling (explosive) while the repaired façades failed by crushing (ductile). The bidirectional wrap gave a 13% higher failure load than the other 2 types. The axial strain was similar for the repaired façades but 6% higher than the unrepaired one.

Based on literature studies, glass fabrics are a common solution for building retrofits. A bidirectional configuration was found desired for obtaining more uniform properties along the retrofit panels. This layout can be achieved with woven glass fabrics, which offer a cost-effective solution for enhancing the overall flexural and impact resistance of the laminate without adding extra thickness, weight, or other non-reinforcing materials [51]. More details about the fiber reinforcement used in this project are available in *Section 3.1.3*.

2.2.2 Epoxy resin

Epoxy resins are thermosetting resins having high strength, high adhesiveness, low shrinkage and toxicity, high electrical and thermal insulation, and a low cost. In addition, they are suited to be used in a wide variety of processes and applications. Epoxy resins could be defined as pre-

polymers with a low molecular weight that contain multiple epoxide groups. Adding a curing agent or hardener to the epoxy resin will result in its curing or undergoing a crosslinking reaction, without leaving any volatiles and byproducts [52].

The development of advanced composites for various engineering applications and sectors, such as buildings, was a result of using epoxy resin as a matrix due to its superior properties over other thermosetting resins. Gopinath et al. [53] compared the mechanical properties of epoxy and polyester resins. The authors conducted tensile and 3-point bending tests on jute/epoxy and jute/polyester composites. The obtained results showed that jute/epoxy composite had a 65% higher tensile strength, 31% higher tensile modulus, and 61% higher flexural modulus than jute/polyester composite. They concluded that jute/epoxy was stiffer than jute/polyester. In a similar study, Hemanth et al. [54] studied E-glass and coconut reinforced epoxy and polyester composites by subjecting them to tensile and 3-point bending tests. In tensile testing, epoxy gave higher values for both fiber types: in comparison with FRP/polyester composites, the tensile strength was 40% and 18% higher for glass/epoxy and coconut/epoxy composites, respectively. The tensile modulus was also higher for FRP/epoxy composites: 30% higher than polyester with glass fibers and 61% higher than polyester with coconut fibers. Similar results were observed for GFRP composites subjected to flexural testing: epoxy/glass composites showed 74% higher flexural strength and modulus than polyester/glass composites. However, the flexural strength of coconut FRPs was similar for both resin types, and the flexural modulus was 115% higher for the coconut/polyester composite.

Epoxy resin exhibits high mechanical properties and good bonding with glass fibers when used as a matrix in GFRP composites. In addition, the thermosetting nature of epoxy resin makes it

compatible with the vacuum assisted resin transfer molding (VARTM) process, which will be reviewed in *Section 2.3*.

2.2.3 Polystyrene foam

In recent years, energy efficiency and sustainability have been prioritized in building design. Thermal insulation plays an important role in reducing heating costs and producing a low-energy building. An ideal insulation material should minimize heat loss, while also being environmentally friendly and having a low manufacturing cost [55]. It should also have a good compressive strength, high moisture resistance, minimal long-term creep, and good durability. Different materials possess such properties, such as cellular glass gravel, cellular glass boards, and XPS boards [56]. XPS is based on the use of a polymerised polystyrol and a foaming agent. It is recyclable and commonly used as an insulation material in buildings. XPS is manufactured in a continuous extrusion process that produces a homogeneous closed cell matrix with each cell fully enclosed by polystyrene walls.

Küçüktopcu and Cemek [57] studied the effects of EPS and XPS as insulation materials on poultry buildings in different cities in Turkey. The calculations considered 5 fuel types for heating the buildings: electricity, natural gas, fuel-oil, coal, and liquefied petroleum gas (LPG). For a 10-year projected period, energy savings between 20% and 70% were observed. For the XPS insulation material and an electrical heating system, the calculations showed 45-60% energy savings. The research also compared the optimum insulation thickness for both insulation types. For an electrical heating system, XPS showed an optimum thickness varying between 1.4” (35.56 mm) and 2.6” (66.04 mm), depending on the city. For the same conditions, EPS gave an optimum thickness varying between 2.4” (60.96 mm) and 3.9” (99.06 mm). The authors concluded that

thinner material was needed for XPS. Another study by Amir and Alibaba [58] compared the thermal properties of XPS and EPS. The results are given in Table 2. On average, XPS exhibited a 15% lower thermal conductivity and 22% higher thermal resistance (R-value) than EPS. Hence, both parameters indicated that XPS was the better insulation material.

XPS was considered a good insulation material for the buildings in this project. The material provides high thermal characteristics and is widely used for insulation around the world. In addition, the foam is commercially available in low prices and customizable sizes.

2.2.4 Polyurethane (PU) foam

Polymeric foams are widely used in multiple industries such as construction, automotive, electrical, aerospace, medical, and packaging [59]. Among the various types of polymeric foams, PU foam holds significant importance due to its low density and thermal conductivity, coupled with noteworthy mechanical properties [60]. These attributes make PU foam a good choice for thermal and sound insulation, as well as structural applications [61]. PUs are polymers created through a reaction between the hydroxyl (OH) groups of a polyol and the isocyanate functional groups (NCO) of an isocyanate compound. The name is derived from the formation of the urethane linkage that occurs because of this reaction [62]. Zhang et al. [63] investigated the thermal conductivity of PU foams and noticed that it increased by 25% from an average value of 0.014 BTU/h.ft.°F (0.024 W/m.K) at 77 °F (25 °C) to 0.017 BTU/h.ft.°F (0.03 W/m.K) at 158 °F (70 °C). Sherman et al. [64] studied the thermal resistance of closed-cell PU foams used in roof insulation. The results showed that the R-value varied between 6-7.8 hr.ft².°F/BTU (1.06-1.3 K.m²/W) per inch (25.4 mm) of material.

Table 2. Thermal conductivity and R-value comparison between XPS and EPS [58].

Material	Thermal conductivity - BTU/h.ft.°F (W.m/K)	R-value/in at 75 °F (23.9 °C) - hr.ft².°F/BTU (m².K/W)
XPS	0.014-0.023 (0.025-0.040)	5 (0.88)
EPS	0.019-0.026 (0.032-0.045)	3.85-4.35 (0.68-0.77)

Comparing literature values for thermal properties between XPS and PU show that closed-cell PU foam performs better as an insulation material: its average thermal resistance is 38% higher than XPS. PU foam was therefore chosen as a second option for insulation in this project. In addition, Prisma composites preform beams (*Section 3.1.4*), which are off-the shelf products used in the marine industry for boats insulation, are widely available. These Prismas consist of stitched glass fabrics bonded to a PU foam core and are available in different shapes and sizes.

2.2.5 Ceramic coating

Silicon-based polymers are well-suited for coating purposes due to their good characteristics, such as strong adhesion to a wide range of substrates, and a high resistance to chemicals, heat, and UV radiation [65]. Moreover, these polymers can be transformed into ceramic materials through heat treatment and, in certain situations, via chemical reactions or radiation [66].

Ceramic coatings are specifically engineered to endure high temperatures, which makes them well-suited for a wide range of systems and applications. They also exhibit good adhesion, even when subjected to repetitive thermal cycling, and could offer exceptional defense against corrosive surroundings and thermal shocks [67]. Schütz et al. [68] conducted laboratory salt melt tests to develop a corrosion protection ceramic coating. The goal of the study was to find a solution for abrasion in super-heater tubes in waste incinerators. The coating was able to withstand a maximum temperature of 986 °F (530 °C). Li et al. [69] studied the bonding between ceramic coatings and steel. They found that the bond strength was influenced by the spraying distance and the temperature at which the coating was laid. The bond strength started decreasing for a spraying distance greater than 3.54” (90 mm). It lost 6% of its original value for a spraying distance of 4.72” (120 mm). The bond strength didn’t change up to a deposition temperature of 392 °F (200 °C). Then, it reached a 10% increase for a temperature of 1,292 °F (700 °C), and

another 30% for 2,012 °F (1,100 °C). The authors concluded that the spraying technique and environment played an important role in bonding characteristics. Finally, Berger et al. [70] tested a silicon-based ceramic coating under UV radiation. The membrane was illuminated by 10 mW/cm² at 0.0000144” (365 nm). The results showed a 60% photodegradation by mass loss after 500 minutes of exposure.

After manufacturing the cladding panels, a coating was needed to enhance the UV resistance. Although ceramic coatings are usually used with metals, their thermal and bonding properties made them an interesting choice to try with the composite structures. As previously mentioned in *Section 2.1.1.1*, UV testing was conducted to check if the coating met the requirements of this project. The properties of the ceramic coatings applied to the panels are given in *Section 3.1.5*.

2.3 Vacuum assisted resin transfer molding (VARTM) manufacturing technique

The selection of the manufacturing process plays a crucial role in the production of complex and large composite parts. VARTM, which is usually regarded as an open mold composite manufacturing process, is highly used for manufacturing large composite parts because of its high dimensional accuracy and strength [71]. This process operates at room temperature and atmospheric pressure, making it easily manageable and controllable [72]. It also offers flexibility in selecting the material for molds and designing the mold tooling [73]. Furthermore, compared to the hand layup process, VARTM gives a more uniform resin distribution inside the composite part. There's a risk of scrapping the composite part if there is a vacuum leakage, which depends on the experience and skill levels of the worker. Continuous monitoring is therefore necessary during the infusion process. Finally, the consolidation materials such as peel ply, sealant tape, and resin tubes are not reusable, requiring individual preparation each time. A typical schematic diagram of a

VARTM setup is given in Figure 4 [74]. The function of each material is explained in detail in *Section 3.2.1*.

Kim et al. [75] studied the epoxy resin spreading pattern and glass fibers mats permeability during the VARTM process. They used woven bidirectional mats, similar to the material used in this project. As might be anticipated, they observed that the mats had the same permeability in both directions, regardless of the infusion point location or the resin flow direction. In another study, Kim et al. [76] gave a more in-depth analysis by comparing the permeability and filling behavior of woven mats during the VARTM process between experimental setup and analytical model. They noticed consistent results between their predictions and the actual testing, which could help the manufacturing of complex shape parts and process optimization using similar types of techniques. Finally, Dhimole et al. [77] highlighted the negative effects of voids exhibited during fabrication of composite parts using VARTM. They stated that a 1% and 2% increase in void content resulted in decreases of 2.5% and 12.7% in tensile and flexural strength, respectively. Although the presence of voids and fiber misalignment in the final part are hard to eliminate completely, their study gave a better understanding of their influence.

Due to the design of the sandwich composite panels that will be used for retrofitting the buildings in Knoxville, TN, as well as their large dimensions, VARTM was chosen as the primary manufacturing process in this project. In addition, because of the nonconsistency in buildings' measurements, an adjustable mold was found crucial. Instead of manufacturing different molds for different panel sizes, a mold with adjustable sides provides a quicker and more economical solution.

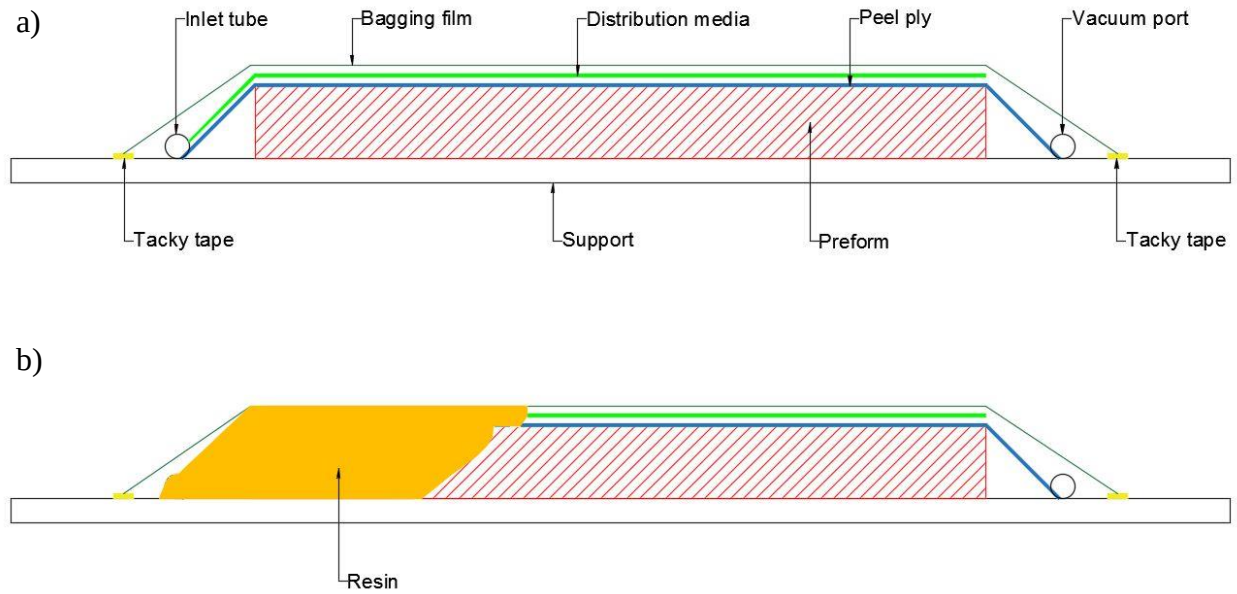


Figure 4. Typical schematic VARTM setup a) before infusion and b) while infusing.

CHAPTER 3: MATERIALS AND METHODS

3.1 Materials

3.1.1 Epoxy resin and hardener

The epoxy resin used to manufacture the modular panels is an Olin product called LITESTONE 1500E. To cure the polymer to a solid state, Olin's LITESTONE 1503H amine curing agent was mixed with the resin with a mix ratio of 100/32 by weight.

This mixture was chosen because it was developed for vacuum infusion processes and cures at room temperature. It offers a long infusion time due to its pot life of 300 minutes and is particularly suitable for manufacturing large sandwich panels and structural glass fiber parts [78]. According to the manufacturer's product information, Table 3 and Table 4 show the properties of the single components and the mixed system, respectively, while Table 5 gives the properties of the cured system.

3.1.2 Extruded polystyrene (XPS) foam

Owens Corning's Foamular 250 (Figure 5) and Foamular 150 XPS foam boards that were used in this project are closed-cell and moisture-resistant. They can be used in a wide variety of building applications, such as insulation, and have a density varying between 1.3 lb/ft³ (21 Kg/m³) and 1.9 lb/ft³ (30.4 Kg/m³). They also come in different thicknesses, varying between 0.5 in. and 4 in. (12.7 mm to 101.6 mm). Table 6 shows the properties of the XPS foam according to the manufacturer [79].

Table 3. Properties of LITESTONE 1500E epoxy resin and LITESTONE 1503H hardener according to Olin.

Property	LITESTONE 1500E Epoxy Resin	LITESTONE 1503H Hardener
Viscosity at 77 °F (25 °C) - mPa.s [ASTM D445]	1,200-1,400	12-18
Density at 77 °F (25 °C) - lb/in ³ (g/cm ³) [ASTM D4052]	0.043 (1.2)	0.034 (0.95)
Shelf Life - months [If stored in a dry and cool place]	12	12

Table 4. Properties of the mixed system containing LITESTONE 1500E epoxy resin and LITESTONE 1503H hardener according to Olin.

Property	LITESTONE 1500E Epoxy Resin + LITESTONE 1503H Hardener
Viscosity at 86 °F (30 °C) - mPa.s [ASTM D2983]	320-350
Gel Time at 73.4 °F (23 °C) - min [Gelnorm Instrument]	300

Table 5. Properties of the cured system containing LITESTONE 1500E epoxy resin and LITESTONE 1503H hardener according to Olin.

Property	LITESTONE 1500E Epoxy Resin + LITESTONE 1503H Hardener
Glass temperature Tg - °F (°C) [Differential scanning calorimetry (DSC), midpoint, 10 K/min]	176 (80)
Tensile Strength - psi (Mpa) [ASTM D638]	10,007.6 (69)
Tensile Modulus - psi (GPa) [ASTM D638]	435,113 (3)
Elongation at Break (%) [ASTM D638]	3.9



Figure 5. Owens Corning's Foamular 250 XPS 2 in. foam board.

Table 6. Properties of the XPS foam boards according to Owens Corning.

Property	Test method	Value
Thermal resistance, R-Value/in - hr.ft. ² .°F/BTU (°C.m ² /W) @ 75 °F (24 °C) mean temperature	ASTM C518	5.0 (0.88)
@ 40 °F (4.4 °C) mean temperature		5.4 (0.95)
@ 25 °F (-3.9 °C) mean temperature		5.6 (0.99)
Water absorption, maximum % by volume	ASTM C272	0.3
Water vapor permeance - maximum perm (ng/Pa.s.m ²)	ASTM E96	1.5 (86)
Dimensional Stability, maximum % linear change	ASTM D2126	2.0
Flame spread	ASTM E84	10
Smoke developed	ASTM E84	175
Oxygen Index, minimum % by volume	ASTM D2863	24
Service Temperature, maximum - °F (°C)	-	165 (74)
Linear Coefficient of Thermal Expansion - in/in/°F (m/m/°C)	ASTM E228	3.5 x 10 ⁻⁵ (6.3 x 10 ⁻⁵)
Tensile modulus - psi (GPa) Foamular 150 - 1" (25.4 mm) thick foam	ASTM D1623	1,000 (0.0069)
Foamular 250 - 2" (50.8 mm) thick foam		940 (6.48)
Poisson's ratio	-	0.3

3.1.3 Woven glass fabric

Owens corning's woven roving bi-directional (0°/90°) E-glass fabrics (Figure 6) were used as reinforcement for the composite panels. They have a consistent glass loading pattern, a uniform porosity, and weigh around 0.16 lb/ft² (0.78 Kg/m²).

3.1.4 Prisma composites preform beams

Prisma Composite Preforms' beams are made of a 2 lb/ft³ (32 Kg/m³) closed-cell PU foam, stitched 0°/90° fiberglass, and a non-woven polyester backing. The beam edges were cut, and the polyester backing was replaced by glass fibers before laying the beams on the woven glass fabric for a resin infusion (Figure 7).

3.1.5 Ceramic coating

Cerakote's C-Series ambient cure ceramic coating was used to paint the modular panels. There are multiple color choices that dictate the properties of the coating, such as density, adhesion, and viscosity. In addition, according to the manufacturer, they can withstand temperatures up to 1,200 °F (649 °C) and extreme weather conditions (UV and moisture exposures). Table 7 shows the cure schedule of the C-Series coating. The coatings "coyote tan" and "o.d. green" were used for testing.

3.2 Methods

This section is divided into 3 main parts in order to explain the reasoning behind every test done in this research. The first part explains the VARTM process that was used to manufacture all the panels. The second part compares the performance of 2 designs of sandwich panels (XPS and Prisma) subjected to a series of lab-scale thermal and mechanical tests. The last part contains all concepts, testing, and simulation related to the current application of the modular cladding panels.

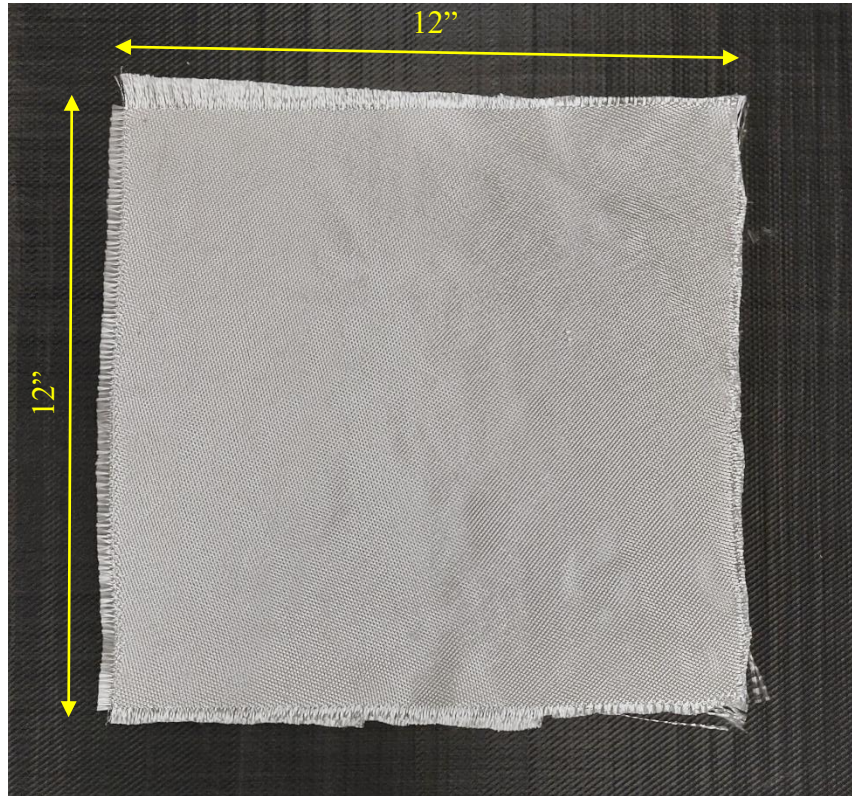


Figure 6. Owens corning's woven roving bi-directional ($0^{\circ}/90^{\circ}$) E-glass fabric.

Table 7. Cure schedule of the Cerakote C-Series coating.

Cure state	Time
Tack free	45-60 minutes
Dry	24 hours
100% cure	5 days

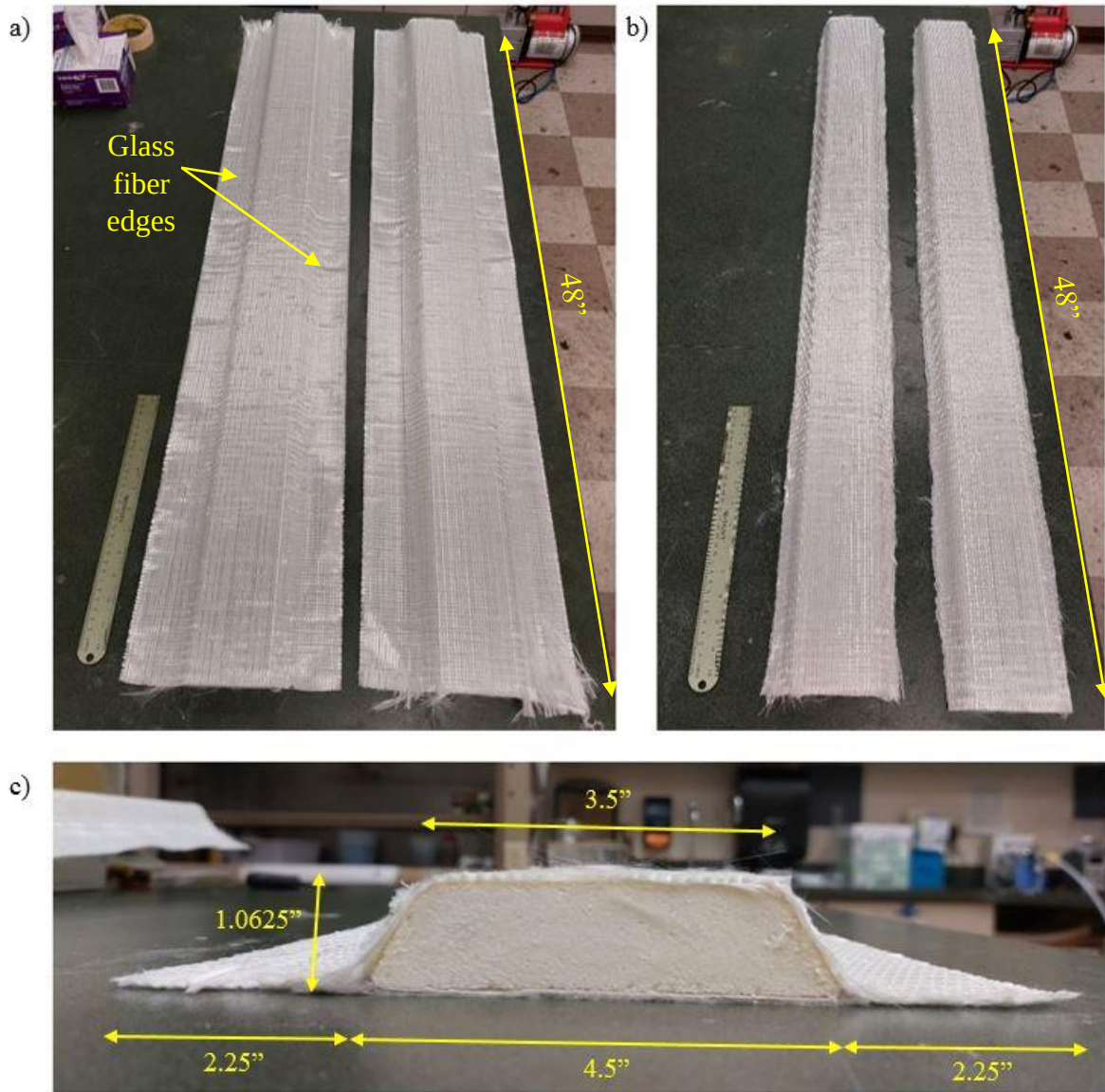


Figure 7. Prisma Composite Preforms' beams a) with fiberglass edges, b) after cutting the edges, and c) section.

3.2.1 Vacuum assisted resin transfer molding (VARTM)

VARTM was the primary manufacturing technique used to make the panels. Figure 8a shows how the glass fabric was laid on both sides of the XPS foam to create a 2' x 2' x 2.24" (609.6 mm x 609.6 mm x 56.9 mm) sandwich panel, while Figure 8b illustrates the different materials used in setting up the infusion process. Each material had a specific function within the manufacturing of panels using VARTM:

- Tacky tape: sealed the part under vacuum by restricting outside air to penetrate through the connection between glass support and bagging film.
- Teflon sheet: allowed the vacuum to pull excess resin and air from the part due to its porous nature. In addition, it prevented all other materials from sticking to the sandwich structure.
- Flow media: helped the resin to flow uniformly within the panel in the vacuum direction.
- Spiral tube (infusion side): helped the resin penetrate inside the sealed area through a uniform line connected to the flow media (Figure 9).
- Membrane tube infusion (MTI) hose (vacuum side): allowed for a constant vacuum pressure along the hose, due to the inability of the epoxy resin to infiltrate the membrane and get into the catch pot (Figure 9).
- Solid tubes: used for resin infusion and air circulation.
- Breather: Prevented the bagging film from closing the pores of the MTI hose due to vacuum pressure.
- Bagging film: sealed the whole part by sticking to the tacky tape.
- Catch pot: used to catch excess resin that leaks out of the sealed area by accident.
- Vacuum pump: used to pull the air from inside the infusion area by applying vacuum pressure and make the resin flow through the part.

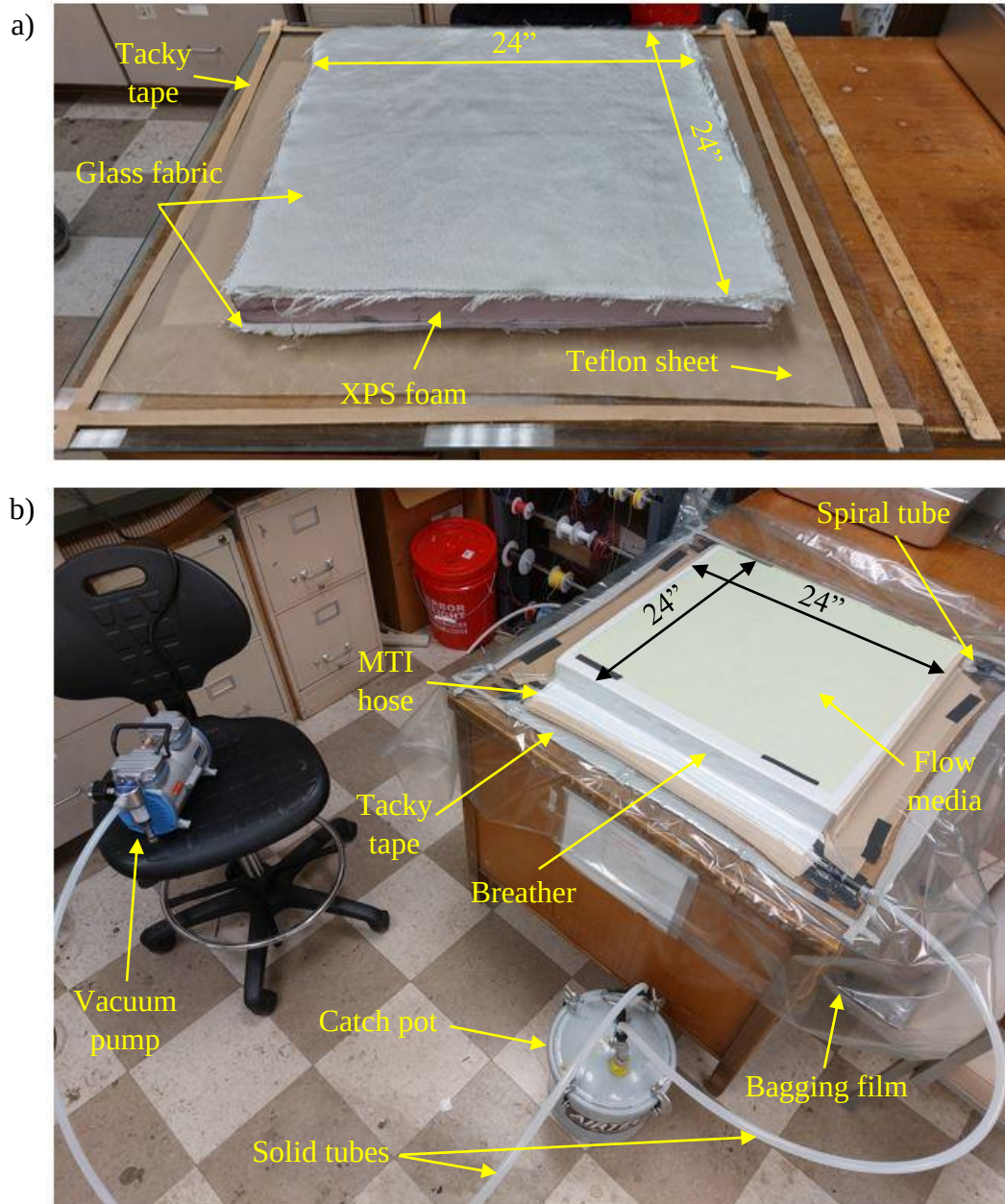


Figure 8. a) Layup of the glass fabric on both sides of the XPS foam, and b) VARTM setup for infusing the sandwich panel.

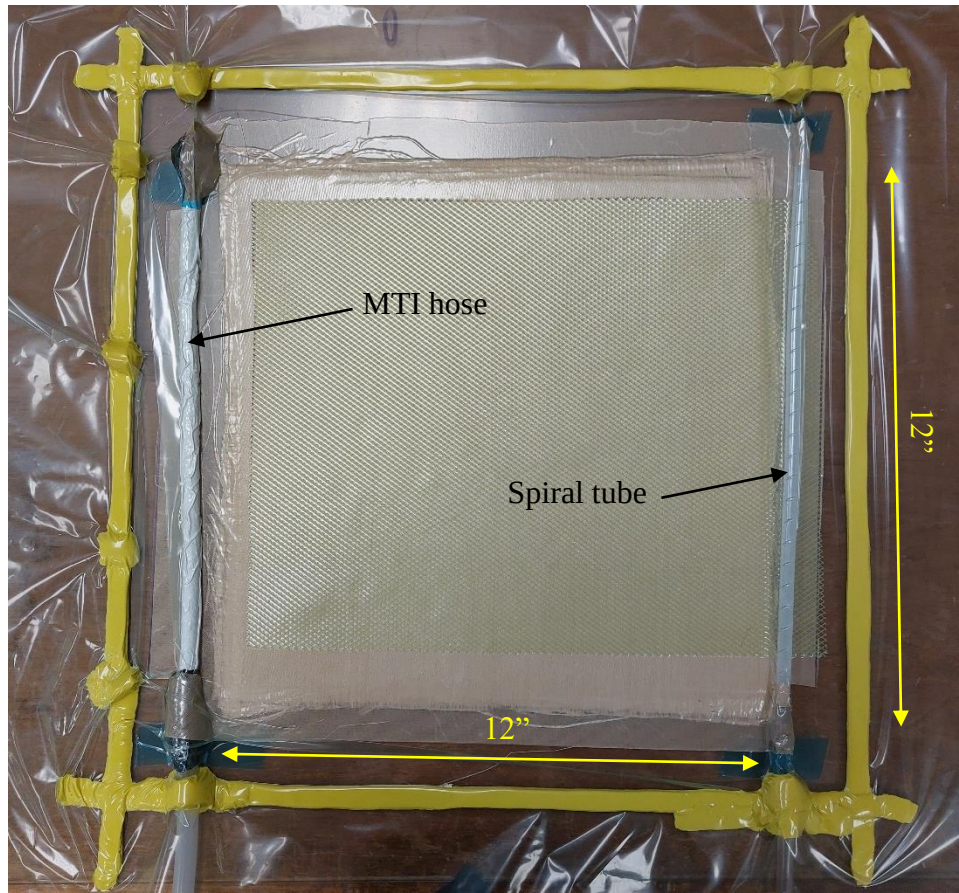


Figure 9. Use of an MTI hose in the VARTM process.

Each panel was kept for at least 3 hours under a constant vacuum pressure of 27.6 inHg (700 mmHg) before infusing it with resin. 2 main sandwich panel types were manufactured using VARTM:

- XPS foam sandwich structure: 4 layers of glass fabric were placed on each side of the foam board.
- Prisma beams sandwich structure: the polyester backing was replaced with 1 layer of glass fabric, and then 3 more layers were placed on both sides of the beams.

For each panel type, multiple infusions were conducted depending on the desired dimensions and whether web joints were needed inside the foam. The densities of the cured panels were measured according to ASTM C271.

3.2.2 Comparison between XPS and Prisma sandwich panels

The main objective of the cladding panels is to increase the thermal resistance of the buildings, while having an acceptable structural performance. Thermal tests were therefore carried out in order to determine the most appropriate sandwich system for this project. Multiple mechanical tests were also conducted to compare the behavior and failure modes of the 2 types of sandwich panels. The Prisma composites preform beams were chosen as a reference due to their use in the marine industry for boats insulation, while XPS foam boards are widely available in low prices and multiple thicknesses.

3.2.2.1 Thermal testing

The thermal performances of XPS panels and Prisma panels were tested and compared. TA Instruments' FOX 304 (maximum specimen dimensions: 12" x 12" x 4" (304.8 mm x 304.8 mm x 101.6 mm)) and FOX 600 (maximum specimen dimensions: 24" x 24" x 8" (609.6 mm x 609.6

mm x 203.2 mm)) heat flow meters were used to measure the thermal conductivity and R-value of the materials according to ASTM C518. Table 8 shows the temperatures used for testing. The upper and lower temperatures are related to the upper and lower faces of the panels, respectively. The mean temperature is the average of the previous values. 3 test runs were conducted for each panel. TA Instruments' differential scanning calorimetry (DSC) 2500 gave the specific heat capacity vs. temperature data according to ASTM E1269. Shavings of GFRP and XPS foam were heated at a rate of 68 °F/min (20 °C/min). Figure 10 illustrates the equipment, while Figure 11 shows the 12" (304.8 mm) square panels used for the initial run of tests using the heat flow meter. A second run of tests was conducted using XPS panels because of their superior thermal resistance. 24" (609.6 mm) square panels having a 2" (50.8 mm) thick XPS foam were therefore prepared (Figure 12).

3.2.2.2 Long beam flexure (LBF)

A 3-point bending test (ASTM D7249) was carried out on XPS and Prisma sandwich samples in order to compare their behaviors and failure modes. 2 Prisma beams were connected and infused together, which resulted in an inclined GFRP web inside the Prisma sandwich sample. Similarly, 2 layers of glass fabric were put between 2 pieces of XPS, which created a vertical GFRP web inside the XPS sandwich sample. Figure 13 shows both types of test samples, having a length of 12" (304.8 mm), a width of 2.5" (63.5 mm), and a thickness of 1.24" (31.5 mm) (1" foam and 0.24" GFRP facers). The testing was carried out on Instron's Satec series static hydraulic system, with a control rate of 0.079"/min (2 mm/min). The test setup is given in Figure 14.

Table 8. Temperatures used for measuring the thermal conductivity and R-value of all panels.

Test run	Lower temp. - °F (°C)	Upper temp. - °F (°C)	Mean temp. - °F (°C)
1	75.2 (24)	24.8 (-4)	50 (10)
2	100.4 (38)	50 (10)	75.2 (24)
3	125.6 (52)	75.2 (24)	100.4 (38)

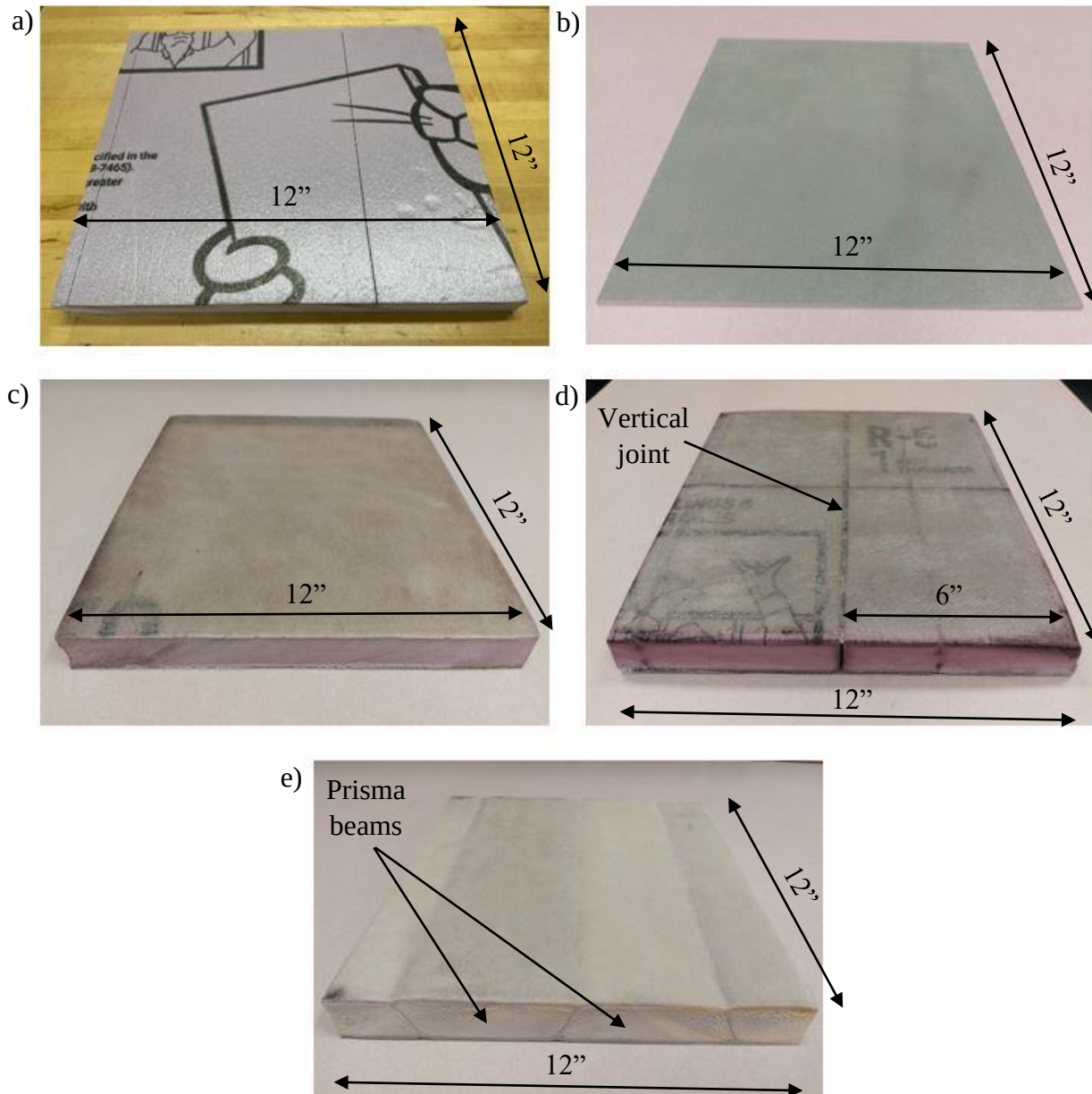


Figure 10. 12" (304.8 mm) square panels for thermal testing: a) XPS, b) GFRP, c) composite XPS without joints, d) composite XPS with a vertical joint, and e) composite Prisma beams.



Figure 11. TA Instruments': a) FOX 304 heat flow meter, b) FOX 360 heat flow meter, and c) DSC 2500.

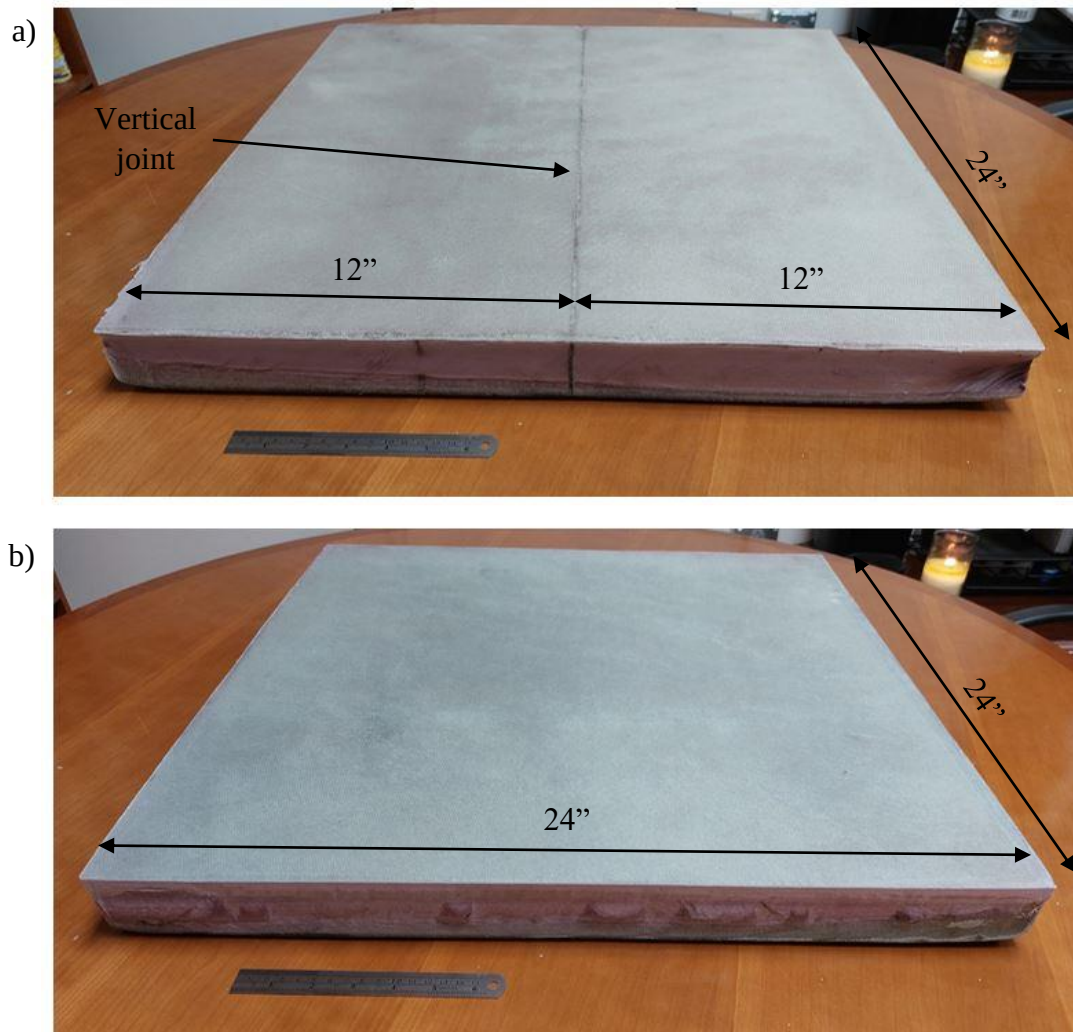


Figure 12. 24'' (609.6 mm) square panels for thermal testing: a) composite XPS with a vertical joint, and b) composite XPS without joints.

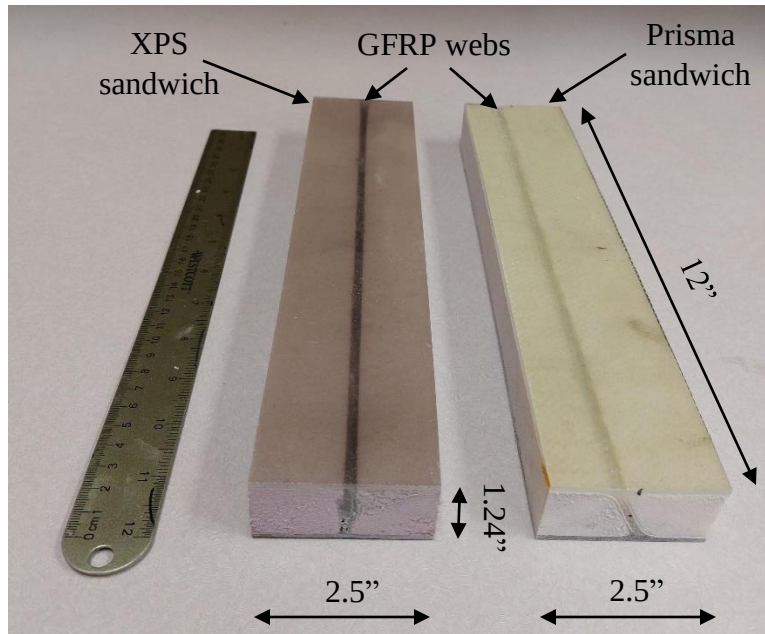


Figure 13. XPS and Prisma sandwich samples with GFRP webs for LBF test.

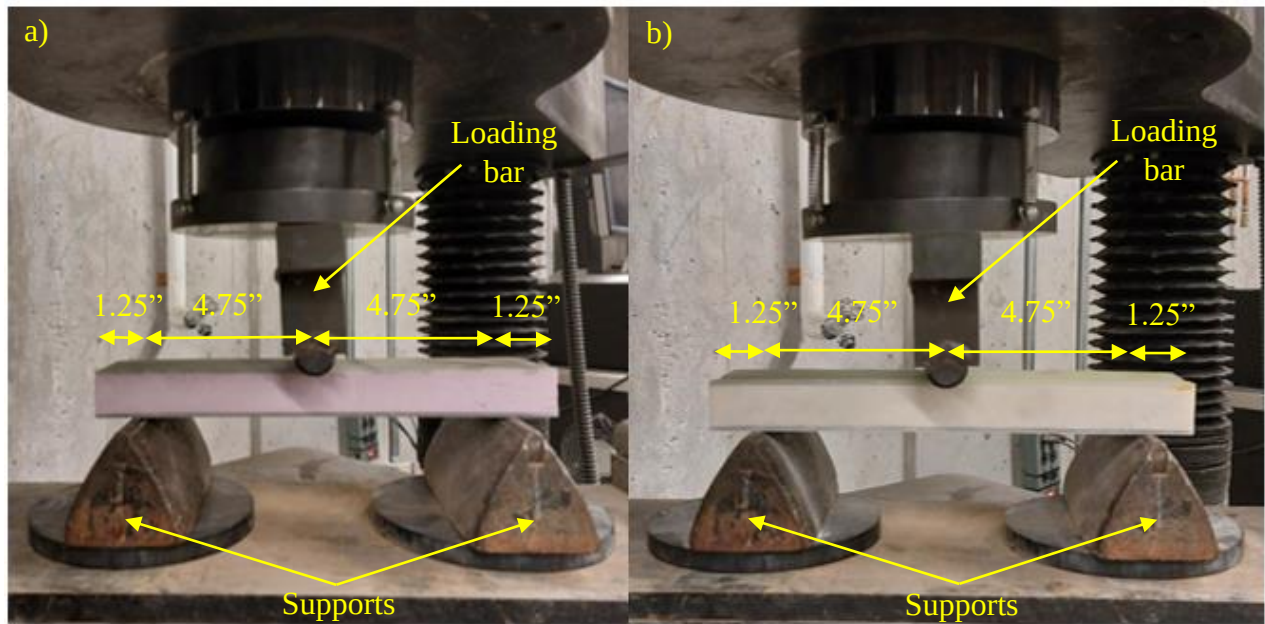


Figure 14. 3-point bending test (ASTM D7249) setup for a) XPS sandwich and b) Prisma sandwich.

3.2.2.3 Short beam flexure (SBF)

A 4-point bending test (ATSM C393) was used as another comparison tool for failure modes under flexural behavior in both sandwich structure designs. The samples were smaller than the ones used for the LBF test and did not contain any GFRP web. The SBF test samples were 6" (152.4 mm) long, 1.6" (40.64 mm) wide, and 0.8" (20.32 mm) thick (0.56" foam and 0.24" GFRP facers) (Figure 15). Test Resources Universal Testing Machine (model 313 series frame, MN), combined with Epsilon technology corp.'s deflectionometer (model: 3540-100T-ST), were used to carry out the testing. Figure 16 shows the third point loading configuration that was chosen for this section. The control rate was 0.197"/min (5 mm/min).

3.2.2.4 Low-velocity impact (LVI)

A low-velocity impact test was conducted using the Instron CEAST 9340 system (Figure 17) to compare the energy absorption capacities between XPS and Prisma beams sandwich structures. ASTM D7136 and ASTM D7766 were the followed standards. The composite samples were 6" (152.4 mm) long, 4" (101.6 mm) wide, and 1.24" (31.5 mm) thick (1" foam and 0.24" GFRP facers), as shown in Figure 18. The process parameters of the LVI test are given in Table 9.

3.2.2.5 "Flatwise" tensile test (FTT)

ASTM D7291 test method was chosen to check and compare the bonding between foam core and GFRP facesheets in both sandwich types. The samples were cut in 1" (25.4 mm) diameter circles and were 0.8" (20.32 mm) thick (0.56" foam and 0.24" GFRP facers) (Figure 19). Aluminum end tabs were glued to both sides of the composite samples using Loctite super glue. The samples and tabs were left to cure before preparing the test setup, as shown in Figure 20.

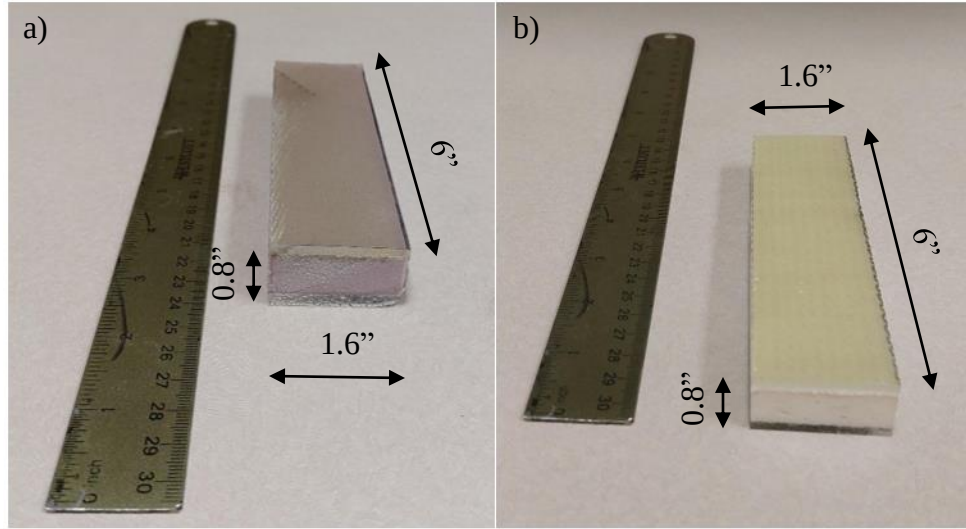


Figure 15. a) XPS and b) Prisma sandwich samples for SBF test.

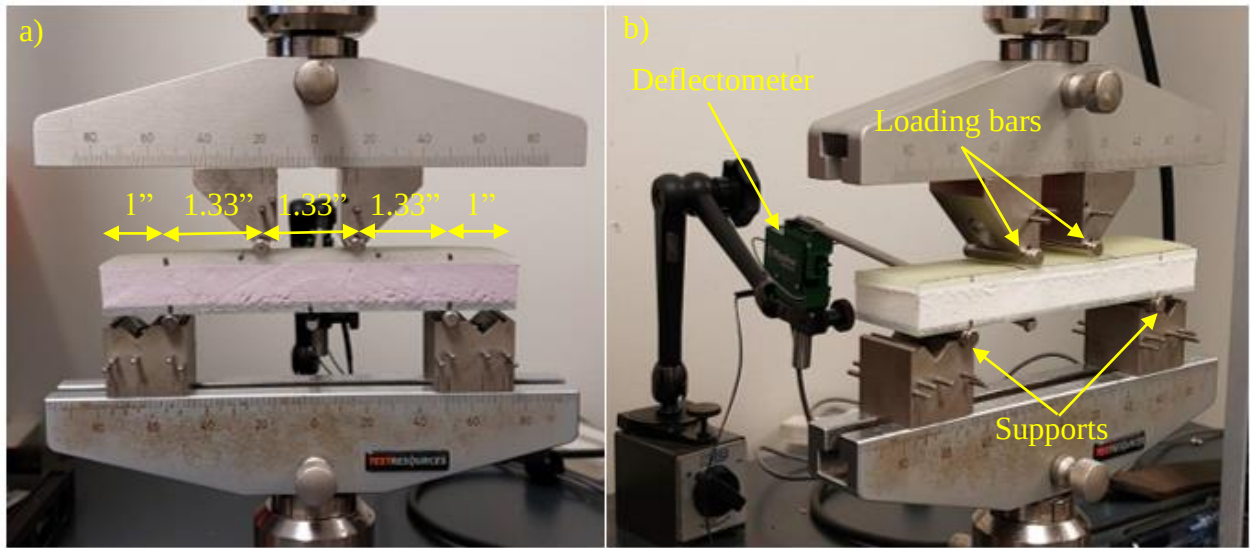


Figure 16. 4-point bending test (ASTM C393) setup for a) XPS sandwich and b) Prisma sandwich.

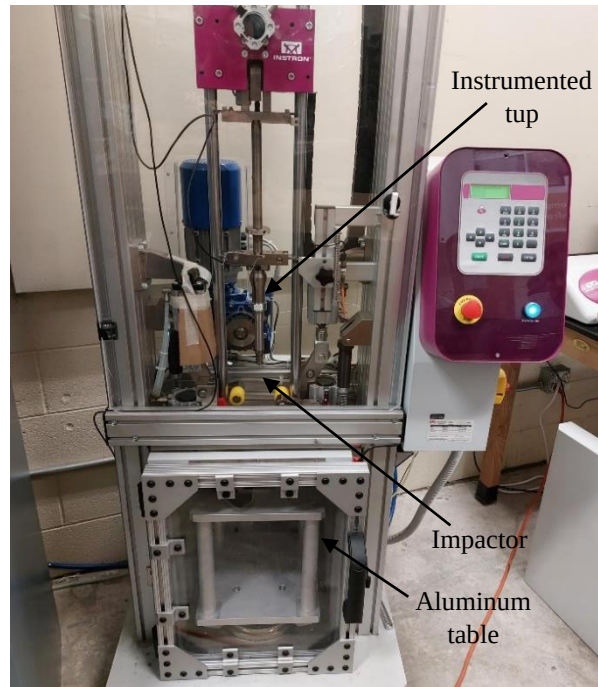


Figure 17. Instron CEAST 9340 system.

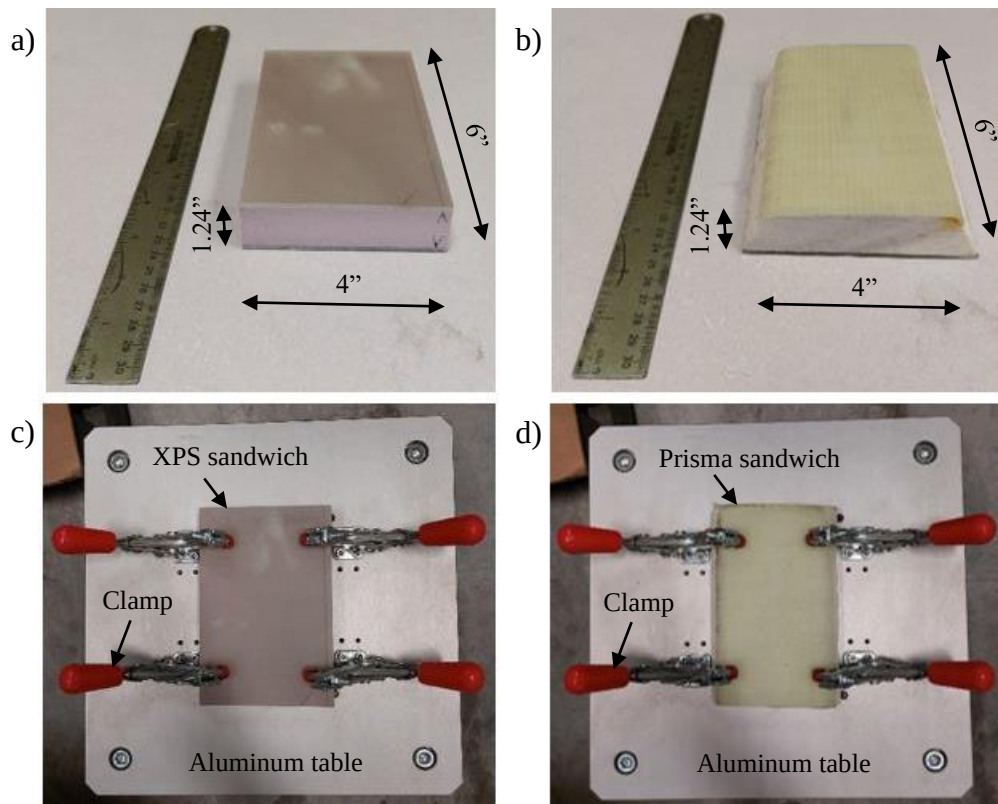


Figure 18. a) XPS and b) Prisma sandwich sample, c) XPS and d) Prisma sandwich setup for LVI test (ASTM D7136 and ASTM D7766).

Table 9. LVI process parameters.

22 kN tup mass - lb (Kg)	Carriage mass - lb (Kg)	Additional mass - lb (Kg)	Total mass - lb (Kg)	Impact height - in (cm)	Impact velocity - ft/s (m/s)
1.58 (0.72)	5.51 (2.5)	19.84 (9)	26.94 (12.22)	42.48 (107.9)	15.1 (4.6)

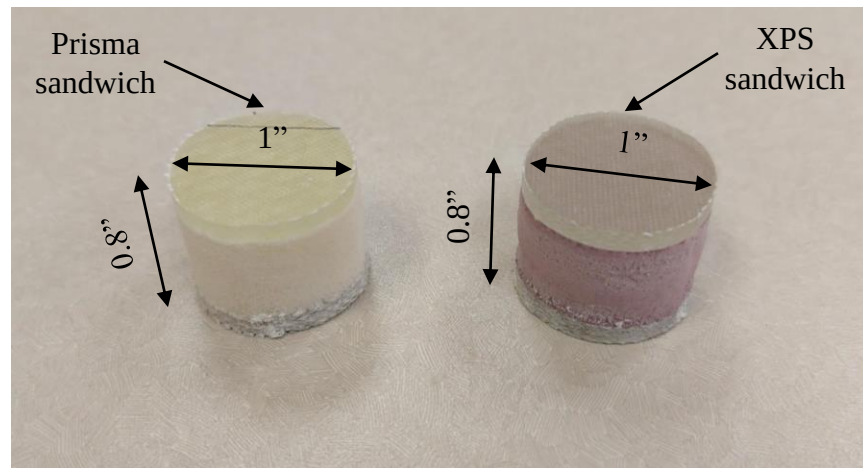


Figure 19. XPS and Prisma sandwich samples for FTT test.

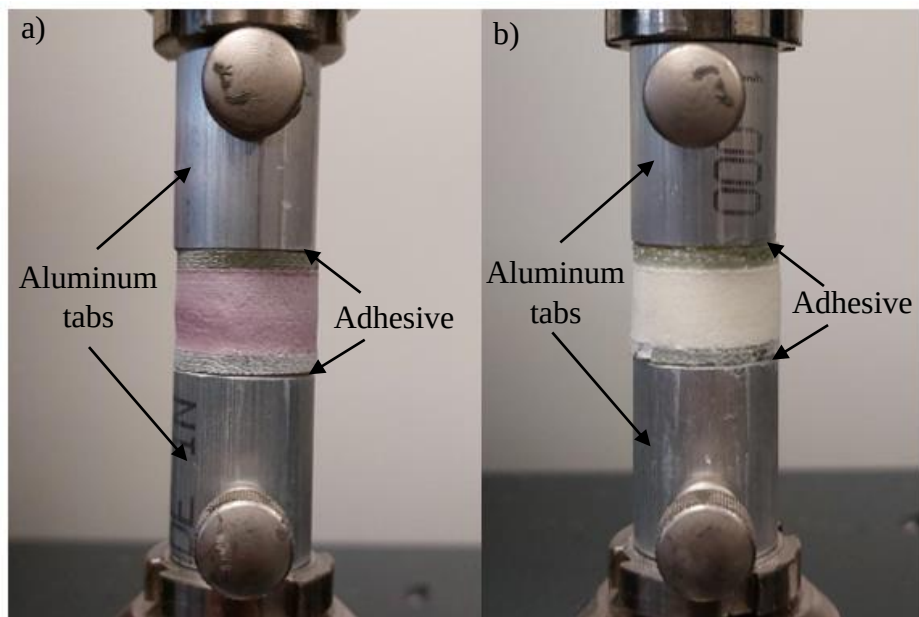


Figure 20. "Flatwise" tensile test (ASTM D7291) setup for a) XPS sandwich and b) Prisma sandwich.

Test Resources Universal Testing Machine (Model 313 series frame, MN) was used in a tensile test configuration. The control rate was 0.00788"/min (0.2 mm/min).

3.2.3 Current application

The cladding panels should meet specific requirements to be considered as an acceptable retrofitting solution. They need to provide adequate thermal, structural, and aesthetic properties. Thermal properties were already discussed in *Section 3.2.2.1*. The panel connections concept was chosen based on manufacturing and installation feasibility, and architectural requirements. The structural performance was then checked by testing a large-scale specimen and conducting FEA simulations. In addition, accelerated environmental tests were performed to choose a surface finish for the panels. Finally, a fire simulation was conducted according to building standards.

3.2.3.1 Tensile testing

Tensile testing (ASTM D3039) was conducted on GFRP samples (Figure 21) in order to determine the elastic modulus (E), Poisson's ratio (ν), and tensile strength (σ_t) of the material. The samples were 10" (240 mm) long, 1" (25.4 mm) wide, and 0.12" (3 mm) thick. Test Resources Universal Testing Machine (Model 313 series frame, MN) was used for the purpose of getting the time, force, and displacement data, while National Instruments' data acquisition (DAQ) hardware (cDAQ-9174 compactDAQ chassis with a NI 9236, 350 Ω 8-channel C series quarter-bridge strain gauge input module) and software (DAQExpress 3.0.0, build number: 6.2.0.52432) gave the strain vs. time data (Figure 22). The longitudinal and transverse strains were both measured by Omega's SGD-7/350-XY11 biaxial, Stacked 0/90° Corner T strain gauge rosettes. The control rate was 0.0787"/min (2 mm/min).

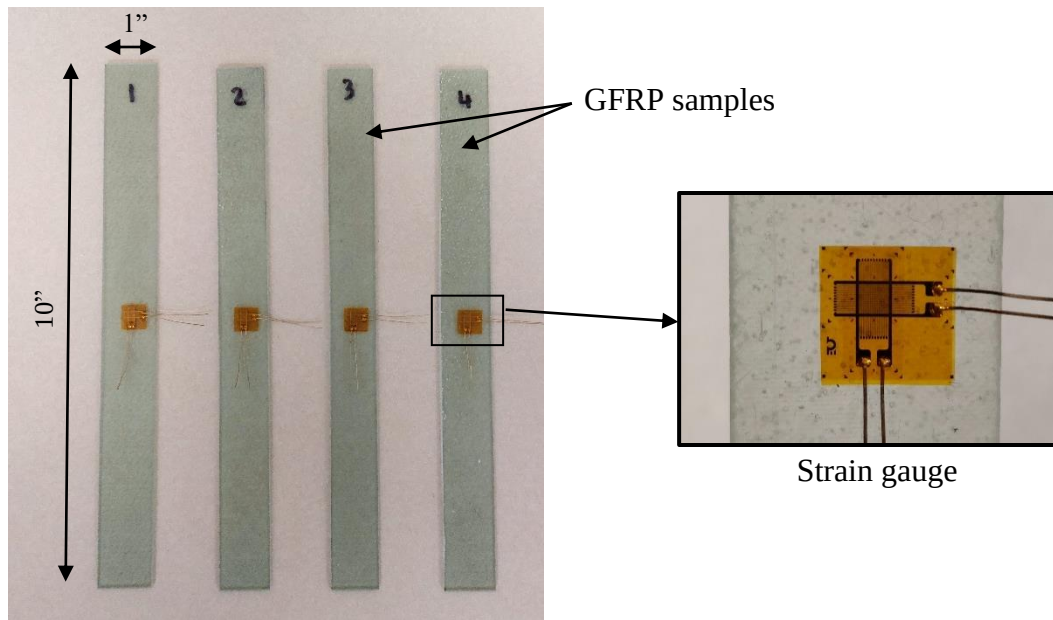


Figure 21. GFRP samples with biaxial strain gauges for tensile testing.

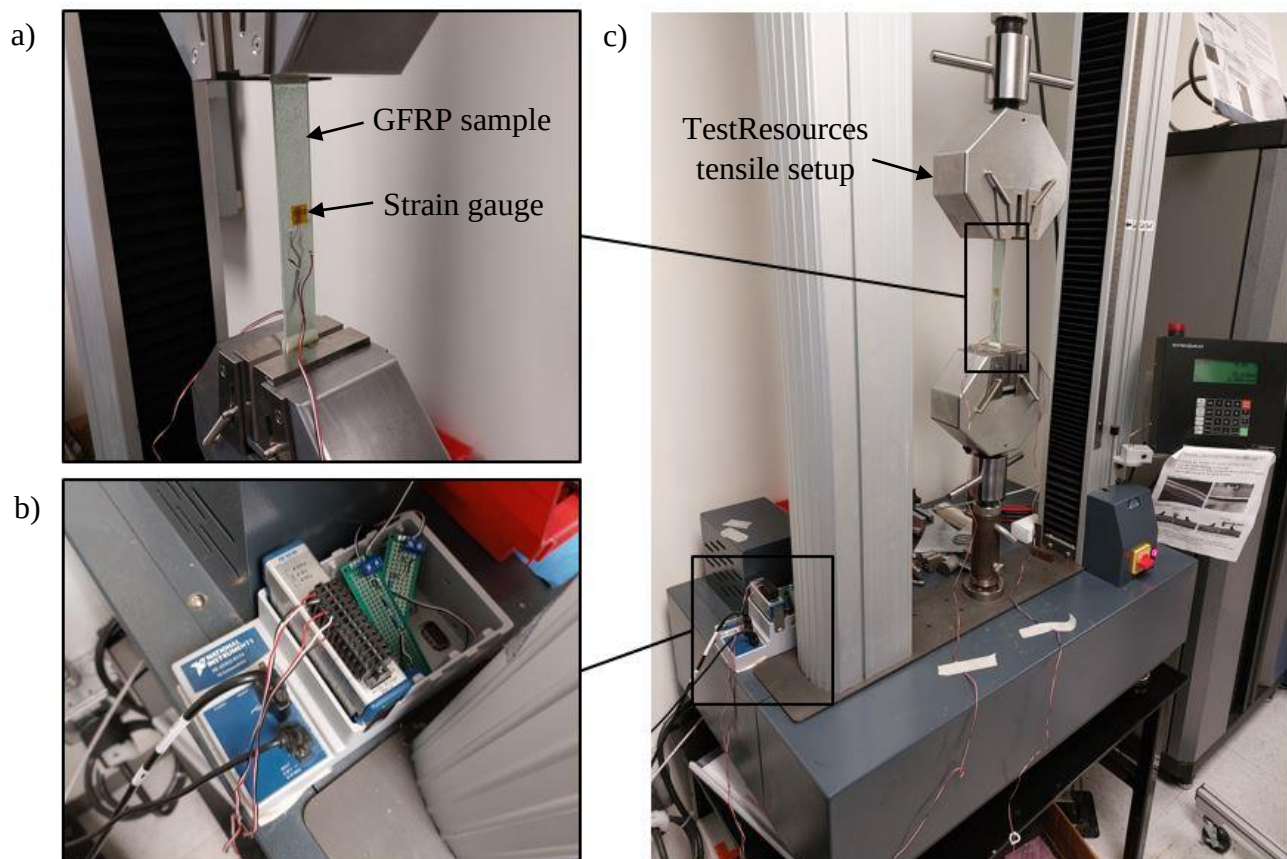


Figure 22. The tensile test setup showing a) the mounted GFRP sample, b) the National Instruments hardware, and c) the TestResources machine.

3.2.3.2 Large-scale flexural testing

3.2.3.2.1 Experimental testing

A 4' x 8' x 4.23" (121.92 cm x 243.84 cm x 107.44 mm) sandwich panel was prepared using VARTM (Figure 23). Each facesheet was made with 4 layers of glass fabric and the foam core was obtained by laying 2 XPS boards that were 2" (50.8 mm) thick. 2 layers of glass fabrics were put on the 4' (121.92 cm) edges of the panel to bond the 2 foam pieces together. No glass fabric was added on the 8' (243.84 cm) edges. XPS foam boards were placed below and above the panel to obtain a good surface finish. In order to check its structural capacity, the sandwich structure was tested under 2 loading configurations, while simply supported on both sides and spanning along its 8' (243.84 cm) length. The first configuration used a total load of 490 lb (222.26 Kg) while the second used a total load of 440 lb (199.58 Kg). Figure 24 illustrates the test setup while Figure 25 shows the 2 loading configurations. The supports consisted of wooden boards sitting on concrete masonry units (CMU). Long-fiber-reinforced thermoplastic (LFT) bags were used to apply the loads, with each bag weighing around 55 lb (24.95 Kg). The GFRP layers that were used for bonding on the 4' (121.92 cm) edges were outside of the supports, and therefore they didn't add any structural resistance. The 2 XPS foam boards were well bonded after the infusion and didn't show any sign of separation. Table 10 gives the loading conditions used for both tests. Finally, All Industrial dial indicator & Noga magnetic base were used to measure the deflection at the center of the structure.

3.2.3.2.2 FEA modeling

The academic version of Abaqus/CAE 6.12-1 was used to model the flexural tests and compare the results with the experimental data. The panel was drawn with 2 GFRP skins and 2 XPS foam boards having the material properties shown in Table 11.

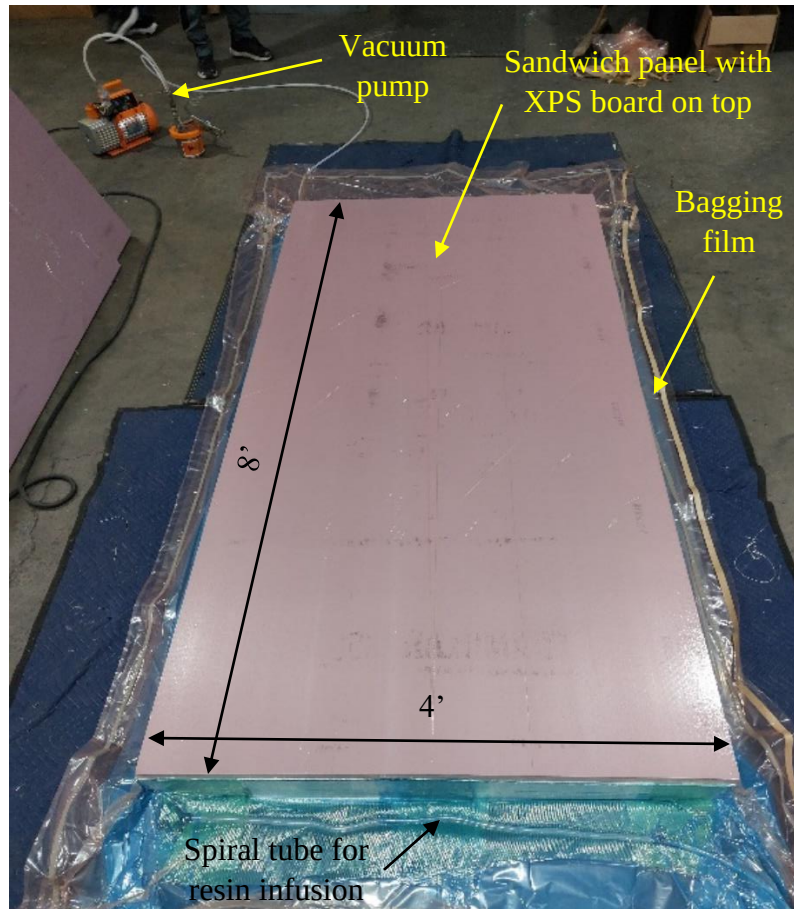


Figure 23. VARTM setup for the 4' x 8' x 4.23'' (121.92 cm x 243.84 cm x 107.44 mm) sandwich panel.

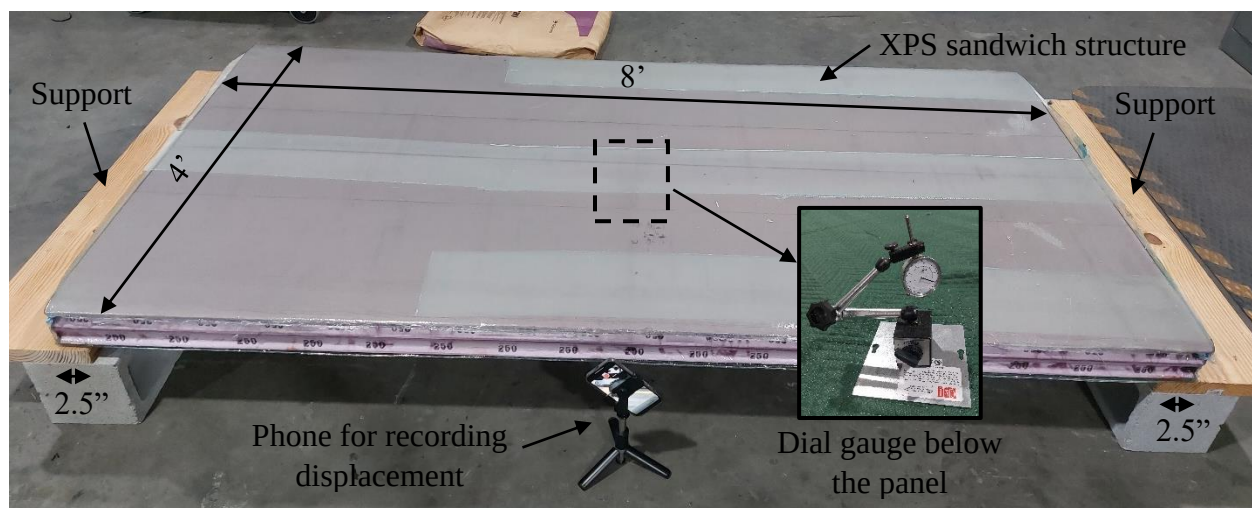


Figure 24. Flexural test setup for the 4' x 8' x 4.23'' (121.92 cm x 243.84 cm x 107.44 mm) sandwich panel.

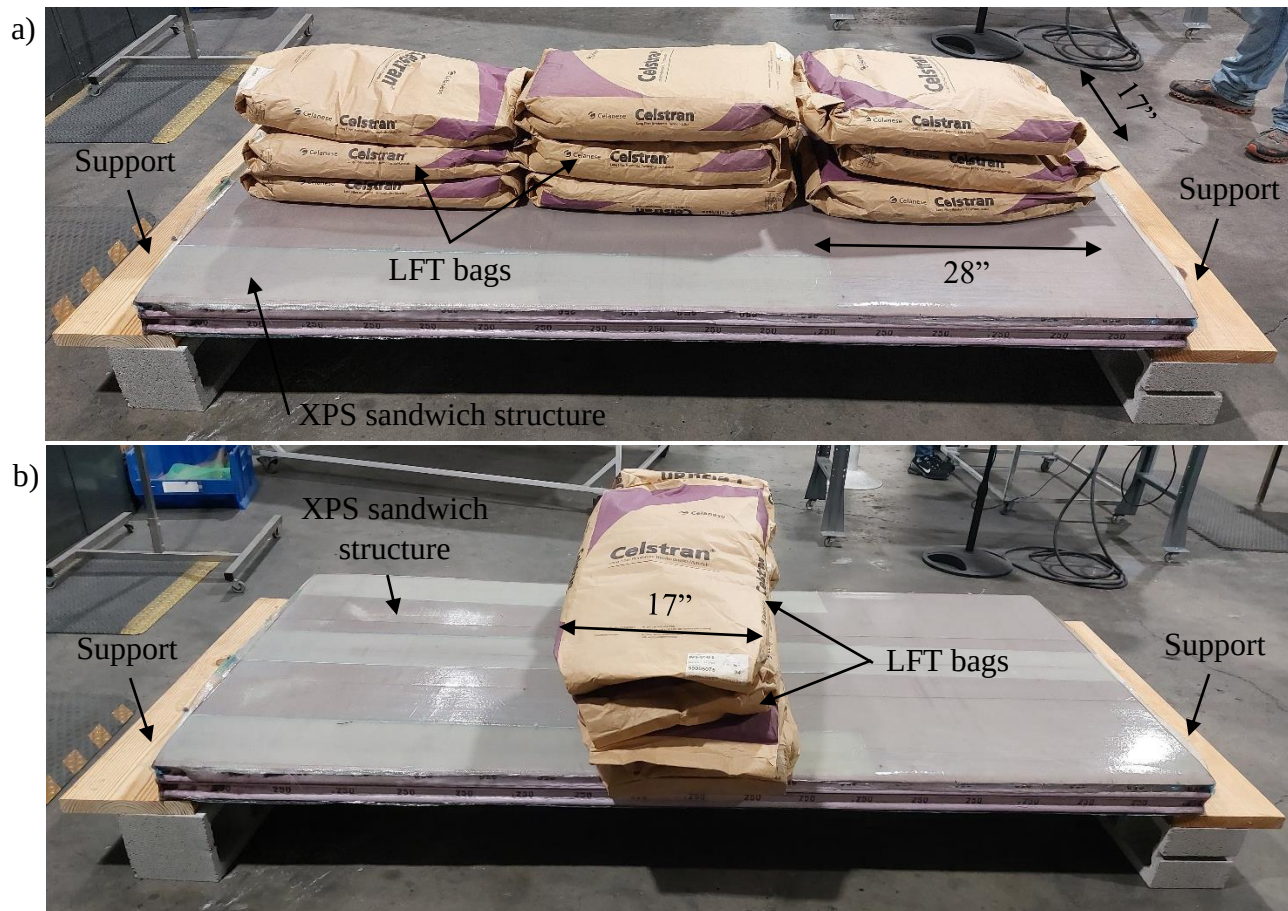


Figure 25. Large-scale flexural test loading configuration for a) Test 1 and b) Test 2.

Table 10. Loading conditions for the 2 flexural tests.

Test type	Loading direction	Loading location	Total load - lb (Kg)	Loading surface - in ² (m ²)	Surface load – psi (Kg/m ²)
Test 1	Along the 8' edge	Center of the panel	490 (222.3)	17 x 96 = 1,632 (1.05)	0.30 (210.9)
Test 2	Along the 4' edge	Center of the panel	440 (199.6)	17 x 48 = 816 (0.53)	0.54 (379.7)

Table 11. Material properties of GFRP and XPS foam.

Material	Density - lb/in³ (Kg/m³)	Elastic modulus (E) - psi (GPa)	Poisson's ratio (v)
GFRP	0.0607 (1,678)	3,190,800 (22)	0.165
XPS foam	0.0009 (25)	942.8 (0.0065)	0.3

The elastic modulus and Poisson's ratio of GFRP were taken from the results of tensile testing in *Section 4.3.1*, while the properties of the XPS foam were given by the manufacturer. To accurately simulate the behavior of the structure, the modeling parameters given in Table 12 were used. The bonding between the layers in the sandwich structure was modeled as "Rough" tangential behavior and "Hard" normal behavior. These interaction properties were used because there was no slippage nor separation between layers. Pinned boundary conditions were deemed acceptable to accurately recreate the experimental supports by taking the normal reaction and friction into consideration. The normal constraint was defined by the vertical displacement being equal to 0 ($U_z = 0$) while the friction was defined by the horizontal displacement along the span being equal to 0 ($U_x = 0$). Due to the simple geometry of the panel, linear, three-dimensional (3D) stress, hexahedral elements were used for FEA. They are defined as C3D8 elements in Abaqus. Multiple element sizes were checked and the resulting deflections were compared. Figure 26 illustrates the 2 loading conditions, while Figure 27 shows the meshing of the panel with 1" (25.4 mm) elements.

3.2.3.3 Panels and connections design

The houses at Western Heights in Knoxville, TN have double wythe brick walls, a 6" (152.4 mm) reinforced concrete (RC) floor, and a 6" (152.4 mm) RC slab. Figure 28 and Figure 29 illustrate the location of the RC slabs and the area to be insulated in the side view and front and back view of the building, respectively. Figure 30 shows the dimensions of the existing duplex. The cladding panels' upper edge needed to coincide with the RC roof's lower edge. This was due to the future integration of a gutter that would be laid on the sandwich panels. In addition, the panels needed not to block the existing air vents.

Table 12. Modeling parameters used in Abaqus for the 2 flexural tests.

Modeling parameter	Description
Interaction between layers	“Rough” tangential behavior and “Hard” normal behavior for all interfaces (GFRP/XPS and XPS/XPS).
Boundary conditions	Linear pin supports along the 4’ edges ($U_z = U_x = 0$).
Loads	- LFT bags: 0.3 psi for test 1 along the 1,632 in² surface and 0.54 psi for test 2 along the 816 in² surface. - Gravity: weight of the panel distributed along its surface.
Meshing	Linear, 3D stress, hexahedral elements (C3D8).

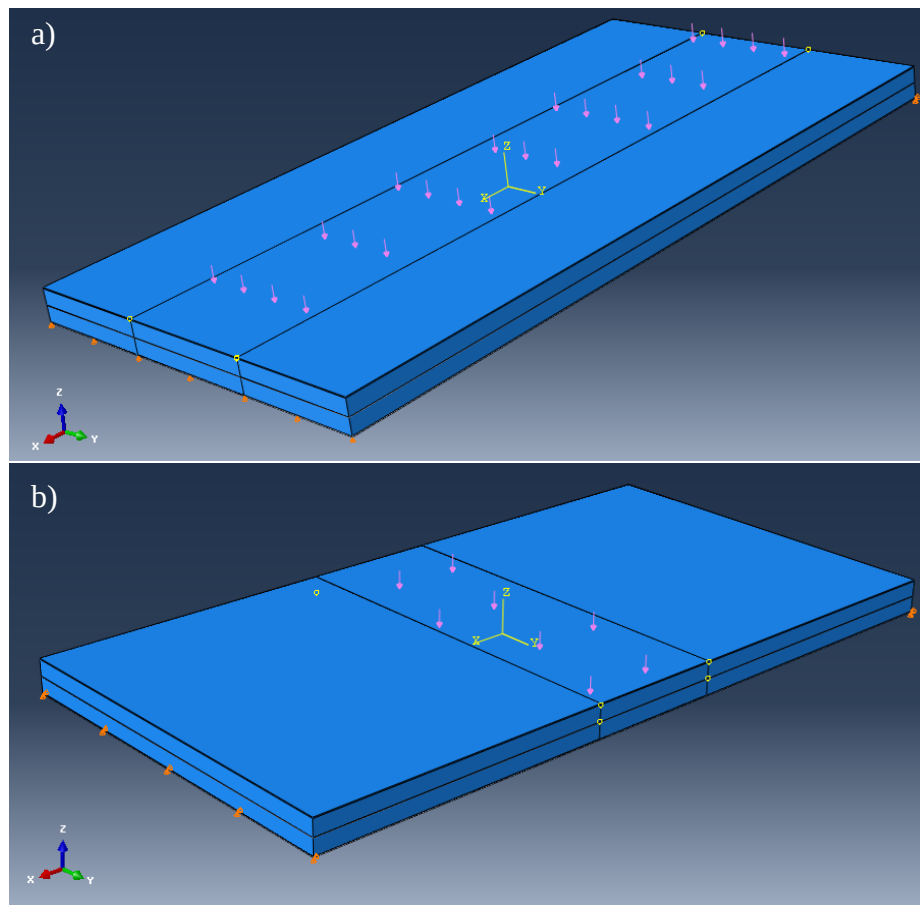


Figure 26. Loading conditions of the sandwich panel recreated in Abaqus for a) Test 1 and b) Test 2.

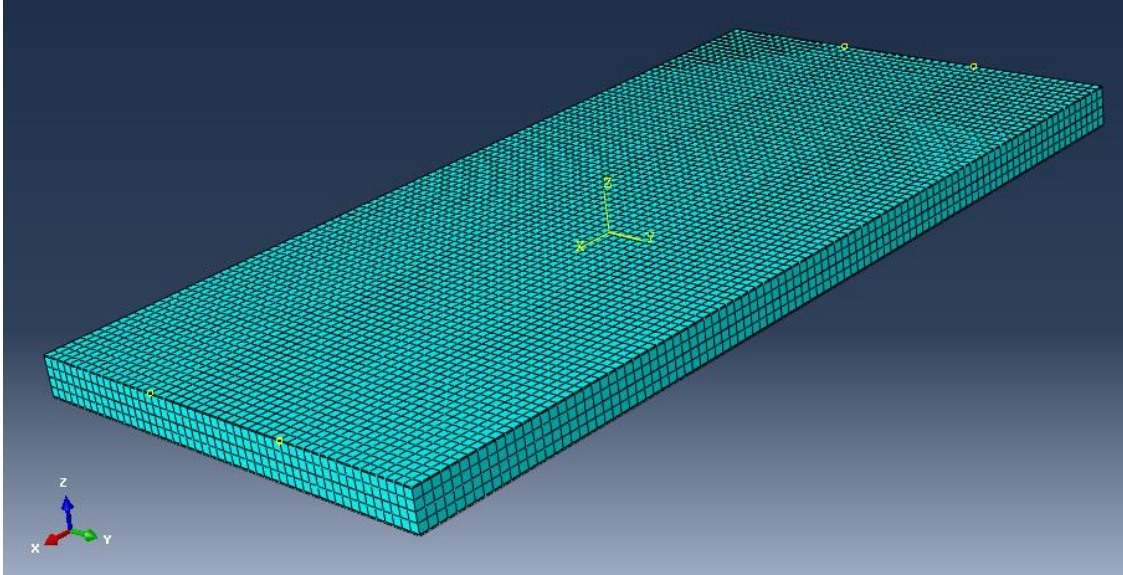


Figure 27. Meshing of the panel in Abaqus using 1" (25.4 mm) C3D8 elements.

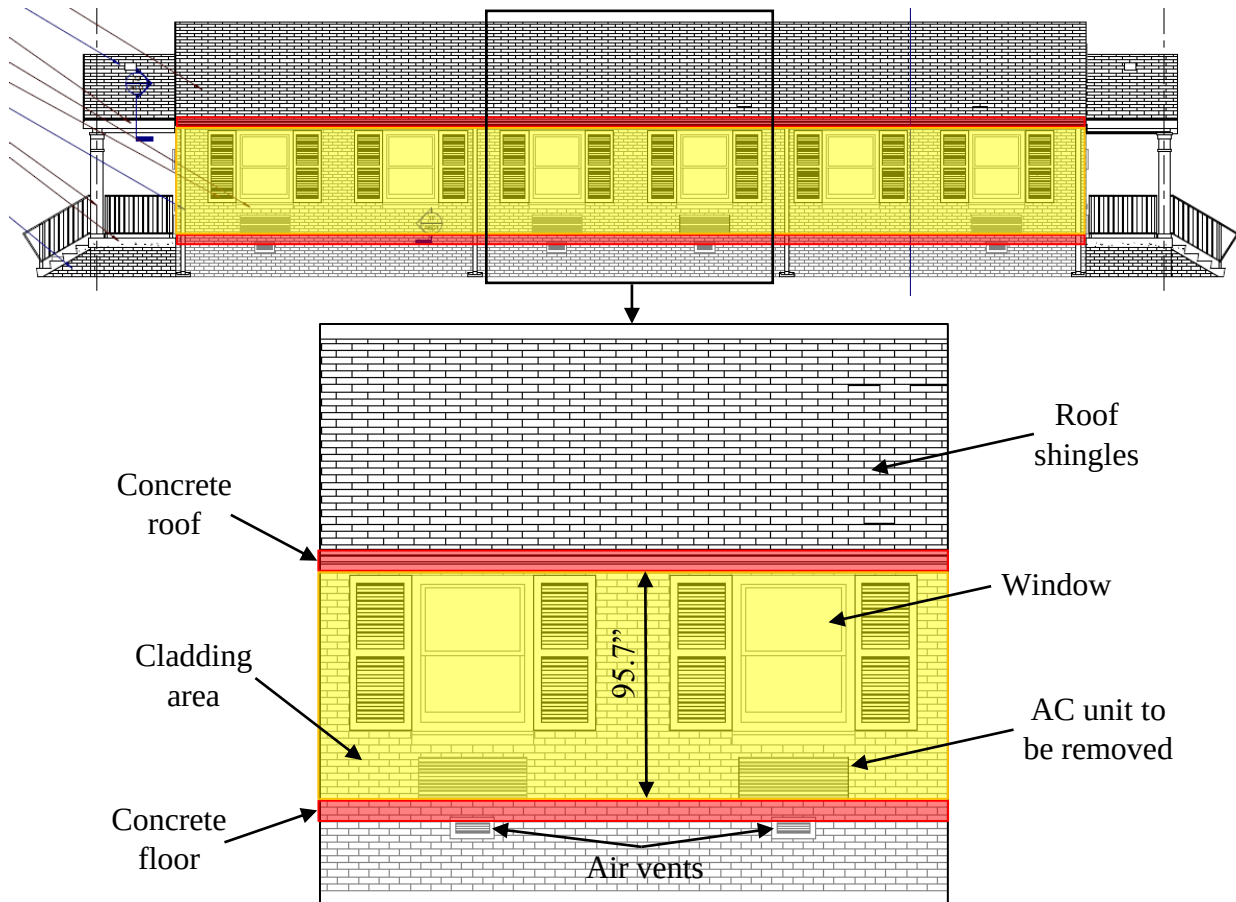


Figure 28. Side view drawing of a Western Heights duplex showing the location of the concrete slabs (red) and the area to be insulated with cladding panels (yellow).

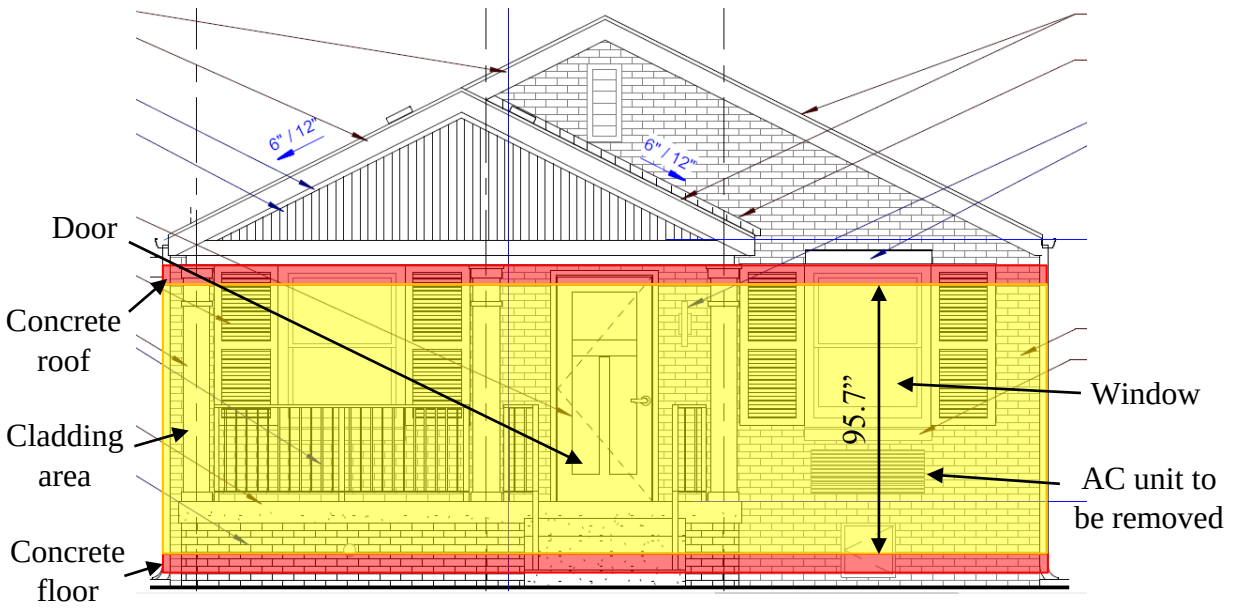


Figure 29. Front and back view drawing of a Western Heights duplex in Knoxville, TN showing the location of the concrete slabs (red) and the area to be insulated with cladding panels (yellow).

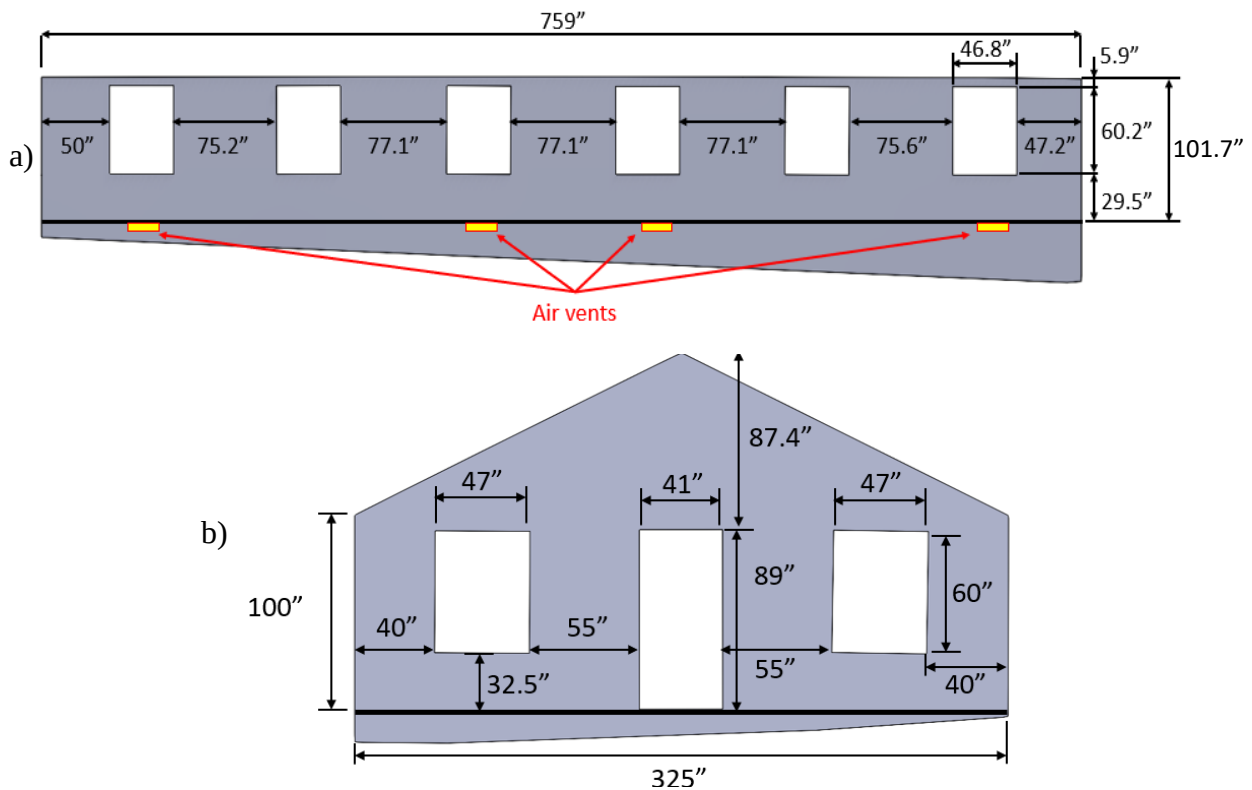


Figure 30. a) Side view and b) front and back view dimensions for a Western Heights duplex in Knoxville, TN.

The lower edge of the panels was therefore taken as the upper edge of the air vents. The RC floor had the same lower edge. Multiple requirements were taken into consideration while coming up with a design concept for installing the panels on the existing structure:

- Panels should be able to withstand wind loads and their dimensions should be chosen accordingly.
- Panel-to-panel connections should prevent water and air infiltration.
- Panel-to-wall connections should present adequate structural performance as supports.
- A 1.5” (38.1 mm) drainage gap between the cladding panels and the existing walls should be present.
- The panels should contain openings at the exact locations of existing windows and doors.
- For maintenance purposes, each single panel should be detachable without removing adjacent panels.

Beside the mentioned requirements, manufacturing feasibility and fast installation on site were taken as key parameters. The connections were chosen to be made from the same GFRP material as the sandwich panels and manufactured using the VARTM process. Steel expansion bolts were used to fix the connections to the RC slabs.

3.2.3.4 Wind loads FEA simulation

After choosing a design concept for the sandwich structures and their connections, an FEA model was created using the academic version of Abaqus/CAE 6.12-1. The goal was to accurately simulate the behavior of the panels and connections under wind loads. Firstly, wind loads were calculated based on the International Building Code (IBC) and American Society of Civil Engineers (ASCE) standards. Then, the biggest cladding panel and its connection supports

were designed on Abaqus while subjected to wind, gravity, and snow loads. 3 load combinations, having safety factors specified by the ASCE standard, were used. The panel was 123.9" (314.71 cm) long, 101.7" (258.32 cm) high, and 4.24" (107.44 mm) thick (4" XPS foam and 0.24" GFRP skins). It also contained a 46.8" x 60.2" (118.87 cm x 152.91 cm) opening for the window frame. The same material properties as *Section 3.2.3.2.2* were used (Table 11). The modeling parameters are given in Table 13. The bonding between the different layers in the sandwich structure was modeled as "Rough" tangential behavior and "Hard" normal behavior. These interaction properties were used because there was no slippage nor separation between layers. Fixed boundary conditions were created where the bolts will be inserted into the RC slabs. No displacements "U" nor rotations "UR" were allowed in any direction. Pinned boundary conditions were defined for contact surface between panel and brackets. No displacements "U" were allowed in any direction. Linear, 3D stress, tetrahedron elements (C3D4) were used for FEA. The panel deflection and strength were checked and compared to the allowable values given by the IBC. Finally, the connections and bolts were designed, and their dimensions were chosen based on the FEA simulation results.

3.2.3.5 UV/moisture testing

Atlas Ci3000+ xenon arc weather-ometer (Figure 31) was used to test GFRP samples under accelerated environmental effects (UV and moisture) after 500 hours and 1000 hours of exposure. The machine uses a xenon arc lamp, maintains temperature and relative humidity, and can spray specimens from the front, the back, and both at the same time. Test standards ASTM G155 and ASTM D2565 were followed and the parameters of the testing cycle ASTM D2565-1A were used, as shown in Table 14. The GFRP samples were 2.5" (63.5 mm) long, 1.5" (38.1 mm) wide, and 0.188" (4.76 mm) thick. 6 unpainted samples were tested in the first stage.

Table 13. Modeling parameters used in Abaqus for wind loads simulation and connections design.

Modeling parameter	Description
Interaction between layers	“Rough” tangential behavior and “Hard” normal behavior for all interfaces (GFRP/XPS and XPS/XPS).
Boundary conditions	- Fixed point supports at the bolts locations ($U_x = U_y = U_z = 0$ and $UR_x = UR_y = UR_z = 0$). - Pinned surface supports at the contact area between panel and brackets ($U_x = U_y = U_z = 0$).
Loads	- Wind: calculated from IBC and ASCE standards (<i>Section 4.3.4.1</i>). - Gravity: weight of the panel and connections distributed uniformly along their volumes. - Snow: calculated based on a height of 6” (152.4 mm) above the panel.
Load combinations (ASCE-7)	(a) 1.4D. (b) 1.2D + 0.5W + 1.6S. (c) 1.2D + 1.0W + 0.5S. D: dead loads; W: wind loads; S: snow loads.
Meshing	Linear, 3D stress, tetrahedron elements (C3D4).



Figure 31. Atlas Ci3000+ xenon arc weather-ometer.

Table 14. Parameters of the testing cycle ASTM D2565-1A.

Parameter	Phase 1	Phase 2
Duration - minutes	102	18
Irradiance - W/(m ² . nm)	0.35	0.35
Wavelength - nm	340	340
Black Panel Temperature - °F (°C)	145.4 (63)	145.4 (63)
Air Temperature - °F (°C)	116.6 (47)	116.6 (47)
Relative Humidity	50%	Not controlled
Light	Yes	Yes
Specimen Spray	No	Yes

The second stage testing was conducted on another 6 samples painted with Cerakote's ceramic coating. Figure 32 shows the setup of the tested specimens. SEM was then employed to study the effects of exposure on both types of samples. Hitachi TM3030 tabletop microscope was used for this purpose.

3.2.3.6 Fire simulation

A fire simulation was conducted using PyroSim (version 6.7.5), a graphical user interface for the Fire Dynamics Simulator (FDS) developed by the National Institute of Standards and Technology (NIST). The goal was to get preliminary results before testing the panel according to the ASTM E84 standard. The modeled sandwich panel was 24' (731.5 cm) long, 2' (61 cm) wide and 4.24" (107.7 mm) thick. A cartesian mesh with 1.8" (45.7 mm) elements was used. The burner had a surface of 26 in² (167.7 cm²) and methane was used with a heat release of 64,905.5 lb.ft/s (88 KW). 2 vents, for air intake and exhaust, were modeled. The fire simulation time, as dictated by the standard, was 10 minutes. The materials' properties used in the model are given in Table 15.

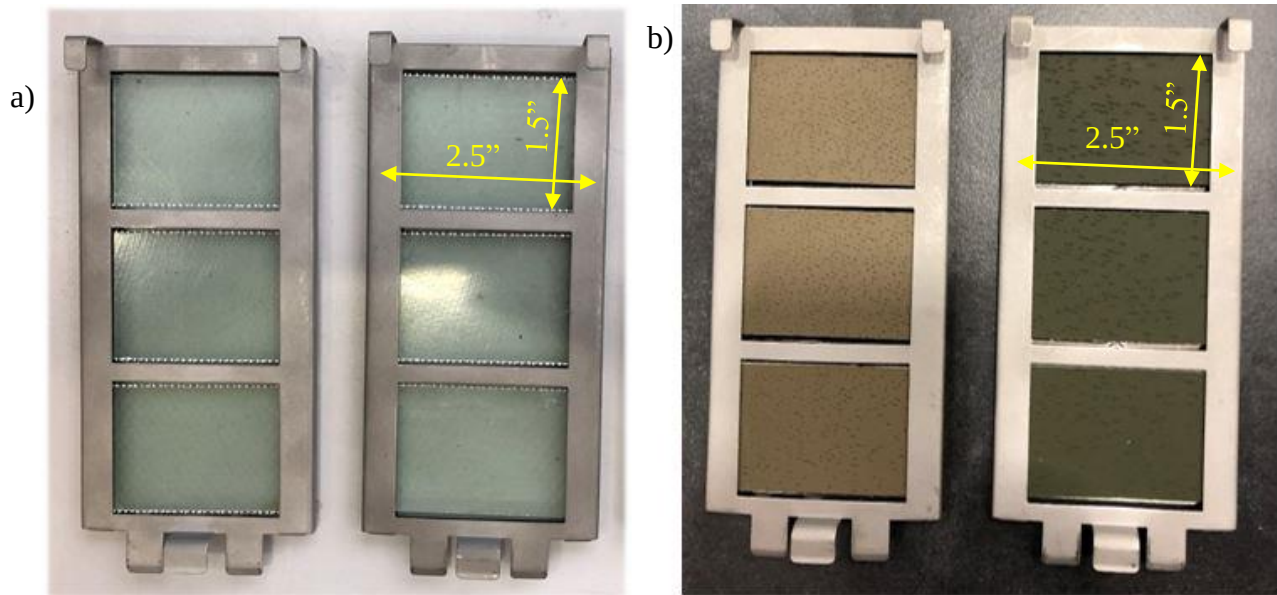


Figure 32. GFRP samples setup for accelerated environmental testing: a) unpainted for stage 1 and b) painted with Cerakote's coyote tan (left) and Cerakote's o.d. green (right) for stage 2.

Table 15. Materials' properties used as input parameters for the fire simulation.

Material property	GFRP	XPS
Density - lb/ft ³ (Kg/m ³)	99.37 (1591.8)	2.044 (32.7)
Specific heat, c_p - Btu/(lb.°F) (J/g.K)	0.239 (1)	0.955 (4)
Thermal conductivity, λ - Btu/(h.ft.°F) (W/m.K)	0.058 (0.1)	0.024 (0.042)
Emissivity	0.9	0.9
Absorption coefficient - 1/ft (1/m)	0.0001524 (0.00322)	0.0001524 (0.00322)

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Vacuum assisted resin transfer molding (VARTM)

The VARTM manufacturing process was used to make all the panels in this study. Different types of infused panels are illustrated in Figure 33, while their weight and resin content are given in Table 16. The resin content by weight is consistent (between 31.0% and 36.3%) for panels having a maximum of 1 GFRP joint. The GFRP plate also gave a similar resin content (33%). However, this percentage increased for the Prisma panel having 3 joints (39.4%). This could be partially caused by the stitched fiberglass layer that was already attached to the PU foam, which absorbed more resin than the added layers of woven fiberglass. In addition, the 3 joints don't have a perfectly straight interface, causing some small gaps to form inside them, which resulted in absorbing more resin to fill the voids.

The densities of 1' x 1' x 1.24" (304.8 mm x 304.8 mm x 31.5 mm) XPS and Prisma sandwich panels were compared according to ASTM C271. The results are given in

Figure 34. The XPS sandwich structure had a lower density than the Prisma panel (2.14 lb/ft² (14.1 Kg/m²) compared to 2.89 lb/ft² (10.4 Kg/m²), respectively). The Prisma sample was 35% heavier due to the presence of 3 inclined GFRP joints. The joints were necessary in order to make a 1' x 1' (304.8 mm x 304.8 mm) Prisma panel due to the geometry of the beams having a 4" (101.6 mm) width. One of the requirements of this project is a lightweight structure, and the XPS panel performed better in this category.

According to literature studies that employed the VARTM technique as an industrial process, the resin should constitute 30%-40% of the weight of the finished part [80, 81]. Therefore, the manufactured composite panels in this work showed acceptable results.

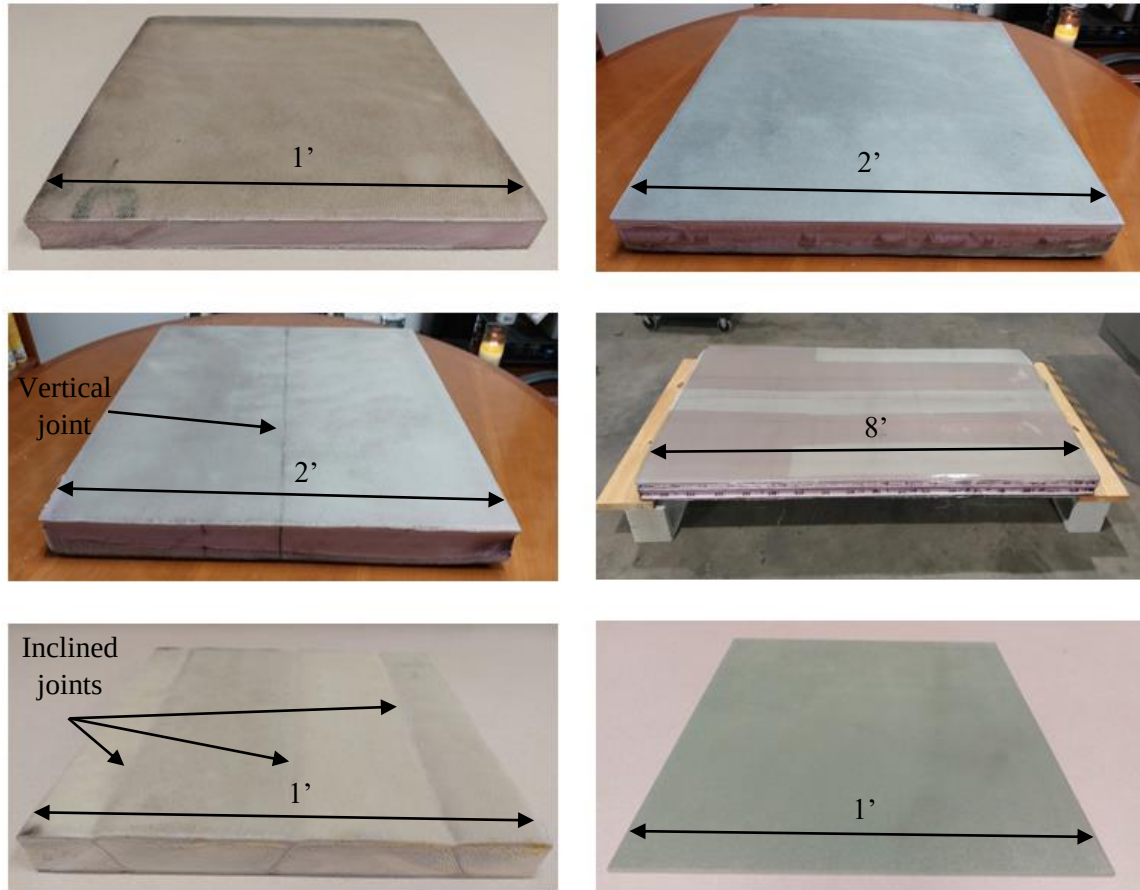


Figure 33. Different types of panels manufactured using the VARTM process: a) GFRP + 1'' XPS with no joints (1x1 ft²), b) GFRP + 2'' XPS with no joints (2x2 ft²), c) GFRP + 2'' XPS with a vertical joint (2x2 ft²), d) GFRP + 4'' XPS with no joints (4x8 ft²), e) GFRP + 1'' Prisma beams (3 inclined joints between beams) (1x1 ft²), and f) GFRP (4 layers) (1x1 ft²).

Table 16. Weight and resin content of different panels manufactured using the VARTM process.

Panel type	Dry weight - lb (Kg)	Total weight - lb (Kg)	Resin content by weight - %
GFRP + 1'' XPS with no joints (1x1 ft ²)	1.48 (0.67)	2.14 (0.97)	31.2
GFRP + 2'' XPS with no joints (2x2 ft ²)	6.31 (2.86)	9.15 (4.15)	31.2
GFRP + 2'' XPS with a vertical joint (2x2 ft ²)	6.4 (2.9)	9.26 (4.2)	31.0
GFRP + 4'' XPS with no joints (4x8 ft ²)	59.28 (26.89)	93 (42.18)	36.3
GFRP + 1'' Prisma beams (3 inclined joints between beams) (1x1 ft ²)	1.76 (0.8)	2.89 (1.31)	39.4
GFRP (4 layers) (1x1 ft ²)	0.66 (0.3)	0.99 (0.45)	33.0

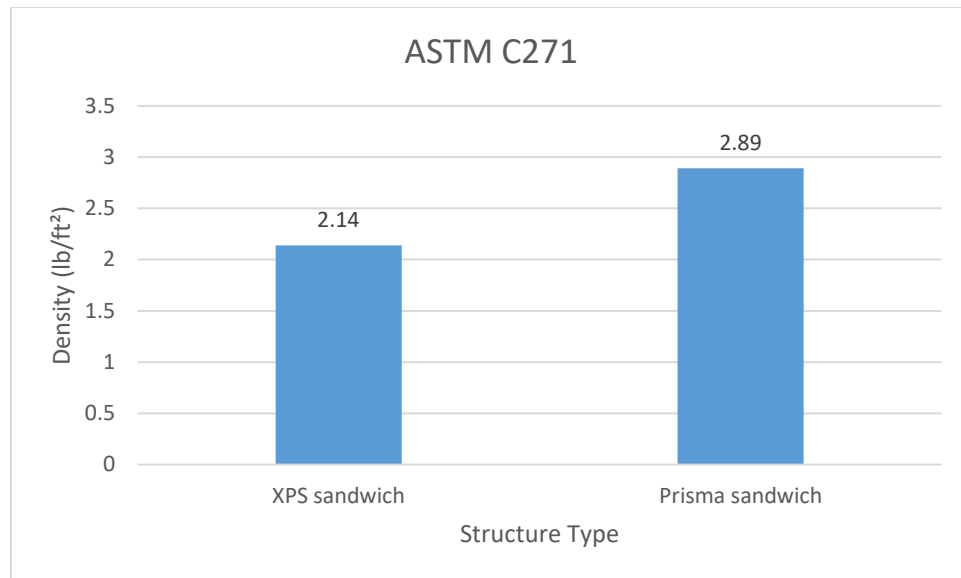


Figure 34. Density comparison between 1' x 1' x 1.24" (304.8 mm x 304.8 mm x 31.5 mm) XPS and Prisma sandwich structures according to ASTM C271.

4.2 Comparison between XPS and Prisma sandwich panels

4.2.1 Thermal testing

To better understand the thermal performance of both XPS and Prisma sandwich structures, multiple comparisons were made. Based on the ASTM C518 standard, the thermal conductivity (λ) of all materials was obtained. The R-value was therefore calculated using Equation 1:

$$(R\text{-value}) = \frac{1}{\lambda} \quad (\text{Equation 1})$$

In order to compare products, manufacturers of insulation materials provide the R-value at a mean temperature of 75 °F (24 °C) [82, 83]. In addition, for comparison purposes, the R-value per inch of material was used for all the charts in this section.

First of all, the thermal resistances per inch of the XPS foam board and GFRP plate were compared. As seen in Figure 35, the R-value/in. of XPS decreased by 8.8% from 5.13 to 4.68 h.ft².°F/Btu (0.9 to 0.82 K.m²/W) when the temperature increased from 50 to 100.4 °F (10 to 38 °C). In contrast, the R-value/in. of GFRP increased by 18.2% from 0.33 to 0.39 h.ft².°F/Btu (0.06 to 0.07 K.m²/W) for the same temperature variation. At a 75 °F (24 °C) mean temperature, XPS had an R-value/in of 4.9 h.ft².°F/Btu (0.86 K.m²/W), which is similar to the manufacturer's properties given in Table 6. This value was 1,189% higher than the 0.38 h.ft².°F/Btu (0.07 K.m²/W) R-value/in of GFRP. This means that the XPS foam would provide most of the thermal resistance of any XPS/GFRP sandwich structure used in this project.

Secondly, the thermal resistances per inch of 2 types of 12" x 12" (304.8 mm x 304.8 mm) XPS sandwich panels were compared (Figure 36). The first type didn't contain any webs, while the second type had a GFRP web inside the XPS foam.

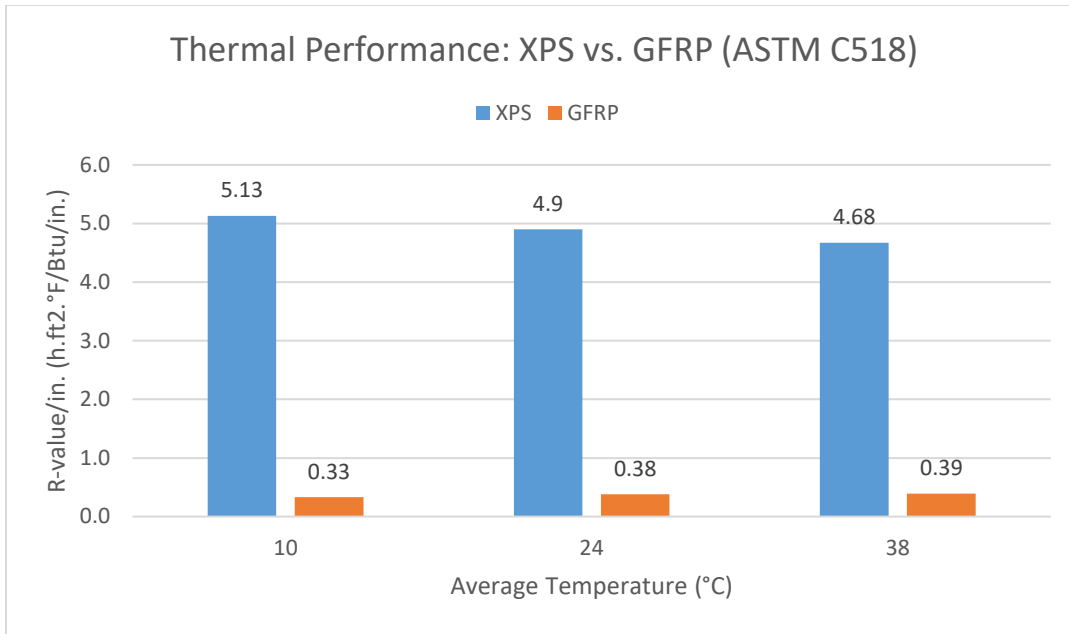


Figure 35. Comparison of R-value results between 12" x 12" XPS and GFRP panels according to ASTM C518.

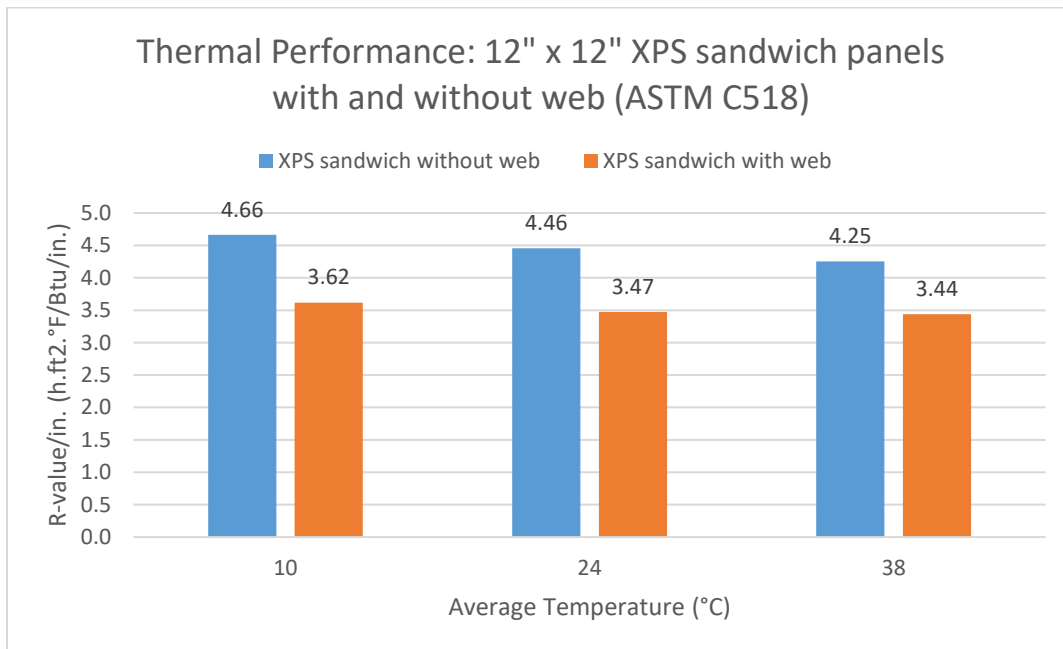


Figure 36. Comparison of R-value results between 12" x 12" XPS sandwich structures (with and without a vertical web) according to ASTM C518.

The R-value/in. of the sandwich with no webs decreased by 8.8% from 4.66 to 4.25 h.ft².°F/Btu (0.82 to 0.75 K.m²/W) when the temperature increased from 50 to 100.4 °F (10 to 38 °C). For the same temperature change, the R-value/in. of the sandwich with a GFRP web decreased by 5% from 3.62 to 3.44 h.ft².°F/Btu (0.64 to 0.61 K.m²/W). At a 75 °F (24 °C) mean temperature, the presence of the GFRP web changed the R-value/in. from 4.46 to 3.47 h.ft².°F/Btu (0.79 to 0.61 K.m²/W). This 22.2% decrease might be caused by the low thermal resistance of the GFRP material present inside the web. Thermal bridging could therefore be the result of heat transfer through the GFRP joint [84, 85].

Thirdly, the thermal resistances per inch of 12" x 12" (304.8 mm x 304.8 mm) XPS and Prisma sandwich panels were compared (Figure 37). The Prisma sandwich structure had 3 GFRP webs due to the dimensions of the Prisma beams used to make the panel. The XPS sandwich structure had no webs because XPS foam boards are commercially available in 4' x 8' (121.92 cm x 243.84 cm) dimensions. As previously mentioned, the R-value/in. of the XPS sandwich panel decreased by 8.8% when the temperature increased from 50 to 100.4 °F (10 to 38 °C). The R-value/in. of the Prisma sandwich panel decreased by 4.5% from 3.79 to 3.62 h.ft².°F/Btu (0.67 to 0.64 K.m²/W) for the same temperature variation. At a 75 °F (24 °C) mean temperature, the Prisma panel had an R-value/in of 3.66 h.ft².°F/Btu (0.64 K.m²/W), which is 17.9% lower than the 4.46 h.ft².°F/Btu (0.79 K.m²/W) R-value/in of the XPS panel. As previously discussed in *Sections 2.2.3 and 2.2.4*, PU foam has a thermal resistance of 6-7.8 hr.ft².°F/Btu (1.06-1.3 K.m²/W) per inch of material [64]. XPS foam has a thermal resistance of 5 hr.ft².°F/Btu (0.88 K.m²/W) per inch [58], which is 16.7% less than the lowest value of PU. However, in terms of sandwich structures, XPS performed better as an insulation core material. Similarly to Figure 36, the results might be caused by thermal bridging inside the 3 GFRP webs present in the PU foam core.

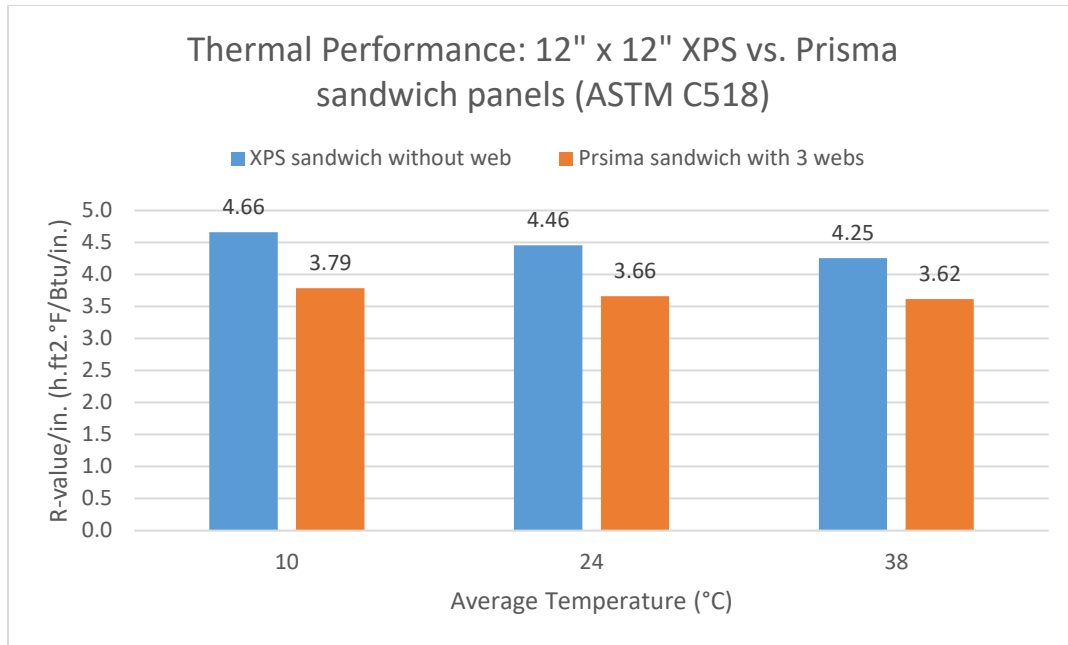


Figure 37. Comparison of R-value results between 12" x 12" XPS and Prisma sandwich structures according to ASTM C518.

Finally, because of the superior thermal properties of the XPS sandwich structure, another comparison was made to better understand the influence of the panel size on the thermal resistance. Figure 38 compares the thermal resistances per inch of 2 types of 24" x 24" (609.6 mm x 609.6 mm) XPS sandwich panels. The first type didn't contain any webs, while the second type had a GFRP web inside the XPS foam. At a 75 °F (24 °C) mean temperature, the presence of the GFRP web changed the R-value/in. from 4.58 to 4.19 h.ft².°F/Btu (0.81 to 0.74 K.m²/W). Like the previous cases, this 8.5% decrease might be caused by thermal bridging inside the GFRP web. Another important observation was that the R-value/in. increased when the panel dimensions increased. For the 12" x 12" (304.8 mm x 304.8 mm) XPS sandwich structures, the thermal resistance per inch was 4.46 and 3.47 h.ft².°F/Btu (0.79 and 0.61 K.m²/W) for the panel without webs and the panel with a GFRP web, respectively. For the 24" x 24" (609.6 mm x 609.6 mm) XPS sandwich structures, the R-values/in. increased by 2.7% and 20.7% for the panel without webs and the panel with a GFRP web, respectively. The increased thermal resistance might indicate that less thermal bridging was occurring around the edges of the panels. For that reason, bigger panels, with a lower number of joints, are favorable in order to obtain a more uniformly distributed thermal resistance across the cladding area.

The specific heat capacity (c_p) represents the needed amount of heat to raise the temperature of 0.0022 lb (1 g) of material by 32 °F (1 °C) [86]. Figure 39 gives the Specific Heat Capacity vs. Temperature plots for both XPS and GFRP materials according to ASTM E1269. The temperature varied from 86 to 140 °F (30 to 60 °C). Within these limits, c_p of XPS increased by 16.4% from 0.85 to 0.99 BTU/(lb.°F) (3.57 to 4.16 J/(g.°C)). For GFRP, c_p increased by 24.5% from 0.24 to 0.3 BTU/(lb.°F) (1.02 to 1.27 J/(g.°C)). XPS had a 228-255% higher specific heat capacity than GFRP, which is consistent with the fact that XPS is the better insulation material.

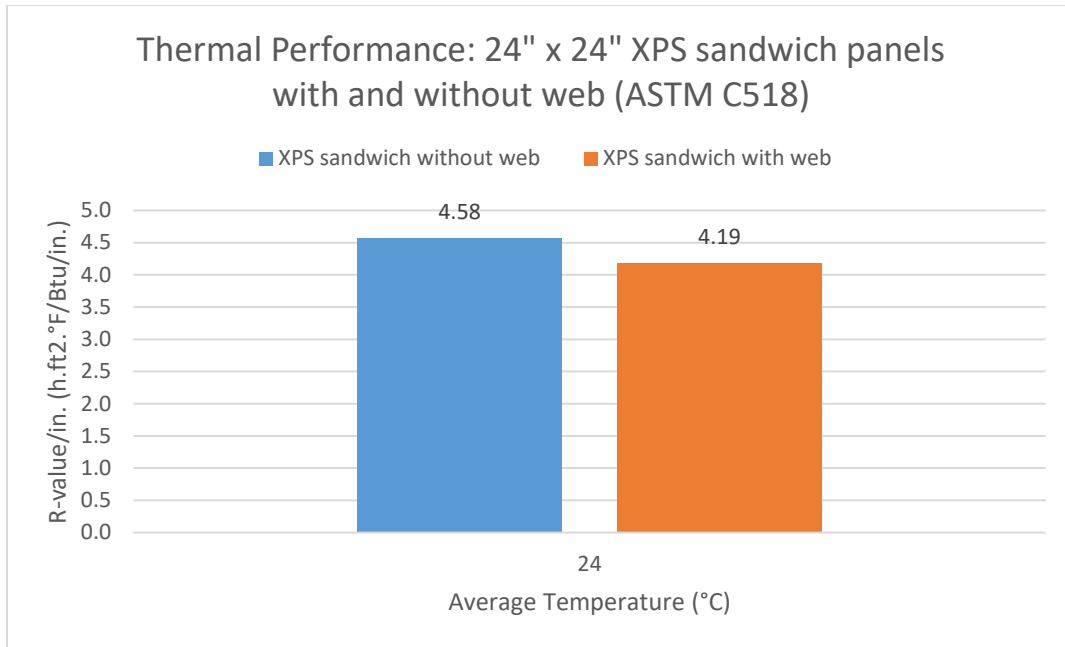


Figure 38. Comparison of R-value results between 24" x 24" XPS sandwich structures (with and without a vertical web) according to ASTM C518.

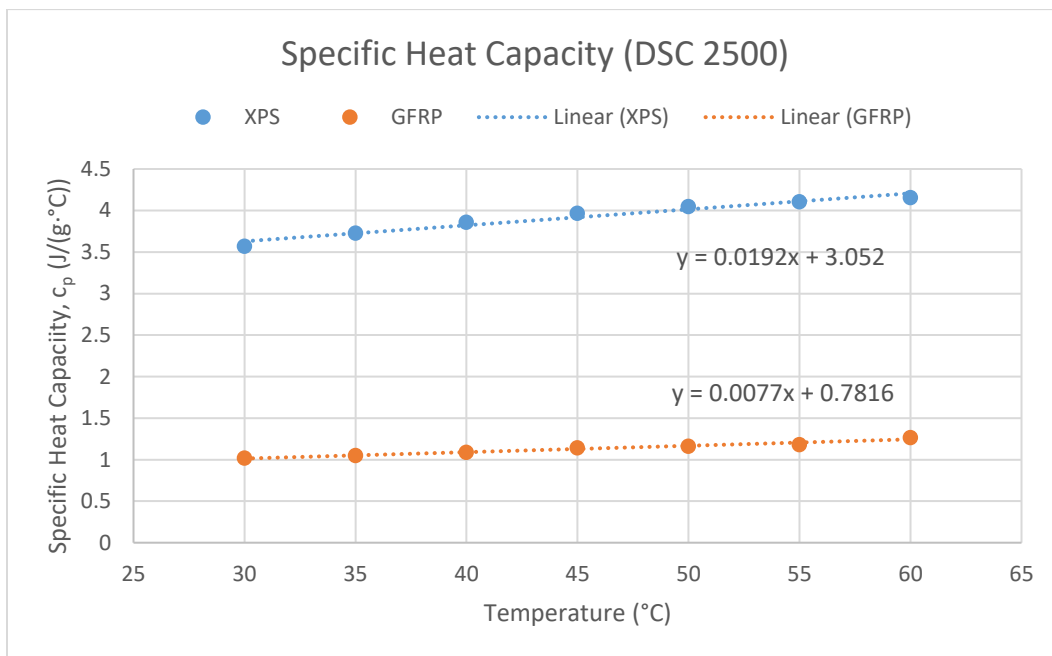


Figure 39. Specific Heat Capacity vs. Temperature plots for both XPS and GFRP materials according to ASTM E1269.

Finally, specific heat capacity results, along with thermal conductivity results, were used as input parameters while conducting a fire simulation in *Section 3.2.3.6*.

4.2.2 Long beam flexure (LBF)

This test investigated and compared the mechanical behaviors and failure mechanisms of the two types of sandwich structures under a 3-point bending test. Figure 40 and Figure 41 illustrate the failure of the sandwich samples, while Figure 42 and Figure 43 show the load vs displacement plots for all the tested samples.

The XPS sandwich structures showed two types of failure modes. The first type of failure started with a delamination of the lower facesheet, followed by a transverse shear crack through the foam core, and ended with a second delamination of the upper facesheet. The first delamination started occurring under a 1,573.66 lbf (7 KN) load and after a 0.28” (7 mm) displacement. The brittle failure was seen when the shear crack and second delamination happened after the sample deflected another 0.04” (1 mm). This type of failure happened in samples XPS 1 and XPS 2, which were located in the center of the infused panel (Figure 44). The second type of failure was the cracking of the web and occurred under a 1438.78 lbf (6.4 KN) load and a 0.24” (6 mm) displacement. Unlike the first type, no delamination or shear cracks were observed and the load vs. displacement curves show a brittle failure. The second type of failure happened in samples XPS 3 and XPS 4 which were located on the edges of the infused panel (Figure 44). Although the failure modes were different, all samples showed an elastic modulus of 25,918.24 psi (0.179 GPa) (Figure 45).

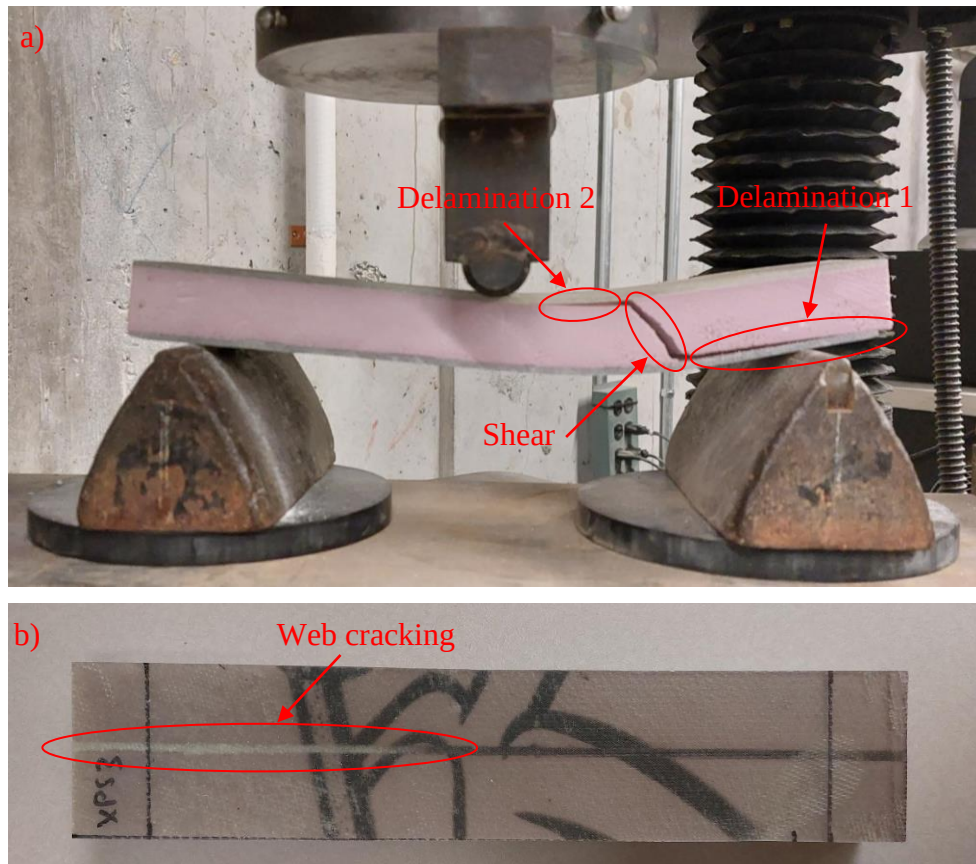


Figure 40. Failure mechanisms of the XPS sandwich under a 3-point bending test (ASTM D7249): a) delamination and shear failure and b) web cracking failure.

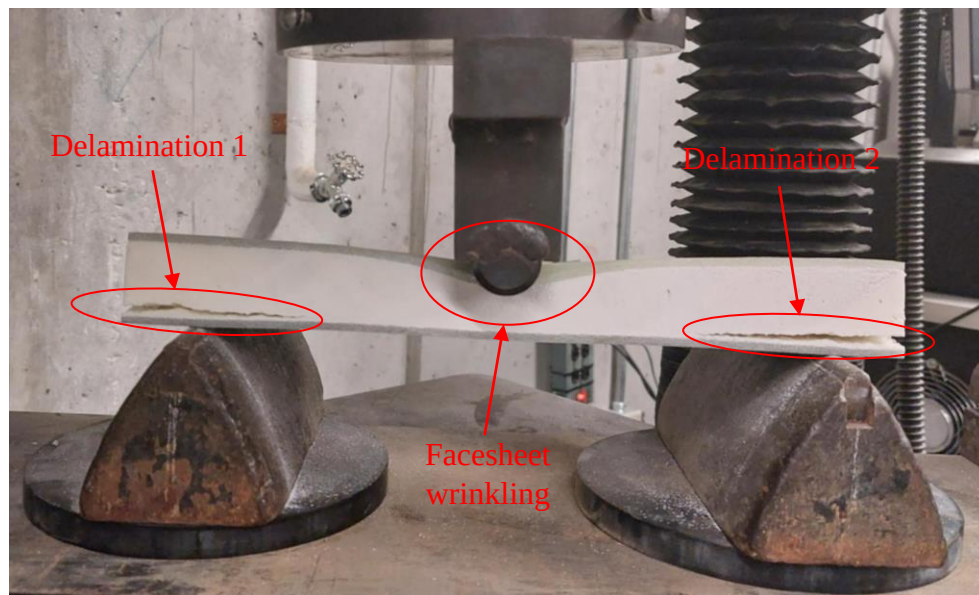


Figure 41. Failure mechanisms of the Prisma sandwich under a 3-point bending test (ASTM D7249).

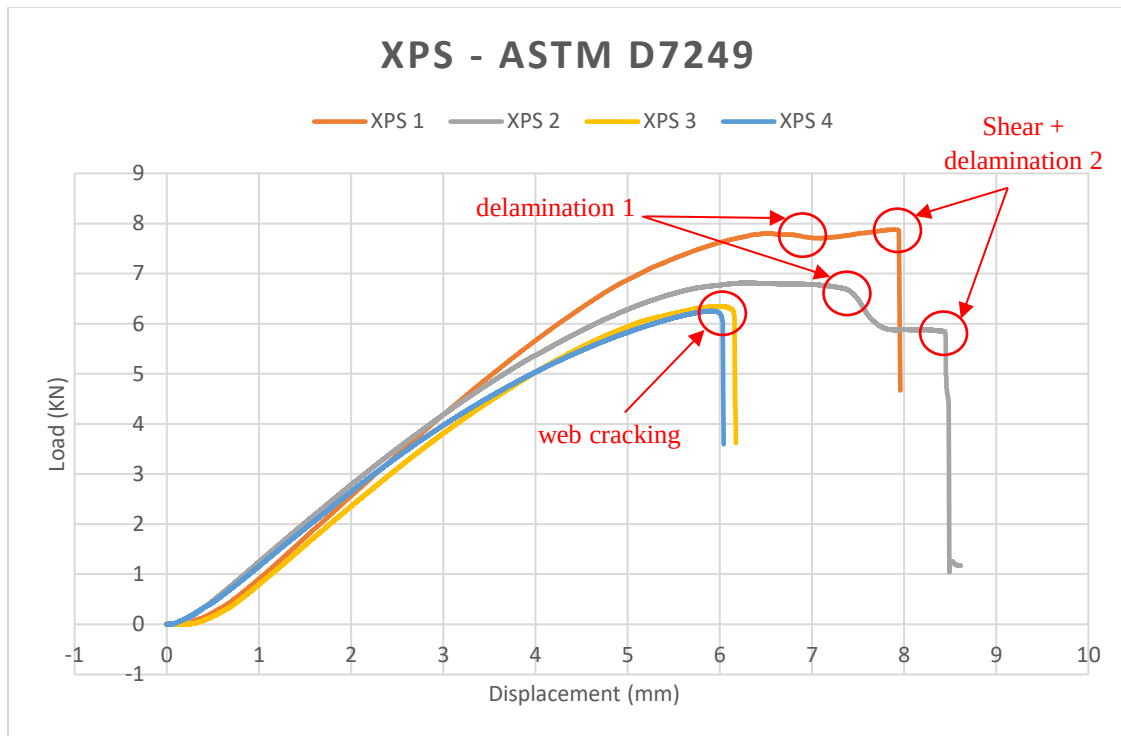


Figure 42. Load vs. Displacement curves of the XPS sandwich samples under a 3-point bending test (ASTM D7249).

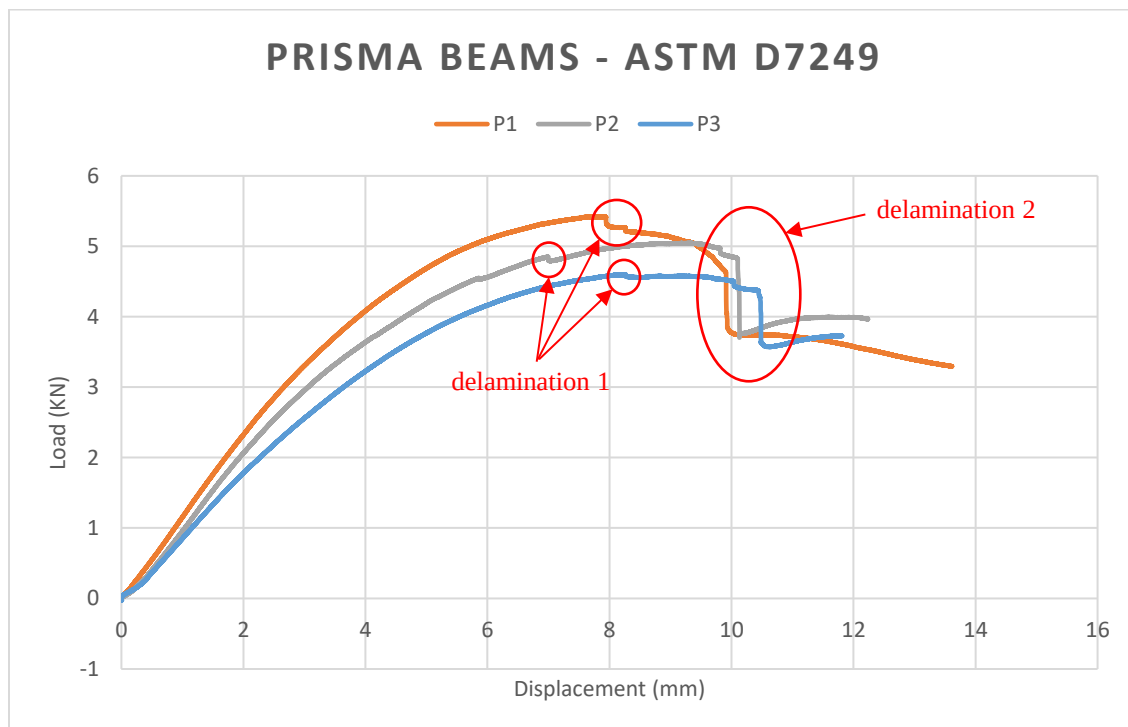


Figure 43. Load vs. Displacement curves of the Prisma sandwich samples under a 3-point bending test (ASTM D7249).

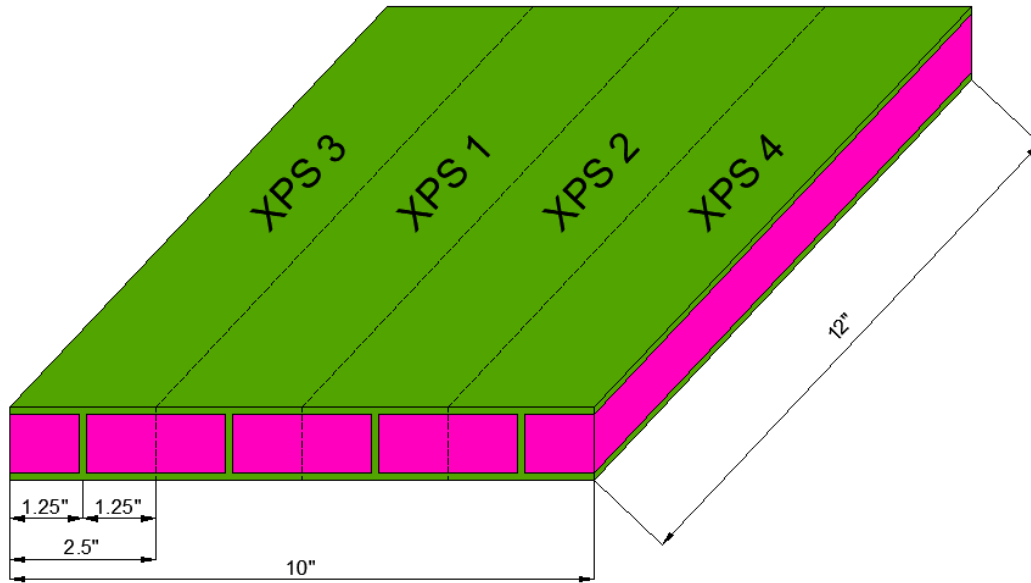


Figure 44. Location of the XPS samples inside the infused panel.

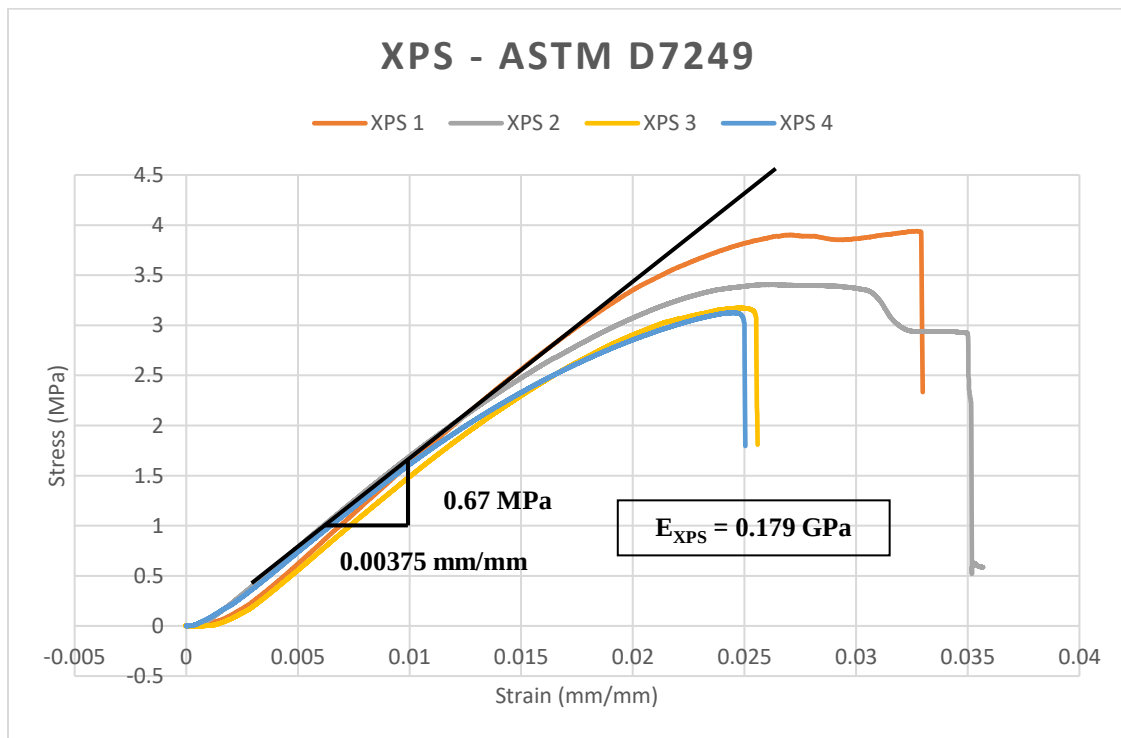


Figure 45. Stress vs. Strain curves and average elastic modulus of the XPS sandwich samples (ASTM D7249).

The Prisma sandwich structures showed more consistency by exhibiting similar failure modes. A first delamination started showing on one edge of the bottom facesheet under a 1,124.04 lbf (5 KN) load and a 0.3” (7.5 mm) displacement. The samples deflected another 0.08” (2 mm) before dropping by 224.81 lbf (1 KN) due to a second delamination in the second edge of the bottom facesheet. Despite a 20% loss in force, the samples showed ductile behavior and continued to deflect until the test was stopped. The average elastic modulus was 18,028.19 psi (0.124 GPa) (Figure 46). Unlike the XPS samples, upper facesheet wrinkling was also observed.

The location of the XPS samples within the infused panel played an important role in determining their failure type. Unlike the edge samples, the center samples didn’t experience a cracked web, which could be due to a better web-to-foam bond. The edge samples are more prone to movement while laying the material for the VARTM process, which might have led to a weaker bond between GFRP web and foam core. This conclusion was also based on the behavior of the Prisma samples, which didn’t experience a web cracking failure. This is due to the glass fabric being already attached to the PU foam, which resulted in a better web-to-core bonding than the other sandwich type. The top facesheet wrinkling of the Prisma panel was caused by 2 factors: the nature of the foam and the properties of the GFRP web. In fact, the Prisma samples’ web was inclined and well bonded to the core. As a result, it became very rigid and the bottom facesheet stayed flat throughout the test. In contrast, both facesheets of the XPS samples had a curved shape during the test. The GFRP web in these samples was therefore flexible, which prevented the top facesheet from wrinkling. As mentioned earlier, the nature of the PU foam also played a role in obtaining facecheet wrinkling without observing any transverse shear cracks. SEM images of XPS and PU foams are shown in Figure 47 and Figure 48, respectively. Even though both foams are closed-cell, PU is more porous than XPS. These pores closed under the load, which made the material more ductile.

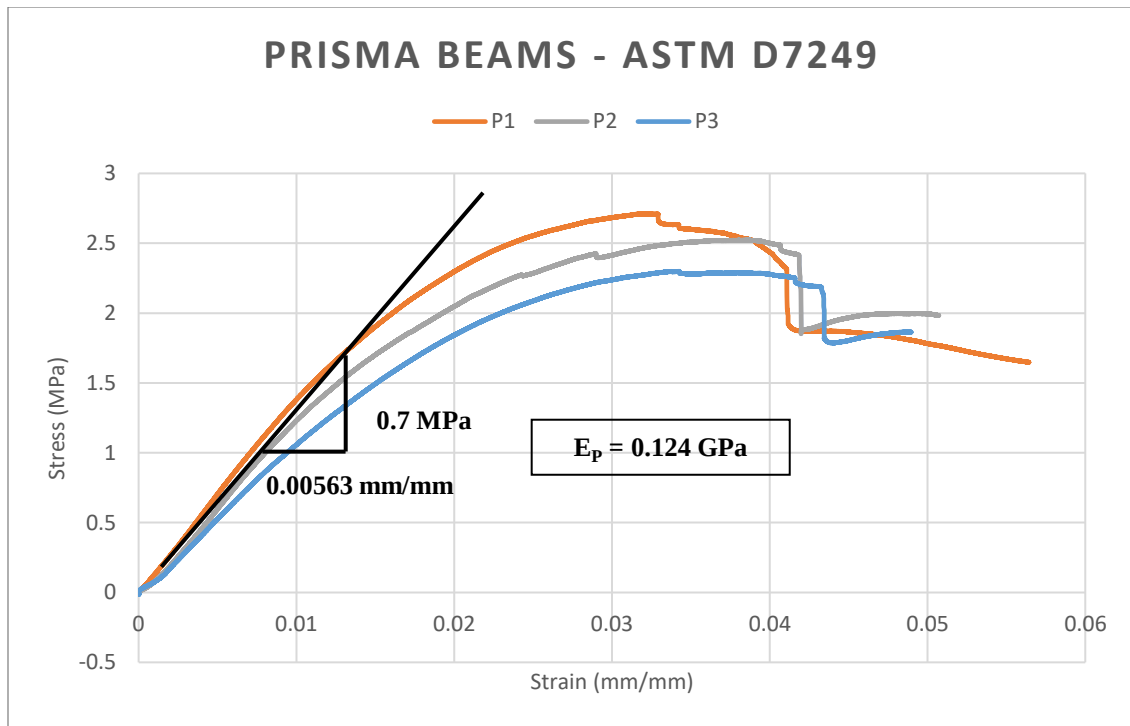


Figure 46. Stress vs. Strain curves and average elastic modulus of the Prisma sandwich samples (ASTM D7249).

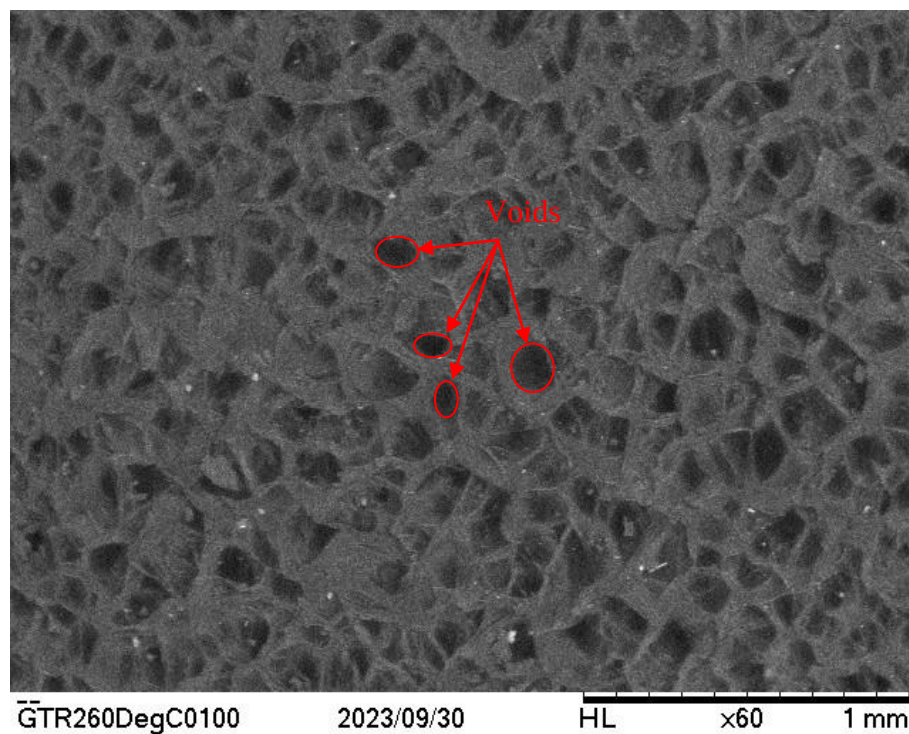


Figure 47. SEM image of closed-cell XPS foam.

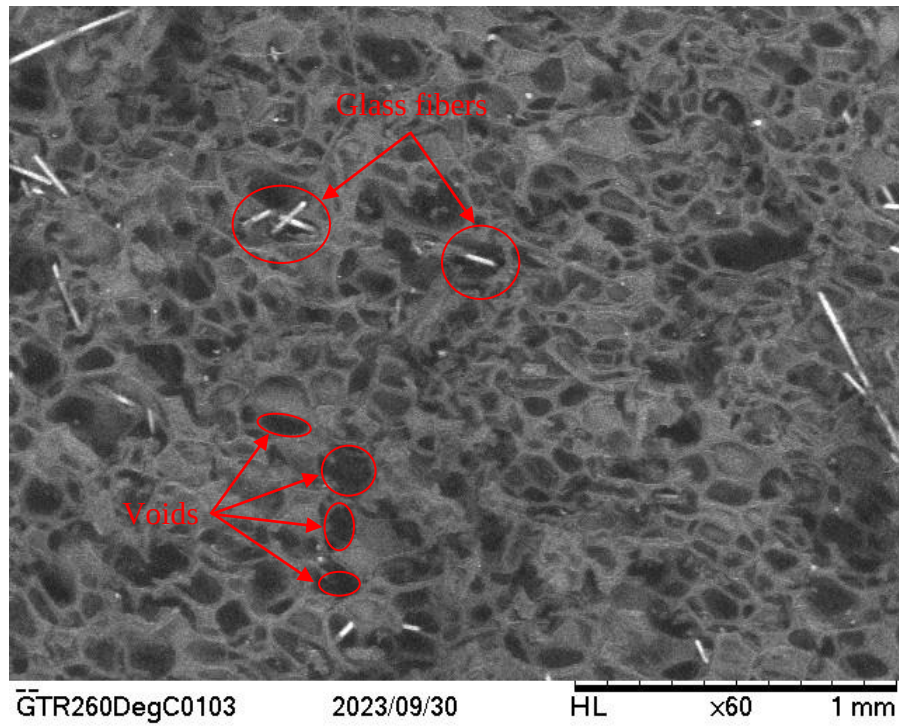


Figure 48. SEM image of closed-cell PU foam.

Similarly, the lower void content of XPS contributed in creating a path for shear stresses after the closing of pores, which created a shear crack along the thickness of the core. Finally, compared to the Prisma samples, the XPS samples had a 43.8% higher elastic modulus, 40% higher failure load (assuming the GFRP web did not fail prior to delamination), and a 15.8% lower displacement at the final load drop. In summary, although the XPS samples showed a brittle failure, they performed better under the quasi-static loading used in this test.

4.2.3 Short beam flexure (SBF)

This test investigated and compared the mechanical behaviors and failure mechanisms of the two types of sandwich structures under a 4-point bending test. Figure 49 and Figure 50 illustrate the failure of the sandwich samples, while Figure 51 and Figure 52 show the load vs displacement plots for all the tested samples.

It was seen that the top facesheet failed in compression in the XPS samples. The cracking occurred at the locations where the loading bars were applied. An average peak load of 584.5 lbf (2,600 N) was obtained and all samples showed a brittle failure after an average displacement of 0.55" (14 mm). Figure 53 shows the stress vs strain curves and the average elastic modulus for the XPS samples ($E_{XPS} = 3,625.94$ psi (0.025 GPa)).

The Prisma samples all failed by cracking of the bottom facesheet due to tensile stresses. They showed a ductile behavior and their load vs. displacement curves contain two clearly visible zones: elastic and plastic. The yield force (427.14 lbf (1,900 N) average) was reached after a 0.45" (11.5 mm) displacement. The samples deflected another 0.31" (8 mm) before reaching their failure load of 472.1 lbf (2,100 N). Figure 54 gives the stress vs. strain curves and the average elastic modulus for the Prisma samples ($E_P = 3,480.91$ psi (0.024 GPa)).

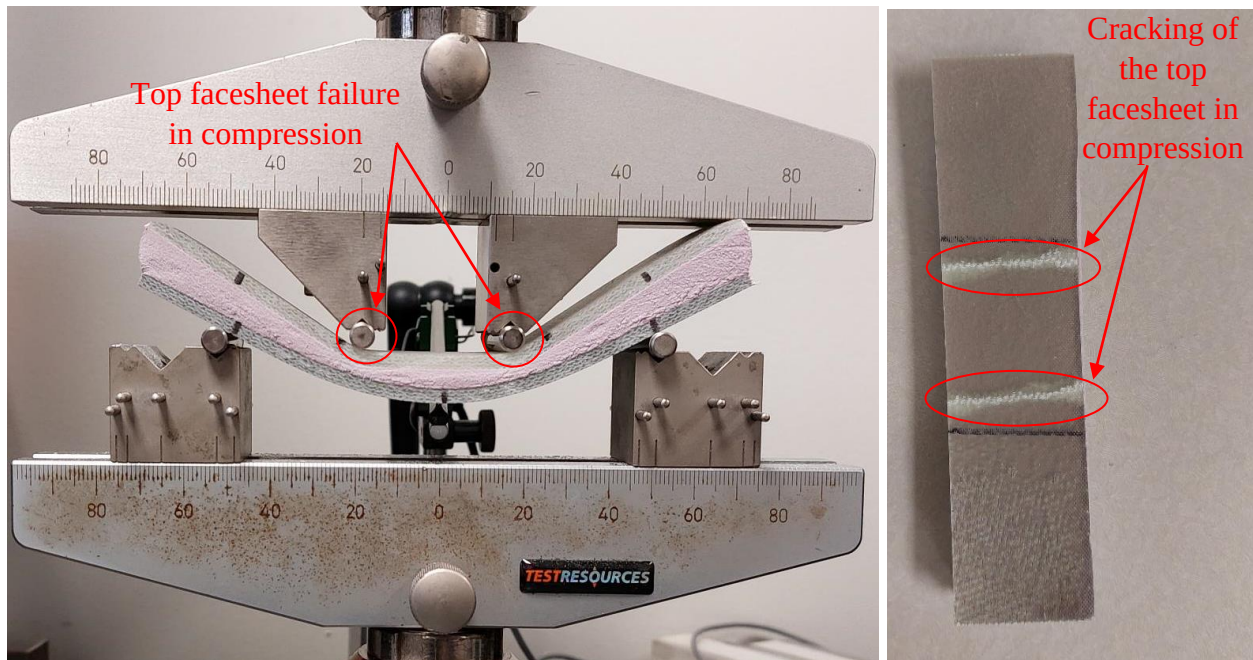


Figure 49. Failure in the top facesheet in compression of the XPS sandwich under a 4-point bending test (ASTM C393).

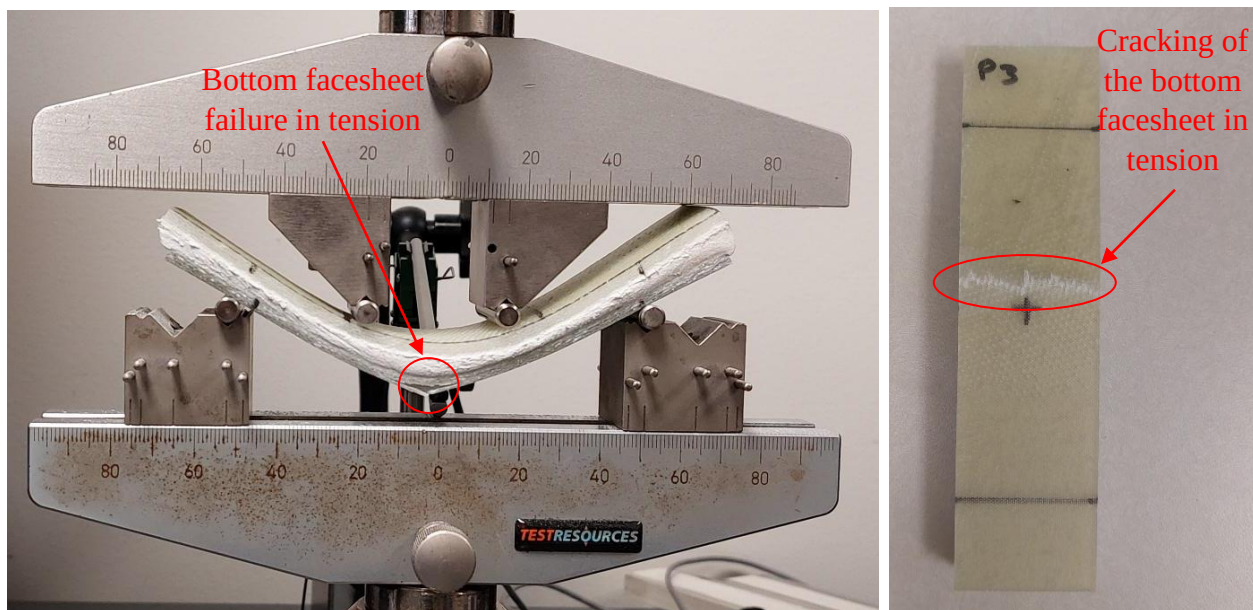


Figure 50. Failure in the bottom facesheet in tension of the Prisma sandwich under a 4-point bending test (ASTM C393).

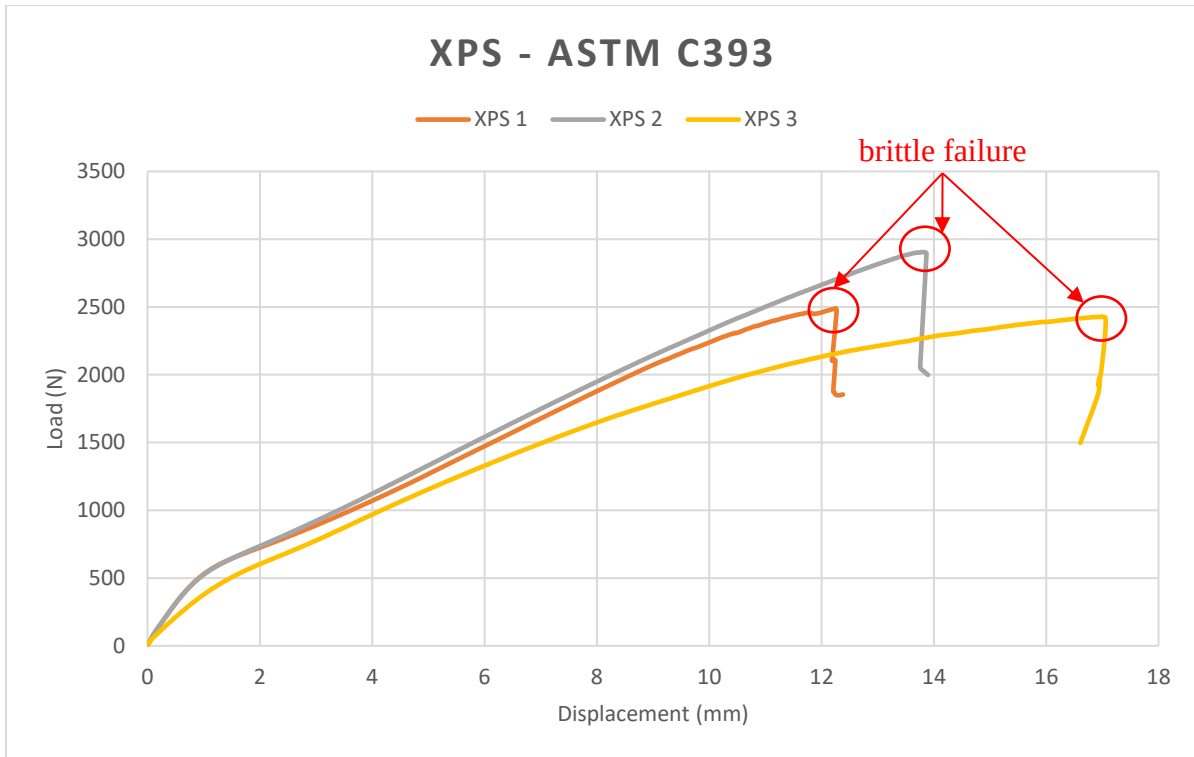


Figure 51. Load vs. Displacement curves of the XPS sandwich samples under a 4-point bending test (ASTM C393).

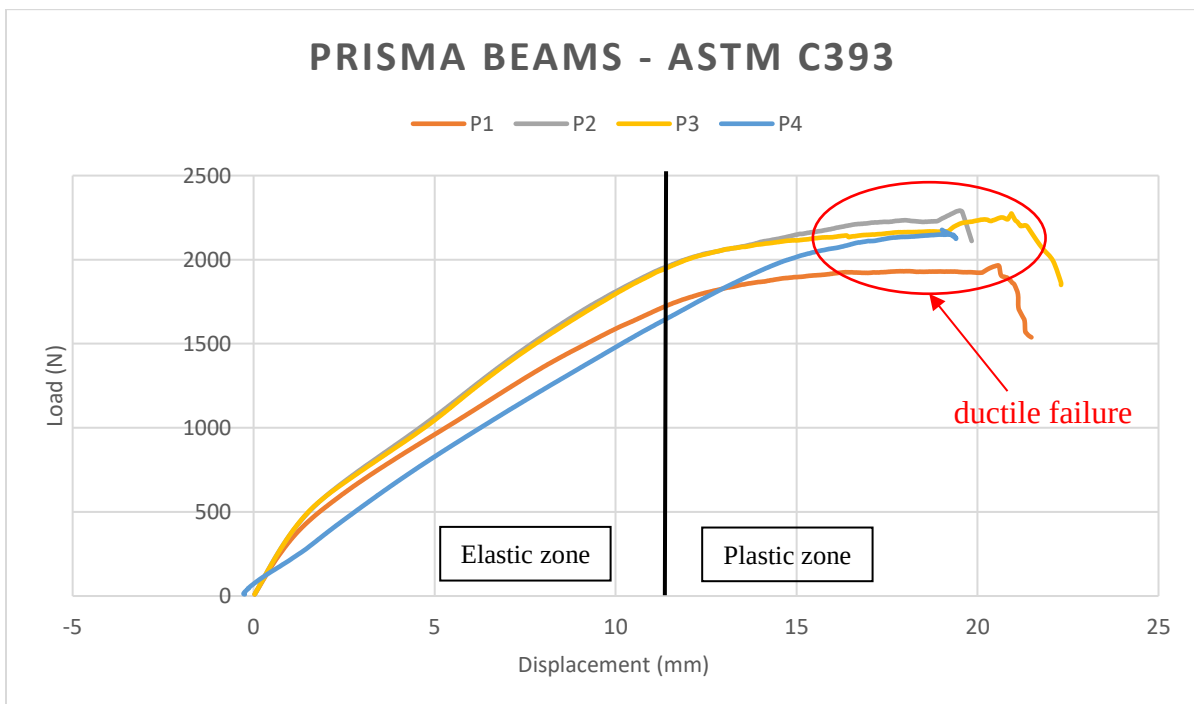


Figure 52. Load vs. Displacement curves of the Prisma sandwich samples under a 4-point bending test (ASTM C393).

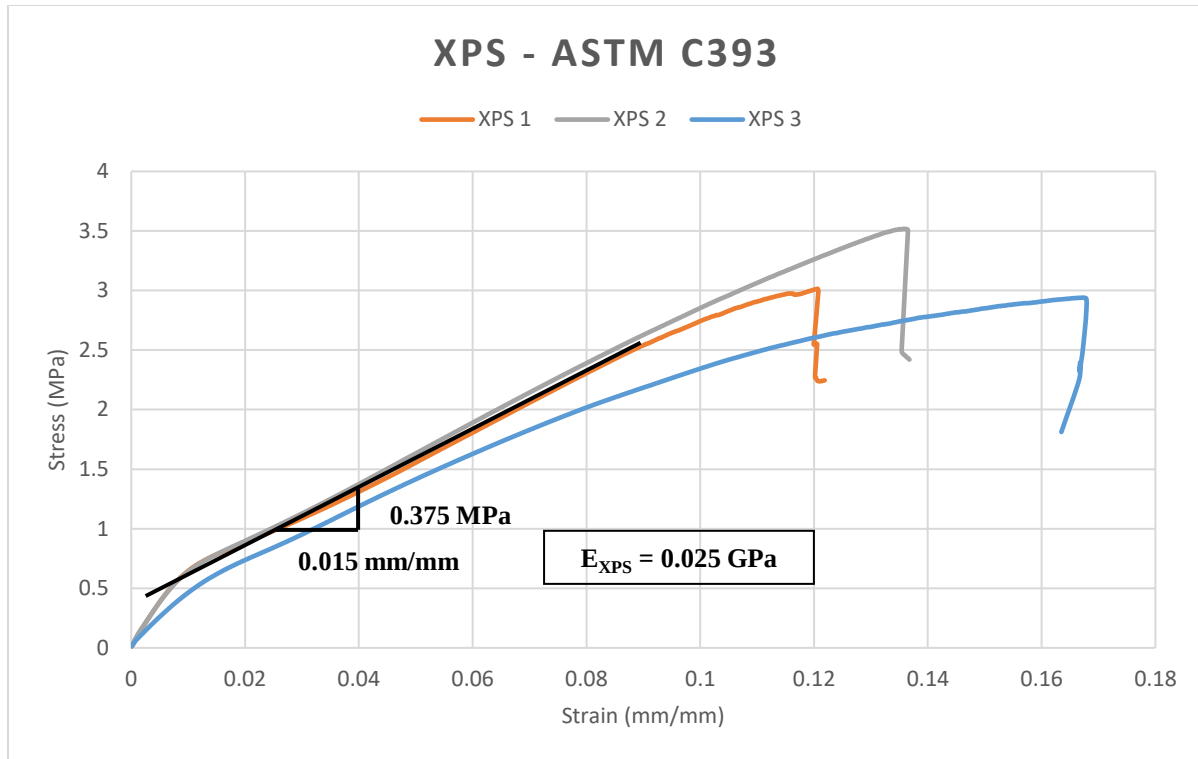


Figure 53. Stress vs. Strain curves and average elastic modulus of the XPS sandwich samples (ASTM C393).

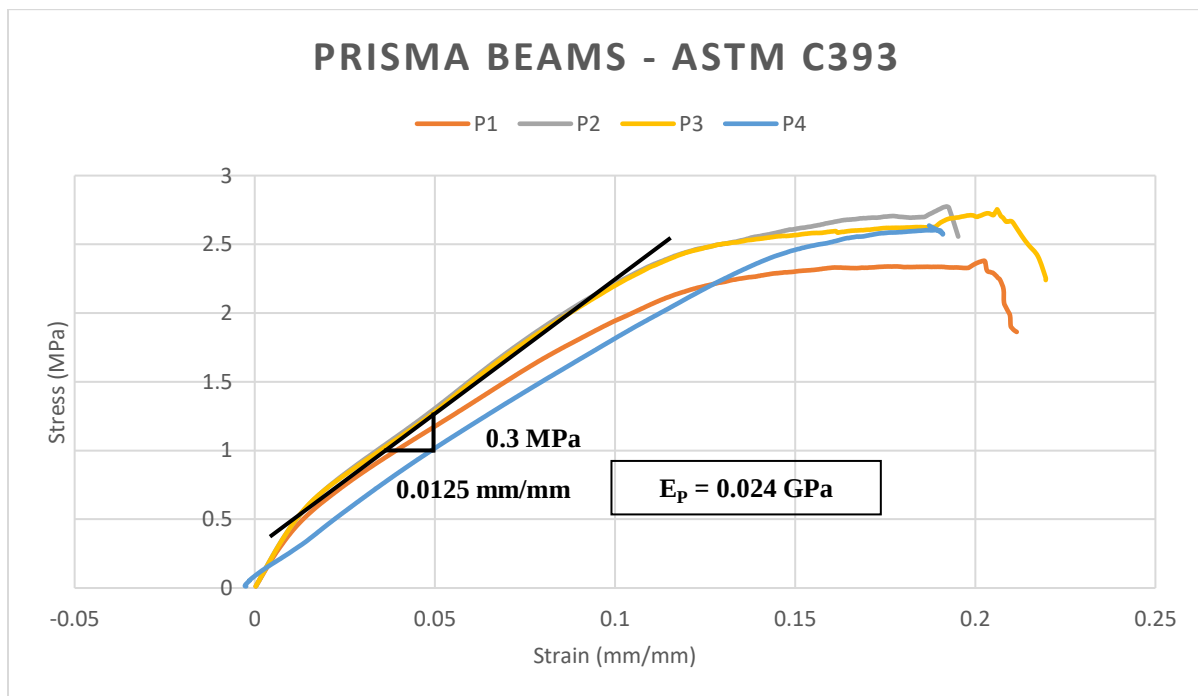


Figure 54. Stress vs. Strain curves and average elastic modulus of the Prisma sandwich samples (ASTM C393).

Similarly to the LBF test, the XPS samples presented a brittle behavior and the Prisma samples failed in a ductile manner. The same material and number of layers were used for the GFRP skins in both sandwich types, which means that the differences in behaviors and failure mechanisms are caused by the different types of foam cores. In fact, it can be seen in Figure 49 that the part of the top facesheet located between the loading bars remained undeformed throughout the test for the XPS samples. This might have caused stresses to accumulate around the loading area in the top GFRP skin, which caused a failure due to compression. In contrast, Figure 50 illustrates a curvature and deformation of that area in the Prisma samples that caused stresses to accumulate in the center of the bottom facesheet. A failure due to tension was the result of that deformation. This difference in behavior could also be attributed to the porosity in foams. PU has more pores than XPS which made the sample more ductile. XPS' lower void content resulted in a more brittle failure in the top facesheet due to stresses accumulation under the loading bars. Finally, by comparing the resulting plots for this test, it can be observed that the XPS sandwich structures had a 23.8% higher peak load and 28.2% lower total deflection than the Prisma sandwich structures. However, they both showed an equal modulus in the elastic zone, which could be caused by the similarity in GFRP skins and their response at the first stage of the test where foam cores were still not affecting the overall behavior of the structure.

4.2.4 Low-velocity impact (LVI)

The dynamic response of the XPS and Prisma sandwich composites was analyzed during an LVI test. The force, energy, and displacement history during multiple stages of damage were compared. The results are given in Table 17. On average, XPS panels exhibited 9.6% higher force, 1.1% lower absorbed energy, and 6.4% lower displacement than Prisma panels.

Table 17. LVI test results for XPS and Prisma sandwich samples.

Sample	Max. Force - lbf (N)	Energy Absorbed - J	Unabsorbed Energy - J	Displacement - in. (mm)
XPS1	1,209.5 (5,380.1)	125.6	2.2×10^{-8}	1.6 (40.7)
XPS2	1,145.3 (5,094.5)	125.1	1.2×10^{-9}	1.51 (38.3)
XPS3	1,195.2 (5,316.6)	125.0	1.8×10^{-8}	1.56 (39.6)
Average (XPS)	1,183.3 (5,263.7)	125.2	-	1.56 (39.5)
P1	1,123.9 (4,999.2)	127.3	8.8×10^{-10}	1.7 (43.1)
P2	1,083.7 (4,820.7)	127.5	6.0×10^{-3}	1.76 (44.7)
P3	1,031.1 (4,586.6)	124.9	6.7×10^{-9}	1.55 (39.4)
Average (Prisma)	1,079.6 (4,802.2)	126.6	-	1.66 (42.2)

The force vs. displacement responses for the 6 tested samples are illustrated in Figure 55. The contact force response in both panels is characterized by 2 normalized phases: loading and unloading. The loading phase shows an inelastic response marked by an increasing oscillatory slope until the maximum contact force is reached. In contrast, the unloading phase is characterized by a decreasing slope after the maximum force is achieved. For both phases, each oscillation is an indication of a combination of brittle matrix failure and fiber breakage, or delamination within the matrix. A higher slope and peak force indicate an increase in rigidity and brittle responses to forces [87]. Under inspection, both samples' facesheets expressed brittle failure with similar oscillation occurring between the initial contact and maximum force. However, a clear distinction between peak force of the first facesheet, unloading phase, and peak force of the second facesheet indicated that the foam core is responsible for variation between samples. The Prisma samples' unloading phase was more gradual than the XPS samples. The lowest force reached had an average of 385.93 lbf (1,716.7 N). The second peak, which was reached at the second face sheet, had an average of 755.79 lbf (3,361.9 N). This corresponds to 70% of the original peak. In contrast, the XPS sandwich structures unloading phase had a larger slope with a lower average minimum of 205.45 lbf (913.9 N) and an average second peak of 1,092.34 lbf (4,859 N). This corresponds to 92.7% of the original peak. The difference in behavior indicates that there was less energy absorbed by the XPS foam under direct contact and impacted the bottom facesheet with a greater velocity.

The energy absorption properties of the sandwich composites are characterized by the principle of energy conservation given by the total energy in the system (Equation 2):

$$E = \frac{1}{2} m.v^2 \quad \text{(Equation 2)}$$

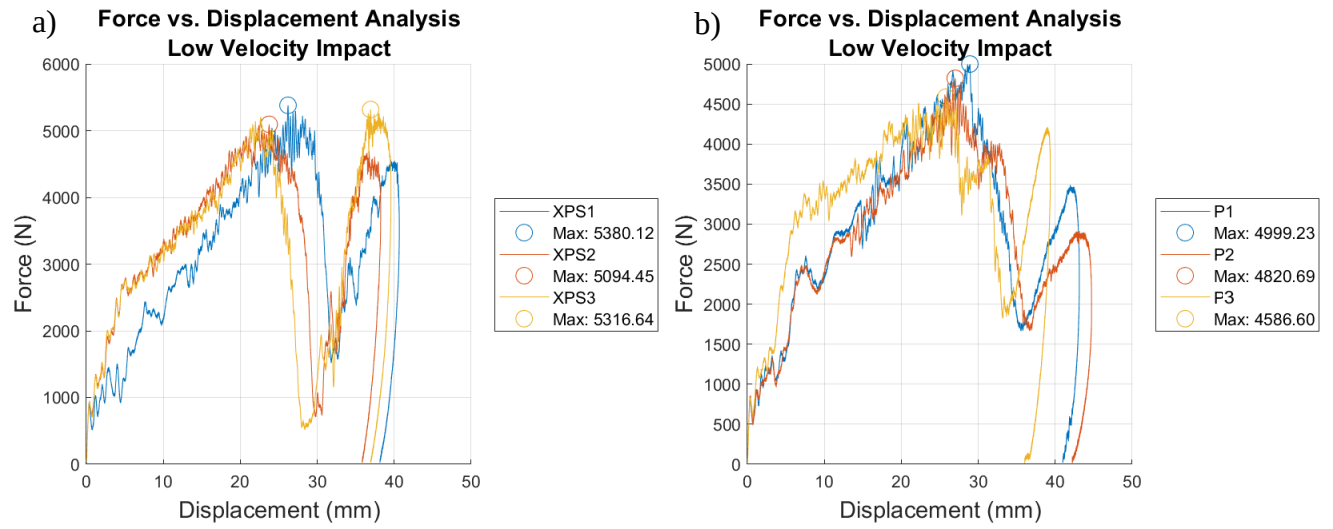


Figure 55. Force vs. Displacement response of a) XPS panels and b) Prisma panels.

Where: E = Kinetic energy (J), m = total mass of impactor (Kg), and v = velocity at time of impact (m/s). Based on Figure 56, the energy absorption can be split into 2 main phases according to the transferred energy from the impactor's kinetic energy to the absorbed energy of the panels [87]. The first phase is characterized by the transfer of energy from maximum velocity until the impactor reached a velocity of 0 (point A). At this point the projectile's kinetic energy was absorbed through the panel's dynamic response. Subsequently, the second phase describes the projectiles rebounding response until stabilization was reached where the total energy of the system has been absorbed by the panel. All XPS and Prisma samples absorbed slightly more energy than put into the system by an average of 1.2% and 2.3%, respectively. This scenario can be attributed to a variety of factors that could affect the overall velocity during impact.

The LVI responses shown in Figure 57 characterize how the panels transfer and absorb the kinetic energy in the system. The energy dissipation occurred during the loading phase of the force vs. time curve until the peak impact force was achieved. The corresponding energy (E_i), denoted as the initiation energy, is the energy required for damage to occur. Furthermore, the energy absorption (E_{A1}) is indicated by the corresponding energy where the impact force dropped to a minimum or 0. The propagation energy (E_p) required for the specimen to have propagation of damage is given by Equation 3:

$$E_p = E_{A1} - E_i \quad \text{(Equation 3)}$$

A higher E_i indicates a stronger and stiffer material that is more brittle under load, while a higher E_p indicates a tougher material that undergoes an inelastic deformation [88-90].

It can be seen from Figure 58 that both sandwich composites exhibited a stiff response based on E_i , which is due to both their facesheets consisting of identical material.

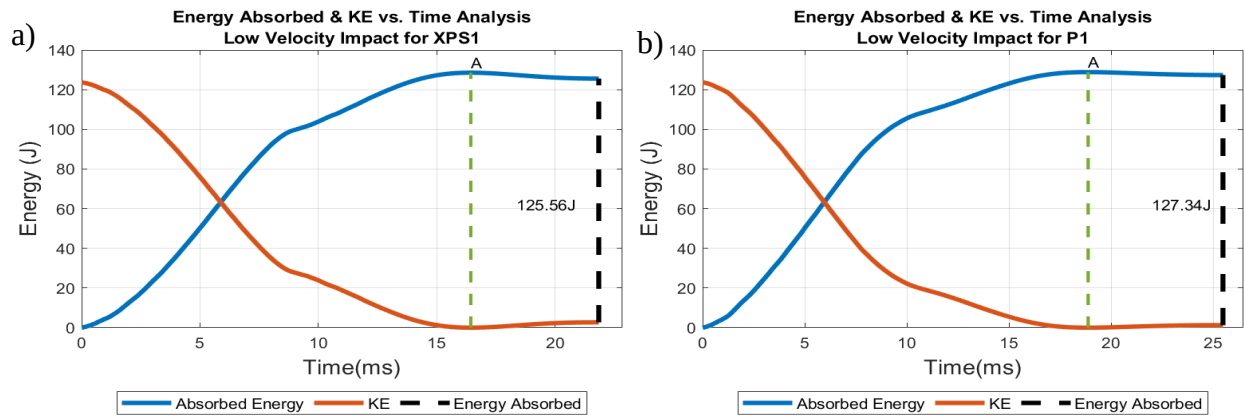


Figure 56. Energy transfer response for (a) XPS1 and (b) P1.

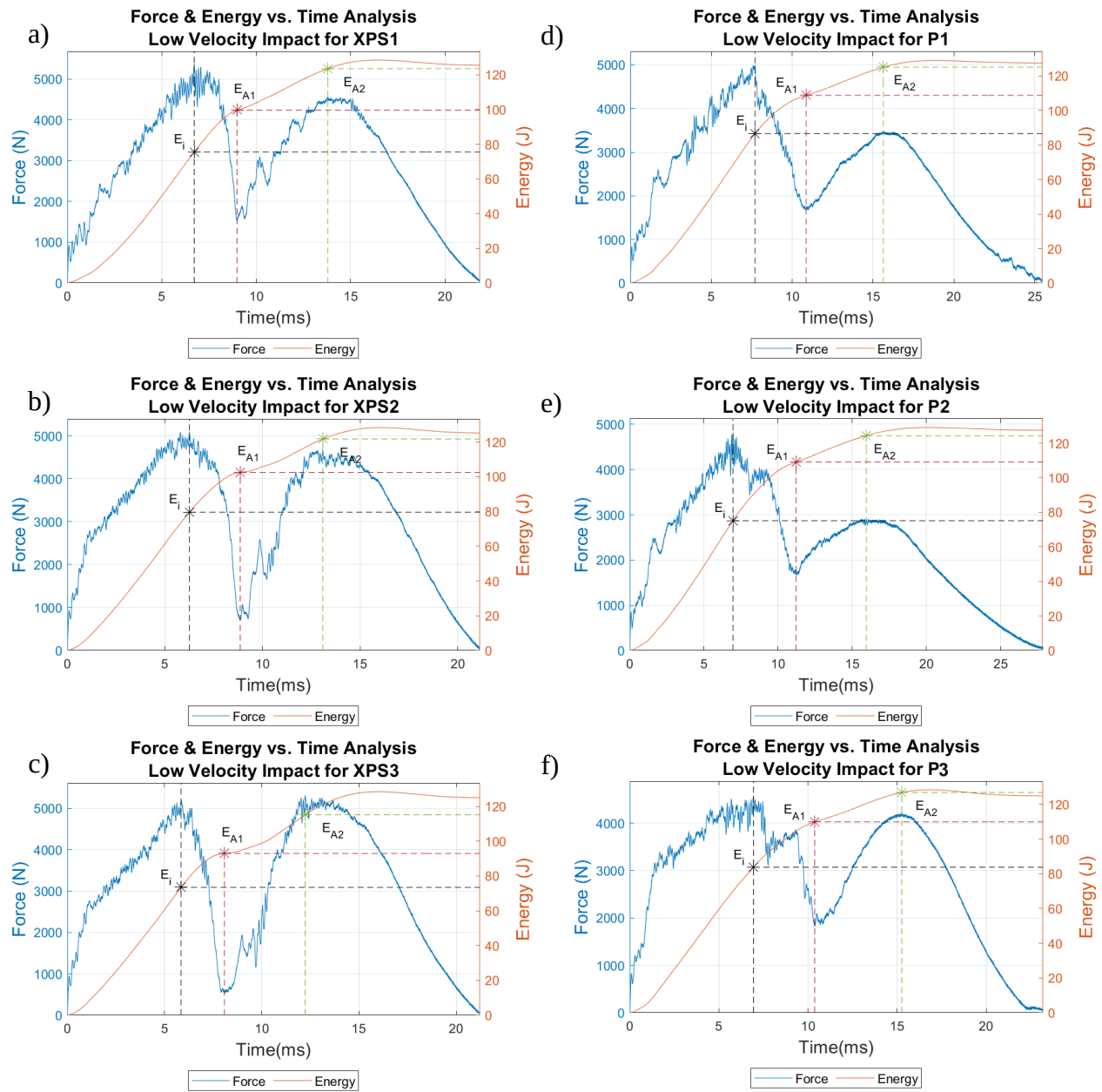


Figure 57. Force/Energy vs. Time LVI responses of all tested XPS and Prisma sandwich panels:
a) XPS1, b) XPS2, c) XPS3, d) P1, e) P2, and f) P3.

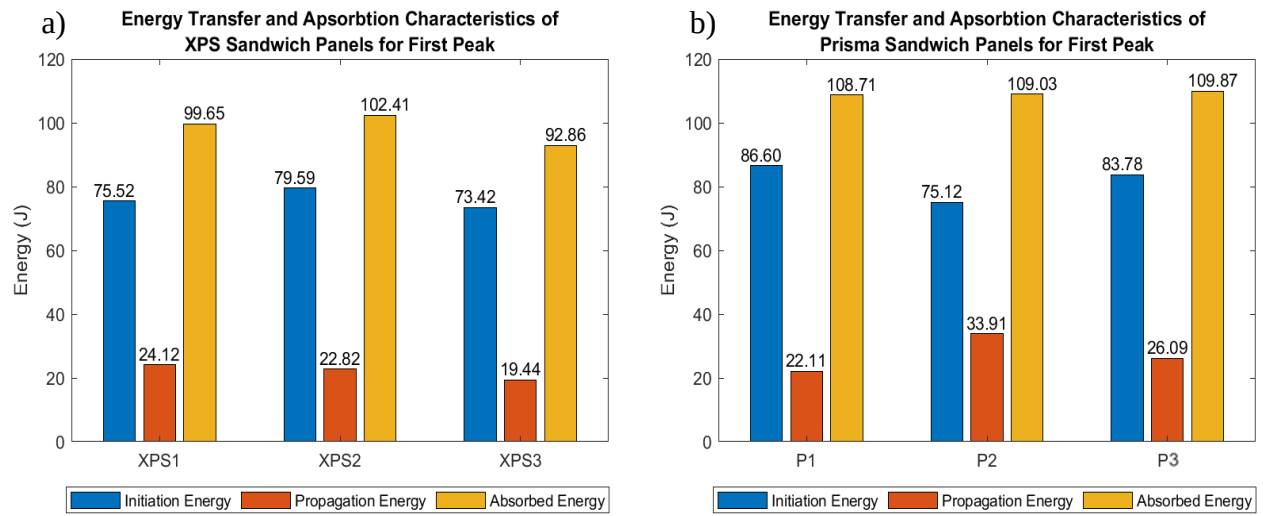


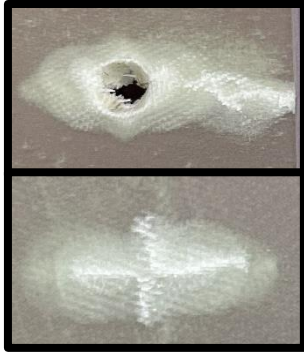
Figure 58. Energy transfer and absorption under LVI for a) XPS samples and b) Prisma samples.

However, the Prisma panels had an average $E_p = 27.36$ J, which is 23.6% higher than the XPS panels ($E_p = 22.13$ J). This could indicate that the PU core contributed to strengthening the sandwich structure and making it resistant to failure under inelastic deformation. In addition, a dimensionless parameter called the ductility index (DI) can be used to indicate how the composite can absorb energy under deformation [88]. DI is given by Equation 4:

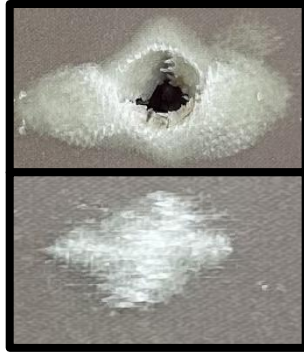
$$DI = \frac{E_p}{E_i} \quad (\text{Equation 4})$$

The DI values were 0.335 and 0.291 for the Prisma and XPS panels, respectively. The 15.2% higher value for the Prisma samples suggests that the PU core underwent greater displacement under impact. The results indicate that PU foam is stiffer than XPS and absorbs a greater amount of energy at the point of initial damage propagation.

Finally, the panels offered little resistance at the initial contact which resulted in complete top penetration through the top layer. Figure 59 illustrates the damage propagation in all tested samples. It can be seen that the impact energy was completely absorbed, which was confirmed by the lack of penetration through the bottom GFRP facesheet. However, there was a clear difference in crack propagation at the initiation energy between the 2 sandwich types. The Prisma samples exhibited greater deformation compared to the localized damage propagation found in the XPS samples. This is due to XPS being more brittle than PU. The same results were observed in Figure 55 and indicate higher stresses were present in the Prisma panels during the unloading phase of impact. Different crack propagation behaviors were therefore obtained [90].



a) XPS1



b) XPS2



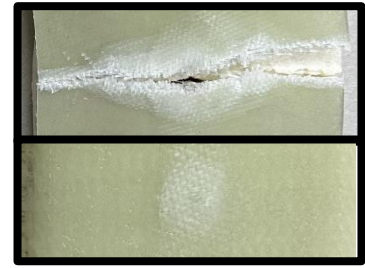
c) XPS3



d) P1



e) P2



f) P3

Figure 59. LVI damage propagation in all tested sandwich structures in the top (top image) and bottom (bottom image) GFRP facesheets.

4.2.5 “Flatwise” tensile test (FTT)

This test investigated and compared the mechanical behaviors and failure mechanisms of the two types of sandwich structures under a “flatwise” tensile test. Figure 60 and Figure 61 illustrate the failure of the sandwich samples, while Figure 62 and Figure 63 show the load vs displacement plots for all the tested samples.

All XPS samples failed due to shear cracks and some of them exhibited partial delamination after shearing. The load vs. displacement curves of the 4 samples showed a similar ductile behavior which started at an average load of 49.46 lbf (220 N) and an elongation of 0.024” (0.6 mm). After another 0.04” (1 mm) elongation, the load started dropping but the displacement kept on increasing. Figure 64 shows the stress vs strain curves and the average elastic modulus for the XPS samples $E_{XPS} = 812.21$ psi (0.0056 GPa).

The Prisma samples failed by delamination between the PU foam and the GFRP skin. The average peak load was 33.72 lbf (150 N). A 27% drop in force was seen after they elongated for around 0.031” (0.8 mm). After the initial sudden drop, the load kept on decreasing while the displacement increased slowly. However, the behavior of the Prisma samples could be considered brittle because of the initial drop. Figure 65 gives the average elastic modulus $E_P = 493.13$ psi (0.0034 GPa) and the stress vs. strain curves for the Prisma samples.

The main purpose of this test was to study the behavior of the foam core and strength of the interfacial bond under tensile loading. It’s clear that the bonding between XPS and GFRP was stronger than the PU/GFRP bond, having withstood 49.46 lbf (220 N) without completely delaminating. In comparison, the Prisma samples were almost completely delaminated after a 32% lesser load. Because of that delamination, it’s hard to understand the behavior of the PU foam subjected to tension.

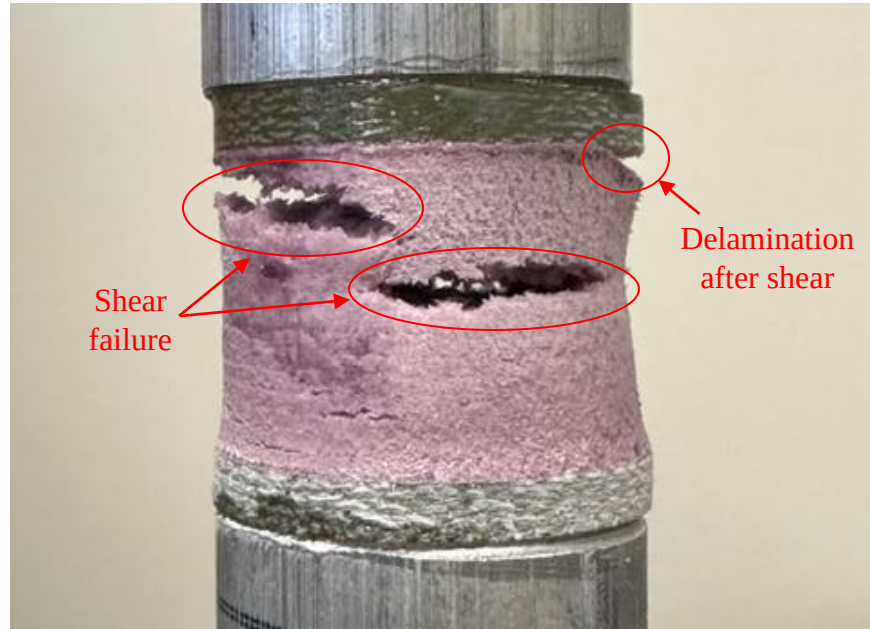


Figure 60. Failure by shear in the XPS sandwich under a “flatwise” tensile test (ASTM D7291).



Figure 61. Failure by delamination in the Prisma sandwich under a “flatwise” tensile test (ASTM D7291).

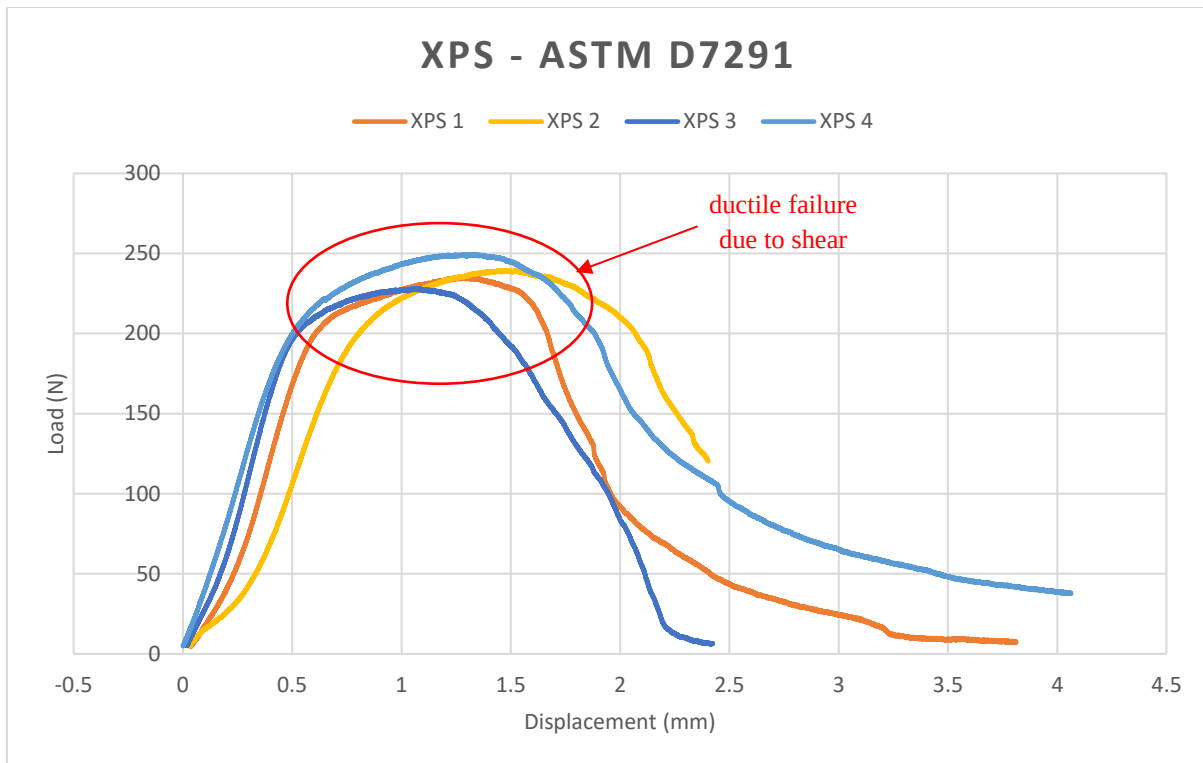


Figure 62. Load vs. Displacement curves of the XPS sandwich samples under a “flatwise” tensile test (ASTM D7291).

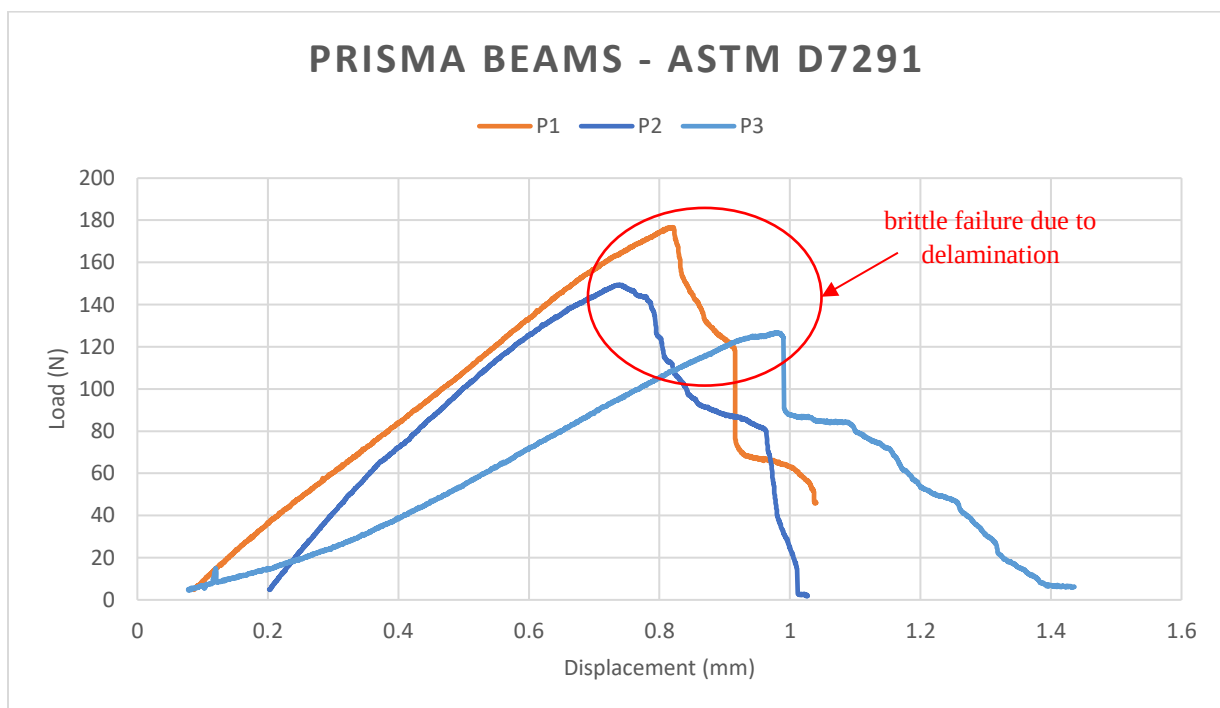


Figure 63. Load vs. Displacement curves of the Prisma sandwich samples under a “flatwise” tensile test (ASTM D7291).

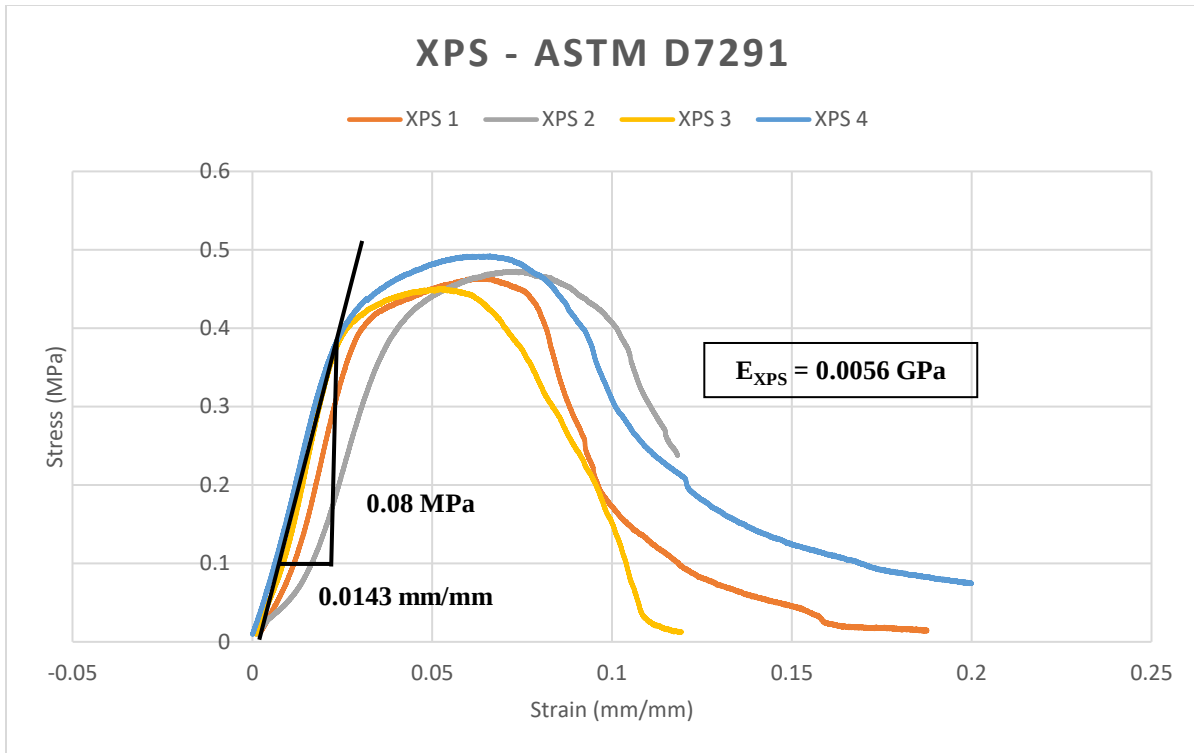


Figure 64. Stress vs. Strain curves and average elastic modulus of the XPS sandwich samples (ASTM D7291).

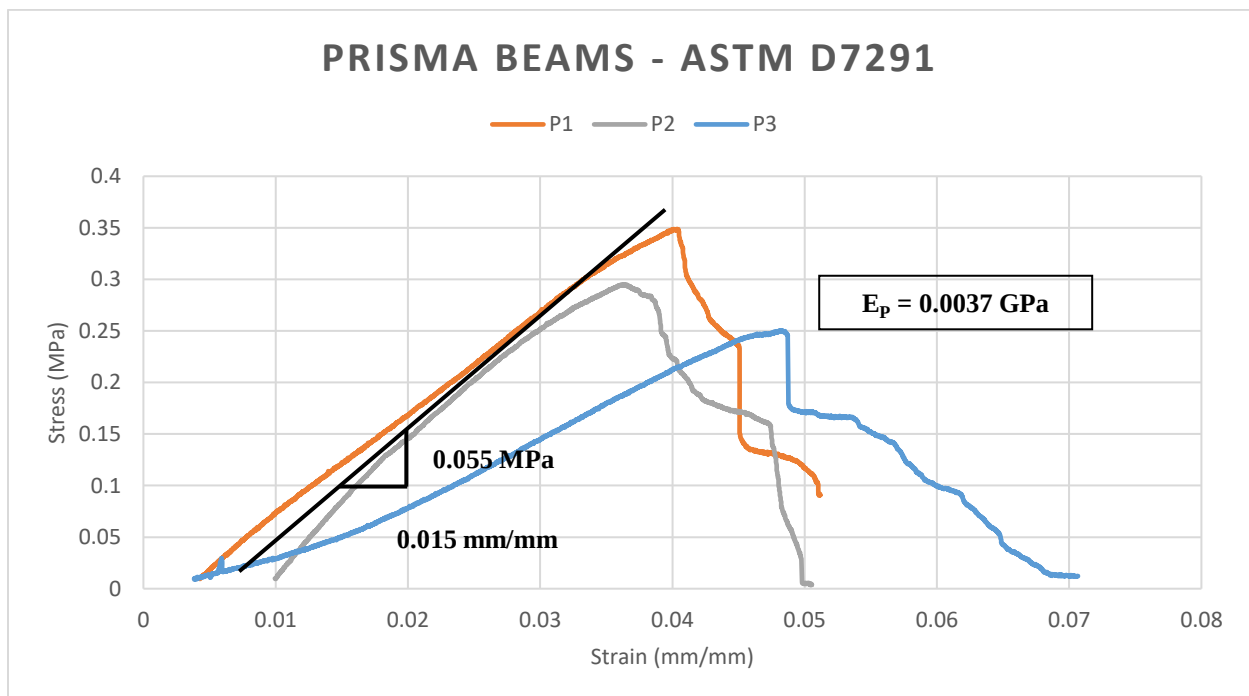


Figure 65. Stress vs. Strain curves and average elastic modulus of the Prisma sandwich samples (ASTM D7291).

However, that behavior was clear in the XPS samples: the strong bond resulted in cracks inside the foam due to shear forces. For that reason, the peak load for the XPS samples could be attributed to shear, while the peak load for the Prisma samples could be attributed to interfacial bond. This means that comparing the peak loads is not accurate in this test. The elastic modulus is a valid comparison tool in this test and demonstrates the behavior of the foam core prior to failure. E_{XPS} is 64.7% higher than E_p which suggests that, in terms of foam properties alone, PU is more ductile than XPS, which correlates well with the other observations made within this section.

In summary, the XPS sandwich structure performed better in this test under quasi-static tensile loading. The samples withstood more load and failed without debonding. The Prisma sandwich structure was more ductile in the elastic zone but delaminated and showed a brittle failure due to a weaker bond.

4.3 Current application

4.3.1 Tensile testing

4 GFRP samples were tested under tensile loading. By matching the time data from the two DAQ software, 2 curves were plotted for each sample: stress vs. strain (Figure 66) and transverse strain vs. axial strain (Figure 67). It can be seen that the samples exhibited a brittle failure. Samples 1, 2 and 3 showed similar curves and rupture stresses. After a strain of 0.019, the peak stress before cracking was around 43,511.3 psi (300 MPa). Sample 4 cracked for a strain of 0.015 and a 37,709.8 psi (260 MPa) peak stress. Figure 68 illustrates the failed GFRP sample. Although there's a 13.3% difference in failure loads between sample 4 and the other samples, they all showed similar behaviors in the elastic zone. All samples were taken into consideration while averaging the results of the elastic modulus, Poisson's ratio, and tensile strength.

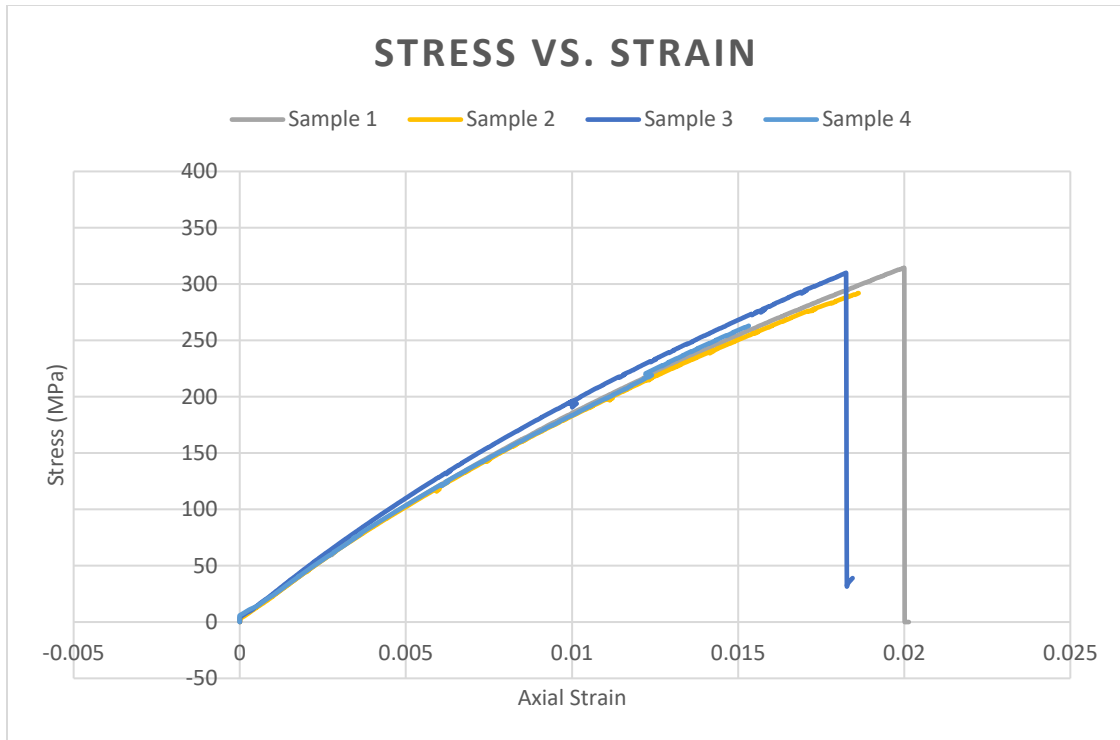


Figure 66. Stress vs. Strain curves of the GFRP samples under tensile testing (ASTM D3039).

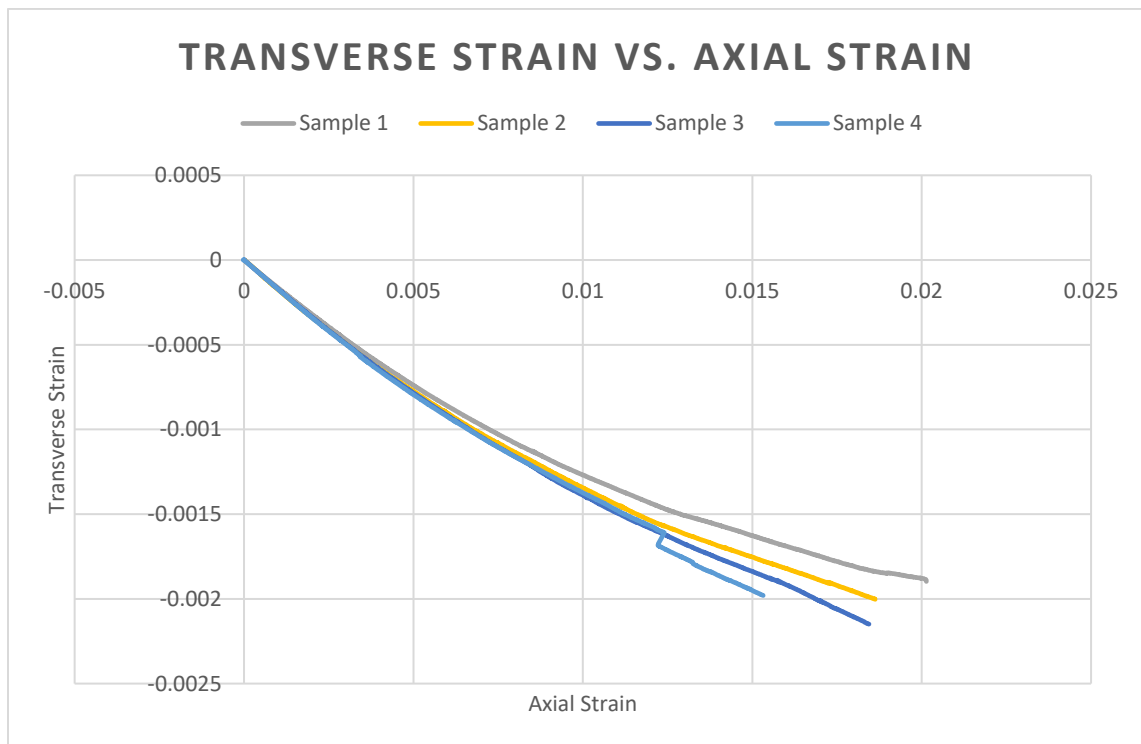


Figure 67. Transverse strain vs. Axial strain curves of the GFRP samples under tensile testing (ASTM D3039).

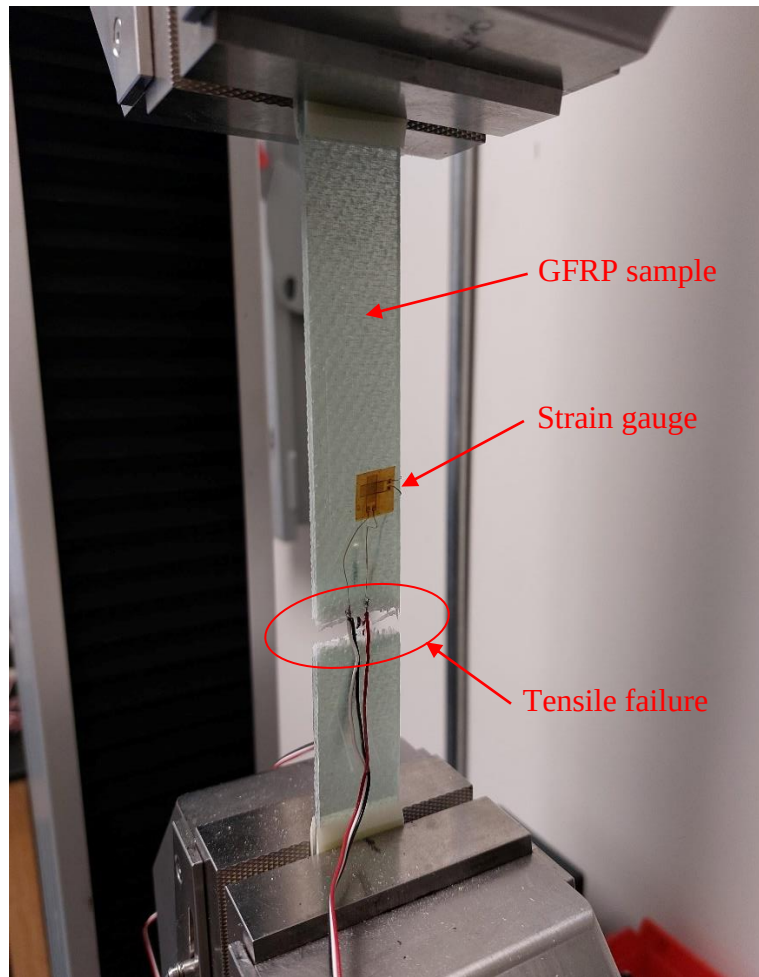


Figure 68. Tensile failure of the GFRP sample (ASTM D3039).

The elastic modulus and Poisson's ratio were calculated for each sample based on Equations 5 and 6, respectively:

$$E = \frac{\Delta(\text{Stress})}{\Delta(\text{Strain})} \quad (\text{Equation 5})$$

$$\nu = \frac{\Delta(\text{Transverse Strain})}{\Delta(\text{Axial Strain})} \quad (\text{Equation 6})$$

Table 18 shows the results for all samples and their average values for the GFRP material used in this research. The average elastic modulus and tensile strength were compared to a paper written by Stanciu et al. [91], who carried out tensile tests on GFRP samples made of 4 layers of 0°/90° oriented plain fabric and a polyester resin. The authors obtained an average elastic modulus of 3,094.67 Ksi (21.34 GPa) and average tensile strength of 33,068.6 psi (228 MPa). Compared to the results obtained in this research, their E and ν show lower values of 2.9% and 22.7%, respectively. Therefore, the elastic modulus compares well with literature, which validates the results of this test. The 22.7% variability in tensile strength might be caused by the different resin systems used. Epoxy resin is known for having higher mechanical properties than other thermosets, as mentioned in *Section 2.2.2*. In addition, due to the consistency of the results, the value of tensile strength at rupture was accepted. Finally, E and ν were inputted as material properties when modeling the composite panels for FEA simulations, while σ_t was used to check if the stresses in the panels exceeded the allowable limit.

4.3.2 Large-scale flexural testing

The 4' x 8' x 4.23" (121.92 cm x 243.84 cm x 107.44 mm) panel was tested under 2 loading conditions.

Table 18. Elastic modulus and Poisson's ratio results for GFRP material under tensile testing (ASTM D3039).

Sample	E - Ksi (GPa)	ν	σ_t - psi (MPa)
1	3,095.1 (21.34)	0.162	45,686.9 (315)
2	3,141.5 (21.66)	0.165	45,251.8 (312)
3	3,325.7 (22.93)	0.169	42,496.1 (293)
4	3,186.5 (21.97)	0.167	37,709.8 (260)
Average	3,190.8 (22)	0.165	42,786.1 (295)

Although the panels that were mounted on the existing buildings had different geometry and design, the results of the flexural tests gave a better understanding of the structural capacity of the sandwich structure. Moreover, a comparison was made between experimental and simulation data, which was necessary to validate the FEA models.

4.3.2.1 Experimental testing

The results of the deflection at the bottom center point of the sandwich panel, which is the critical deflection in a simply supported setup, are given in Table 19 for both tests. The deflections were compared to the allowable limit given by the IBC Table 1604.3 for exterior walls with brittle finishes. The maximum allowable deflection is given by Equation 7:

$$\delta_{\max} = \frac{l}{240} \quad (\text{Equation 7})$$

Where $l = 91''$ (231.14 cm) is the span length. In this test setup, $\delta_{\max} = 0.379''$ (9.63 mm).

According to the results, the deflections for test 1 ($\delta_1 = 0.118''$ (3 mm)) and test 2 ($\delta_2 = 0.157''$ (3.99 mm)) were both smaller than 50% of $\delta_{\max}$. δ_2 is 33% higher than δ_1 , even though the total load for test 2 was 8.2% smaller than the total load used in test 1. This result was caused by more critical loading conditions in the second test, with all the loads being put at the center of the panel, which created more stress and deformation in comparison with the first test.

According to the resulting deflections in both tests, the sandwich structure showed good structural integrity. FEA simulations were also used to check if close values for deflections will be obtained.

Table 19. Deflections at the bottom center point of the sandwich panel under the two loading configurations.

Test type	Deflection δ in. (mm)
Test 1	0.118 (3)
Test 2	0.157 (3.99)

4.3.2.2 FEA modeling

9 element sizes, ranging from 4" (101.6 mm) to 0.6" (15.24 mm), were used for meshing the structure and getting the deflection at the center. With each decrease in element size, the software computational time, as well as the accuracy of the results increased. This was due to more C3D8 elements being used for iterations. Figure 69 and Figure 70 show the variation in the computed deflection with respect to element sizes used for FEA in tests 1 and 2, respectively. Both plots show an increase in deflection while the elements decreased from 4" (101.6 mm) to 0.6" (15.24 mm). It can also be seen that the slope of the curve, calculated from the slope of its tangent lines $\tan 1$ and $\tan 2$, decreased when the mesh size decreased beyond 2.1" (53.34 mm) for test 1 and 2.3" (58.42 mm) for test 2. The slope was reduced by 52% and 49% for tests 1 and 2, respectively. Thus, the results started to converge more towards the solution for a mesh size lower than the mentioned values. 0.6" (15.24 mm) was the lowest element size that could be attained given the restrictions of the academic version of Abaqus, which can simulate a maximum of 250,000 nodes. Therefore, the deflection values for 0.6" (15.24 mm) C3D8 elements were compared against the tests results.

Figure 71 and Figure 72 show the FEA simulation results while Figure 73 gives the comparison between numerical and experimental data. The first test gave an experimental deflection of 0.118" (3 mm) and a simulation deflection of 0.1224" (3.11 mm). The second test gave an experimental deflection of 0.157" (3.99 mm) and a simulation deflection of 0.1584" (4.02 mm). The error is therefore 3.7% for test 1 and 0.9% for test 2, which validates the modeling parameters and FEA simulation.

Finally, the resulting tensile stresses in the GFRP layers given by the model were compared against the tensile strength of GFRP given in *Section 4.3.1*.

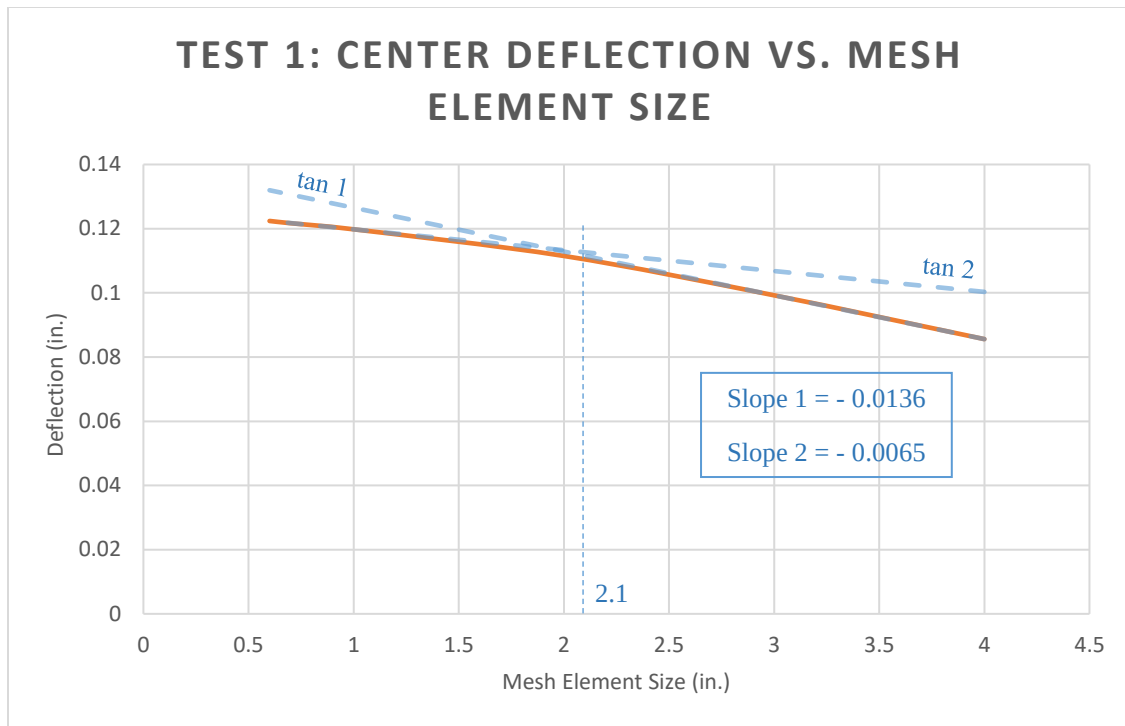


Figure 69. Variation in the computed deflection in test 1 based on the mesh element size in Abaqus.

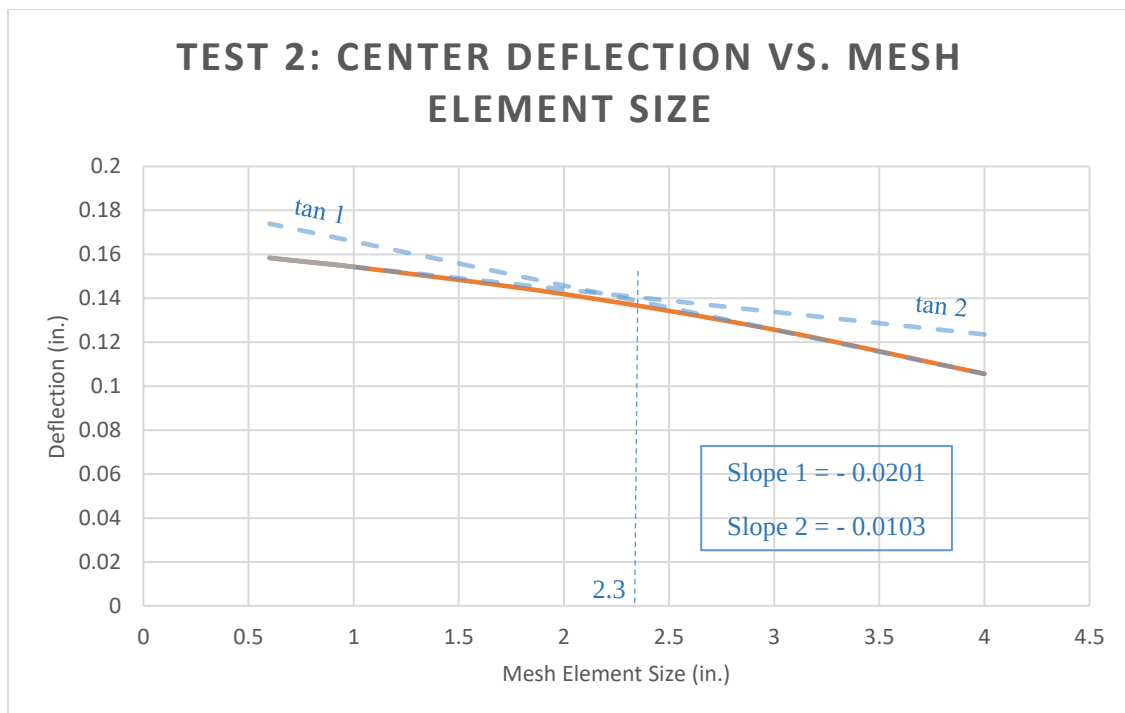


Figure 70. Variation in the computed deflection in test 2 based on the mesh element size in Abaqus.

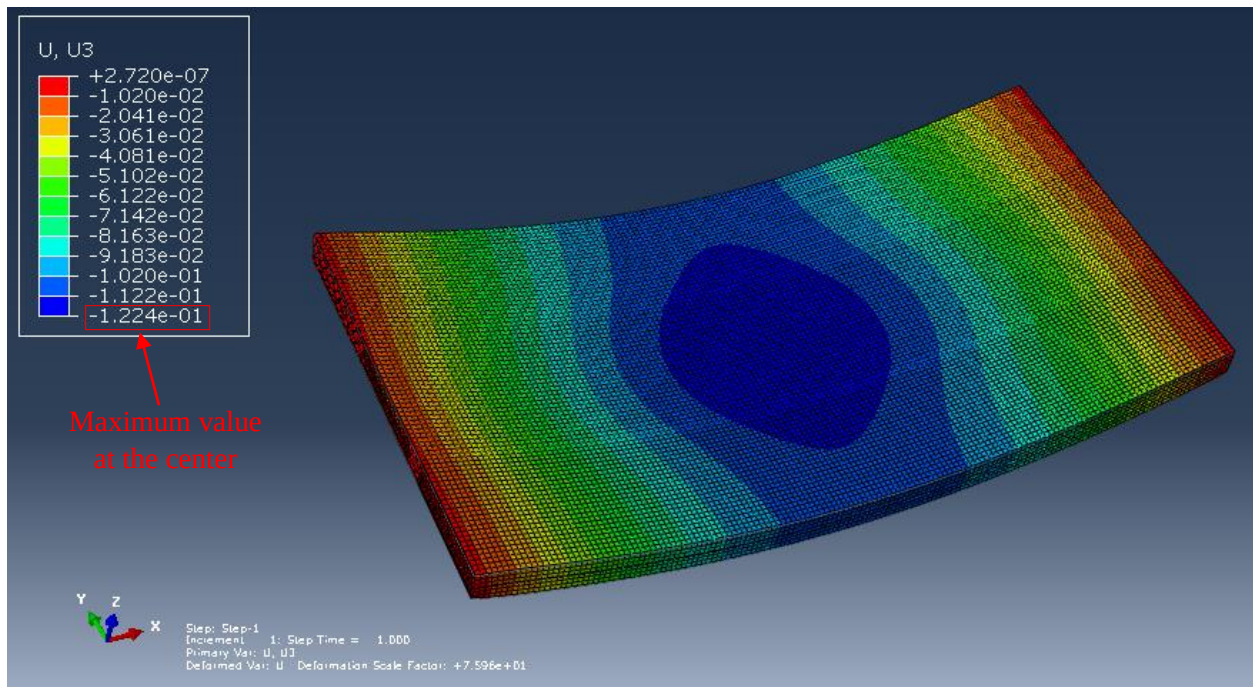


Figure 71. Test 1 deflection map along the Z-axis for 0.6" (15.24 mm) C3D8 elements in Abaqus.

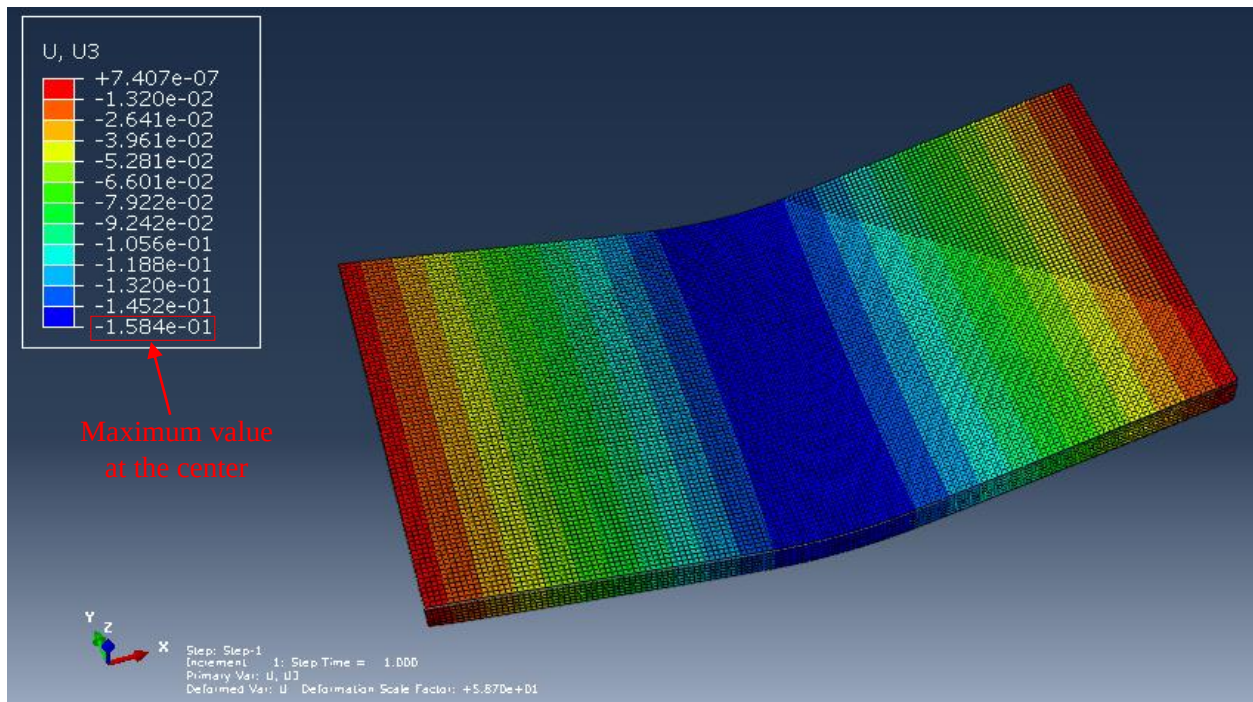


Figure 72. Test 2 deflection map along the Z-axis for 0.6" (15.24 mm) C3D8 elements in Abaqus.

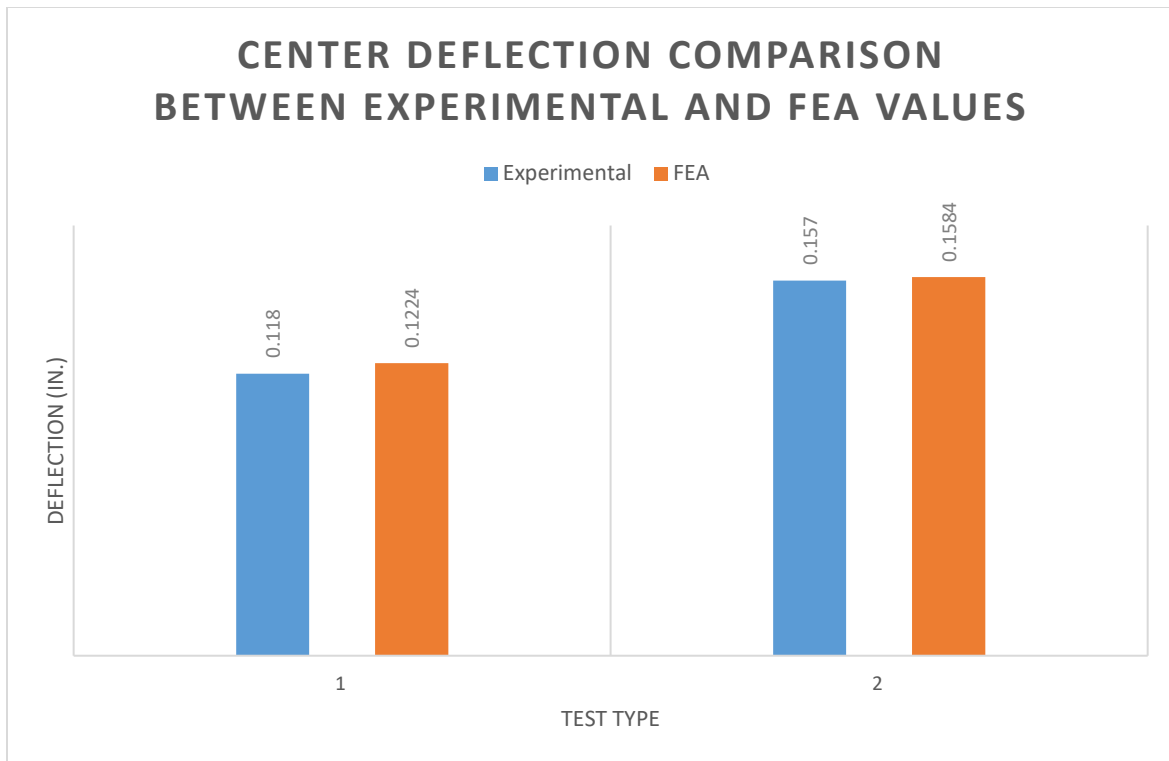


Figure 73. Comparison between experimental and FEA center deflection values for both tests.

The highest stresses based on FEA were $\sigma_1 = 292.8$ psi (2.02 MPa) for test 1 and $\sigma_2 = 435.1$ psi (3 MPa) for test 2. These values are very low compared to the tensile strength $\sigma_t = 42,786.1$ psi (295 MPa), which indicates that an elastic analysis was sufficient for this test.

4.3.3 Panels and connections design

Multiple concepts regarding the design and installation of panels and connections were studied and modeled. This section briefly reviews the most accepted ones, while stating the issues encountered in each concept. Then, the approved final concept is described in more detail.

Figure 74 illustrates the first concept for installing the cladding panels on the existing building. 3 types of panels would be found around each window opening. Panels A would be installed below the windows, panels B would be installed next to them, and panels C would be installed above them. The bottom, middle, and top anchors would be fixed by bolts to the existing masonry walls. The installation sequence for this concept would be:

Bottom anchors → panels A → middle anchors → panels B → top anchors → panels C.

The goal of this design was to manufacture small panels for easy transportation and installation. However, multiple issues were found:

- Around 80 panels and 100 anchors would be manufactured for each duplex: manufacturing and installation time would increase, and panels alignment might be a challenge.
- Each panel would have complex trims around the edges to fit inside the anchors and adjacent panels: manufacturing would become harder.
- Joints between panels would be located on the 4 corners of the window openings: an easy path for crack propagation and water infiltration would be available.

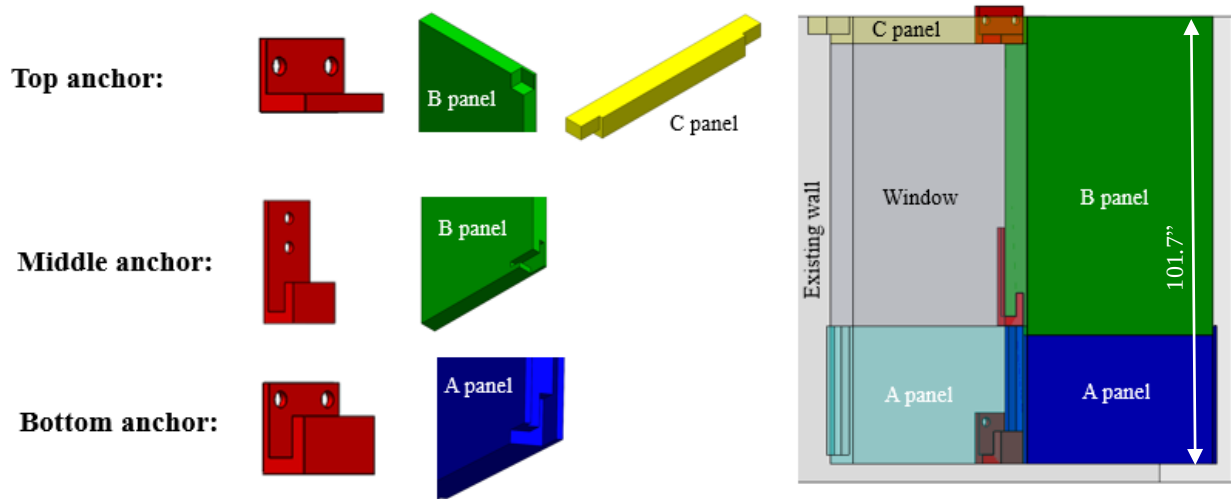


Figure 74. First concept for installing the cladding panels on the existing building.

Figure 75 illustrates the second concept for installing the cladding panels. A similar approach to the first concept was followed for installing the anchors and panels on the existing walls. However, instead of having 6 panels around each window opening, 1 large panel would be manufactured.

The goal of this design was to reduce the number of panels and anchors, while eliminating the joints around window openings. In addition, the middle anchors, which would have been fixed to the brick walls, would no longer be used. The RC slabs would therefore be the main supporting structures. Nonetheless, 2 major issues were found with this concept:

- Some complex trims around the edges of the panels would still be needed.
- Removing a panel for maintenance would mean removing the top anchors first: this would also include removing the bolts holding the top anchors to the brick wall and concrete slab.

Figure 76 illustrates the third concept for installing the cladding panels on the existing building. Corner and middle beams, made with the same GFRP and XPS materials, were added to act as supporting elements for the panels. The goal of this design was to eliminate the anchors, and their bolts, used in the previous concepts. 3 consecutive cladding panels would be joined together and laid between the structural beams. The major advantage was that the structural elements would be separated from the panels. However, multiple issues were also found:

- It wouldn't be possible to remove single panels for maintenance.
- A crane would be needed to lift the 3 attached panels.
- Complex panel shapes would still be present.
- Holes in the beams might be needed to fix them to the bottom concrete slab: even though they would be closed by caps, they might not be aesthetically pleasing.

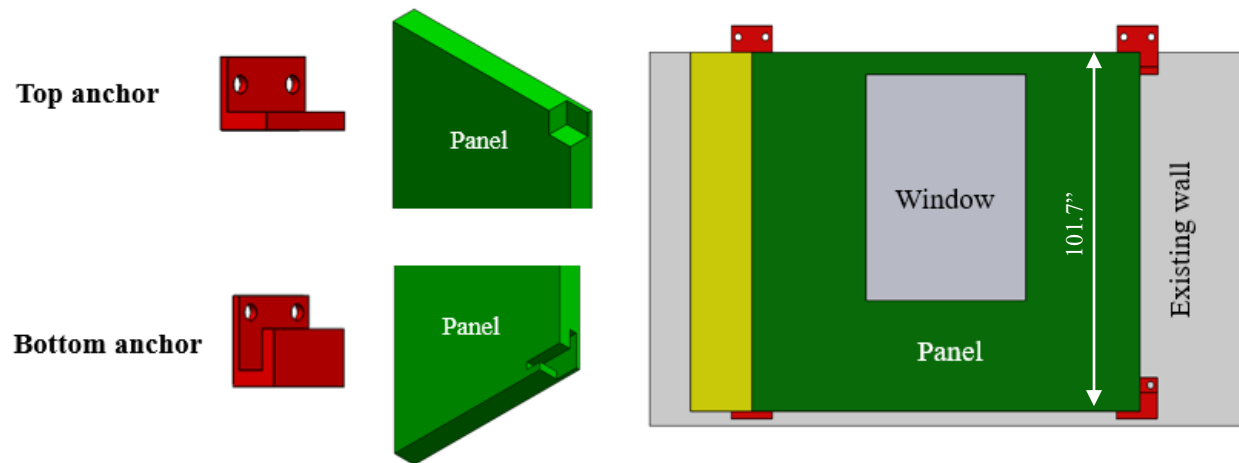


Figure 75. Second concept for installing the cladding panels on the existing building.

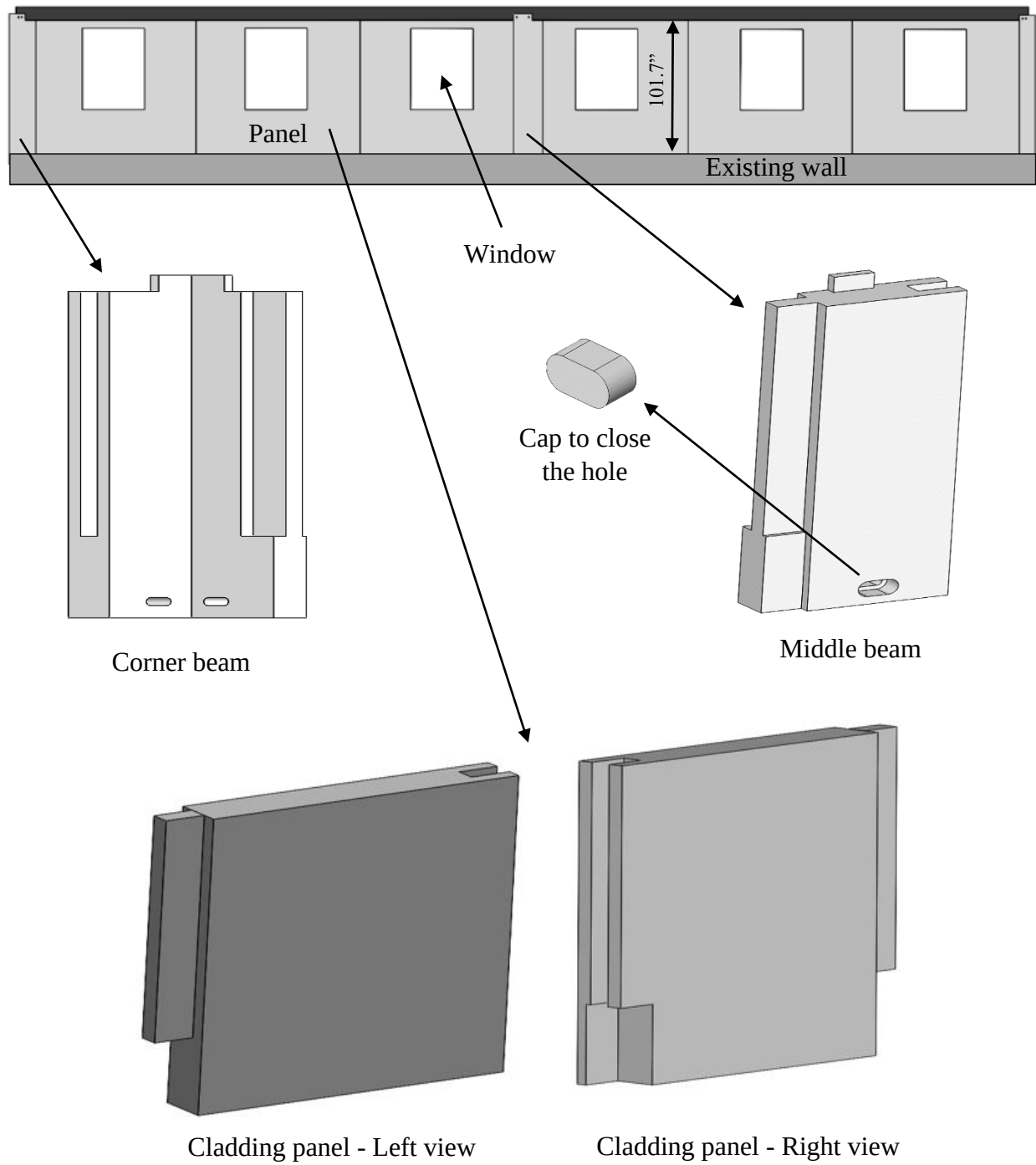


Figure 76. Third concept for installing the cladding panels on the existing building.

Finally, the approved concept for installing the cladding panels on the existing building is shown in Figure 77. The panel size and top and bottom anchors are similar to the second concept. However, the panels would not be directly bolted to the top anchors. F-brackets and J-brackets would constitute an independent structural system, not directly connected to the cladding panels. They would be fixed to the RC slabs by expansion bolts. A tapered tongue and groove connection between the F-bracket and the bottom edge of the panel would restrain any horizontal movement at the lower limit. Similarly, the connection between the L-bracket and J-bracket would restrain any horizontal movement at the upper limit. The L-bracket could be integrated into the sandwich structure while manufacturing. The design of the brackets would specify the required number of holes for the expansion bolts. However, more holes should be considered. Some bolts might not be easily inserted in the RC slabs because of existing steel rebars. All brackets would therefore be continuous along the panel's edges. Panels might also be subjected to uplifting. For that reason, caps would be installed above the panels to restrain any vertical movement. The side edges of the panels, which connect them to adjacent panels, would be flat. This would allow for easy detachment of a single panel due to maintenance needs. Rubber gaskets would be installed along the edges to eliminate any water infiltration. The installation sequence for this concept would be:

F-bracket → J-bracket → Panel (L-bracket included) → Caps.

4.3.4 Wind loads FEA simulation

4.3.4.1 Wind loads calculations

Knox County allows the use of the IBC in construction, which references the ASCE 7 standard design requirements.

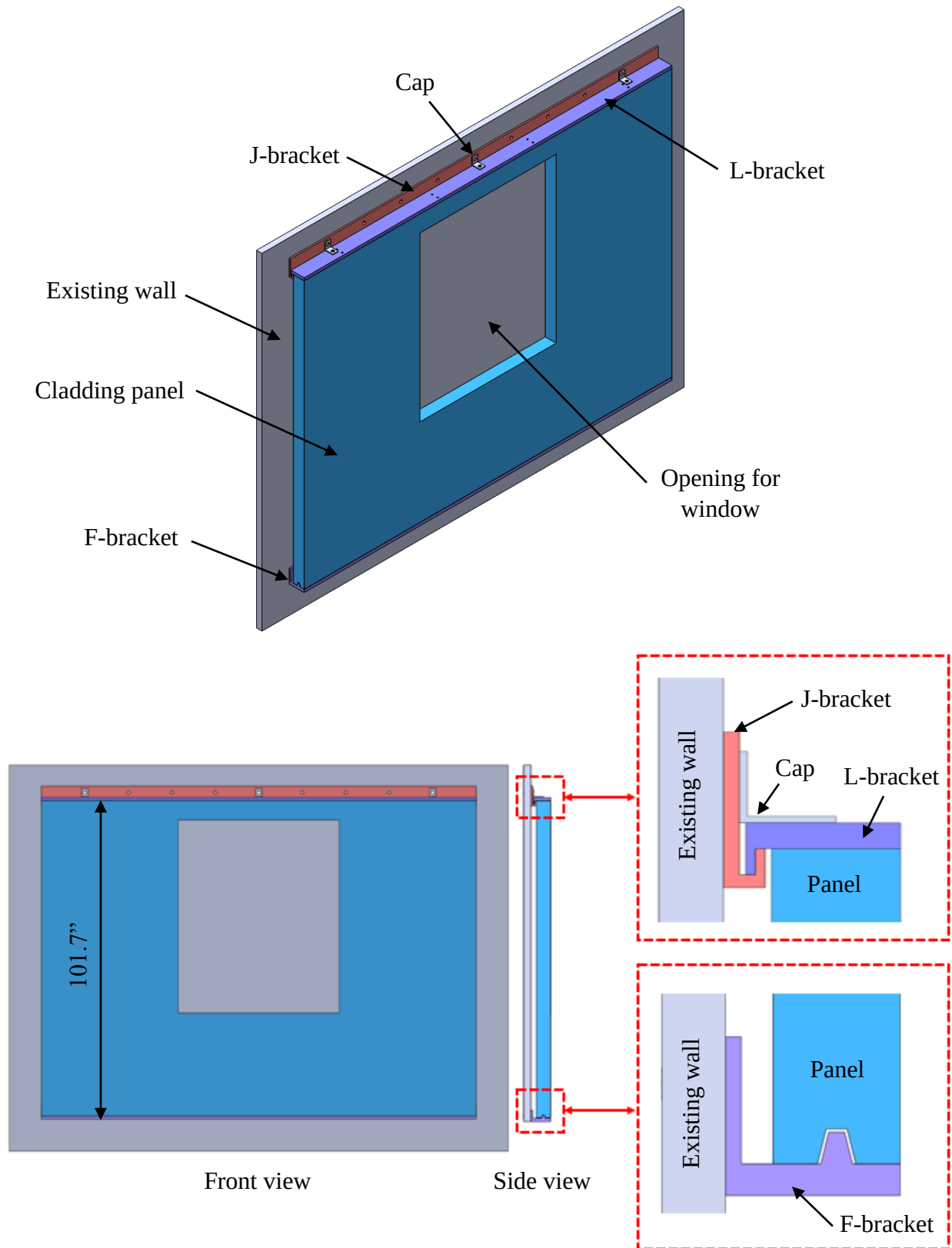


Figure 77. Approved final concept for installing the cladding panels on the existing building.

Therefore, chapters 26 (Wind Loads: General Requirements) and 30 (Wind Loads: Components and Cladding) of the ASCE 7-16 standard were used to calculate the wind loads acting on the modular panels.

Before starting the calculations according to the mentioned chapters for wind loads design, the risk category of the existing houses needed to be defined: according to ASCE Table 1.5-1, a risk category of II should be used for residential buildings and structures.

Velocity pressure for Knoxville, TN:

- Basic wind speed in Knoxville $V = 104$ mph (ASCE Figure 26.5-1B for risk category II).
- Wind directionality factor $K_d = 0.85$ (ASCE Table 26.6-1 for buildings - components and cladding).
- Topographic factor $K_{zt} = 1.0$ (ASCE Section 26.8.2 for buildings and structures that do not meet all the conditions specified in ASCE Section 26.8.1).
- Ground elevation factor $K_e = 1.0$ (ASCE Table 26.9-1 for all elevations).
- Exposure category: B (ASCE Section 26.7.3).
- Velocity pressure exposure coefficient K_z (ASCE Section 26.10.1):

$$\text{For } z < 15 \text{ ft., } K_z = 2.01(15/z_g)^{2/\alpha}.$$

$$\text{For } 15 \text{ ft.} \leq z \leq z_g, K_z = 2.01(z/z_g)^{2/\alpha}.$$

α and z_g are given in ASCE Table 26.11-1 for the exposure category B.

By replacing α and z_g by their values from the tables, the final K_z equations were obtained:

$$K_z = 2.01(15/1,200)^{2/7} = 0.57 \text{ for } z < 15 \text{ ft.}$$

$$K_z = 2.01(z/1,200)^{2/7} \text{ for } 15 \text{ ft.} \leq z \leq 1,200 \text{ ft.}$$

Since the mean height of the buildings ($h_{\text{mean}} = 12.5 \text{ ft.}$) was smaller than 15 ft.:

$$K_z = K_h = 0.57.$$

The velocity pressure is given in ASCE Section 26.10.2 by: $q_z = q_h = 0.00256 K_z K_{zt} K_d K_e V^2$.

By replacing all the parameters with their values, the pressure was obtained: **$q_h = 13.42 \text{ psf (0.643 kPa)}$** .

Design wind pressures for Knoxville, TN:

- Minimum design wind pressures: $p_{\text{min}} = 16 \text{ psf}$ (ASCE Section 30.2.2).
- No composite panels had a tributary area larger than 700 ft^2 . Therefore, according to ASCE Section 30.2.3, they are not permitted to be designed using the provisions for main wind force resisting systems and should be designed as components and cladding elements.

Design wind pressures equation according to ASCE Section 30.3.2: $p = q_h \times [(GC_p) - (GC_{pi})]$

- ASCE Figure 30.3-1 was used to find the external pressure coefficient (GC_p) (Figure 78). For a more critical approach, only (GC_p) for zone 5 was calculated and applied to all panels. The largest cladding panel had an effective area of: $A = 8 \times 10.4 = 83.2 \text{ ft}^2$.
- Positive (GC_p) for pressures acting toward the surface: $+ 0.85$.
- Negative (GC_p) for pressures acting away from the surface: $- 1.05$.
- Internal pressure coefficient (GC_{pi}) = ± 0.55 (ASCE Table 26.13-1 for partially enclosed buildings).

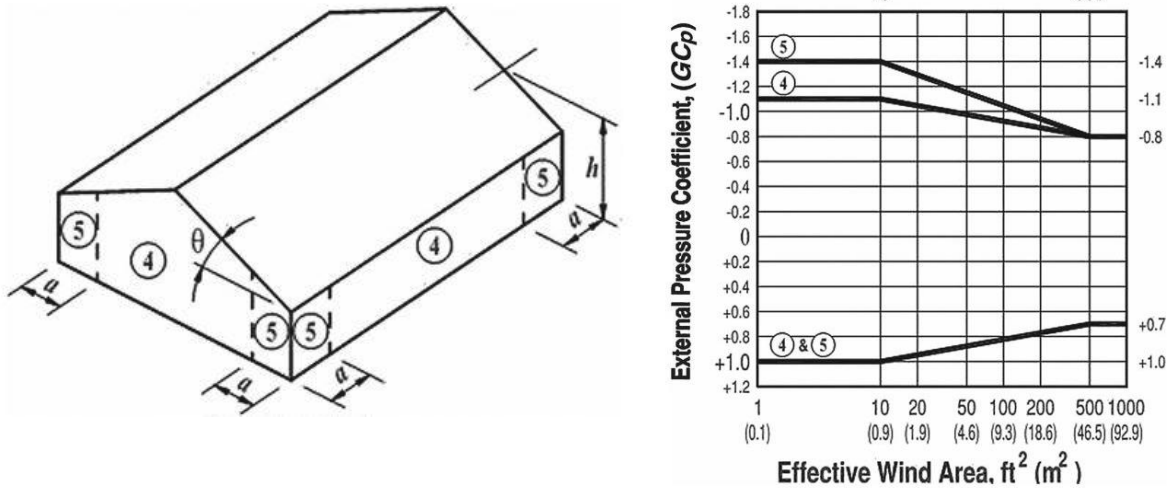


Figure 78. ASCE Figure 30.3-1 for calculating the external pressure coefficient (GC_p).

After finding the pressure coefficients, the wind pressures acting on the modular panels were calculated:

1. Positive wind pressure: $p_+ = 13.42 \times (0.85 + 0.55) = 18.8$ psf.
2. Negative wind pressure: $p_- = 13.42 \times (-1.05 - 0.55) = -21.5$ psf.

Therefore, a windward pressure of **0.13 psi (0.9 kPa)** and a leeward pressure of **– 0.15 psi (- 1.03 kPa)** were used to design the panels and connections.

4.3.4.2 Wind loads modeling

Based on the final design concept, the dimensions of the modeled structures are given in Figure 79. 3 separate models were created on Abaqus to simplify the analysis and decrease the simulation time:

- First model: the sandwich panel and L-bracket were modeled based on the assumption that no slippage nor separation would occur between them. A pinned line support (no displacements in all directions) was defined at the bottom of the panel. This line represents the contact between the sandwich panel and F-bracket. Similarly, the connection between the L-bracket and J-bracket was defined as pinned surface supports in the L-bracket. The panel was subjected to vertical dead (gravity) and snow loads, and horizontal wind loads. Only the leeward wind pressure was modeled because it was more critical than the windward pressure in this case.
- Second model (Figure 80a): the J-bracket was modeled with 11 holes every 12” (304.8 mm). However, only 3 fixed supports (no displacements and rotations in all directions) on the edge and middle holes were defined to represent the location of the bolts. Vertical and horizontal loads were applied to the structure as per Table 20.

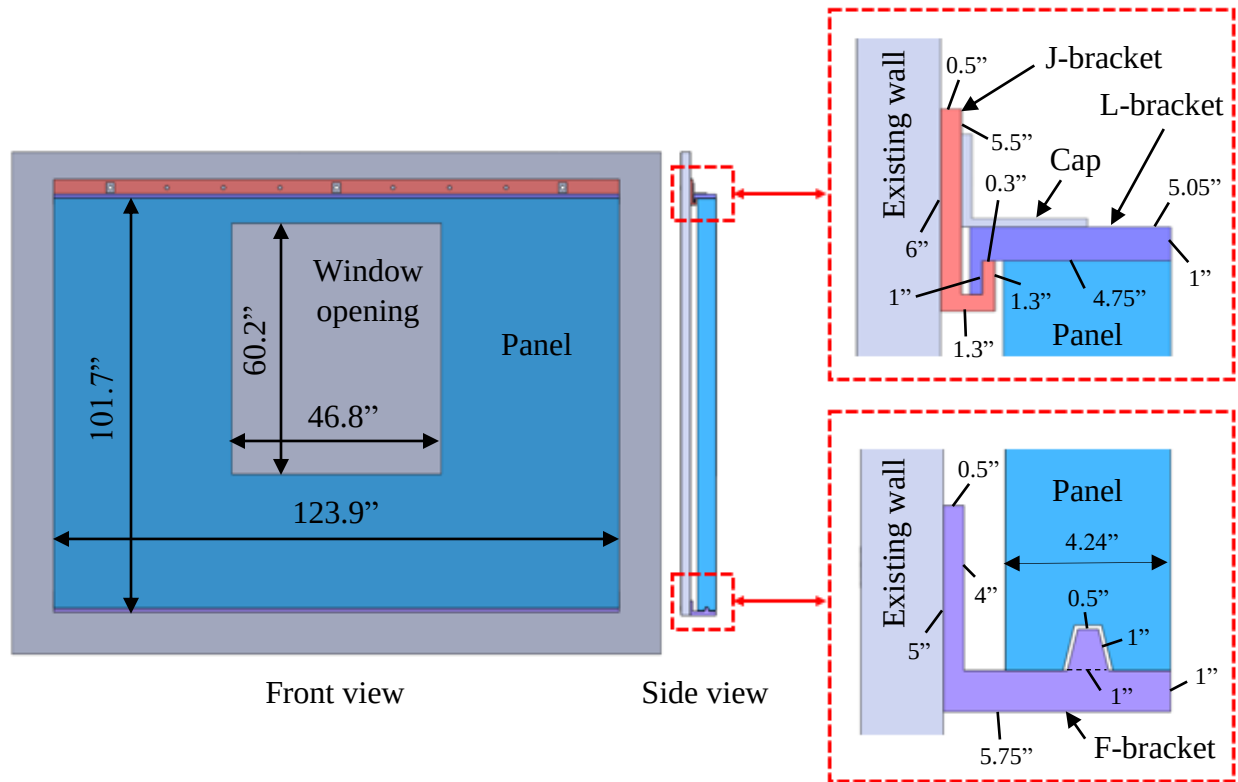


Figure 79. Sandwich panel and brackets dimensions used for the FEA simulations.

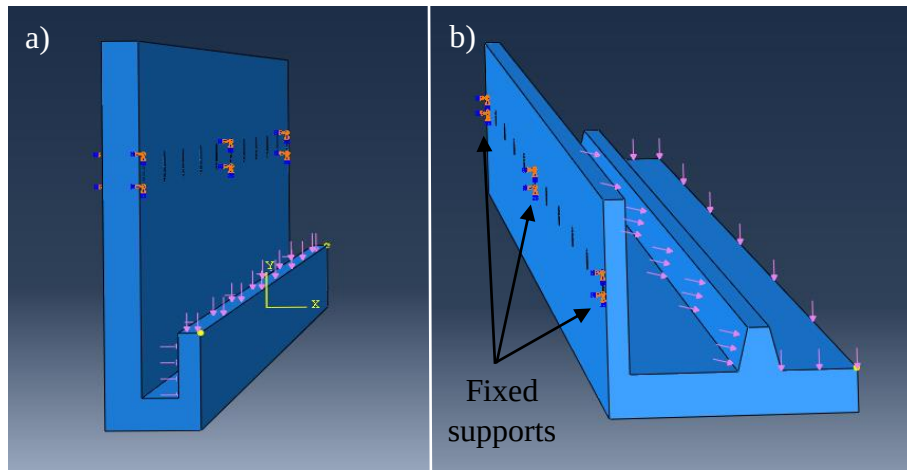


Figure 80. a) J-bracket and b) F-bracket models in Abaqus showing the fixed supports and vertical and horizontal loads.

Table 20. Vertical and horizontal loads applied to the J-bracket and F-bracket according to different load combinations.

Load Combination	J-bracket		F-bracket	
	Vertical load - psi (MPa)	Horizontal load (windward/leeward) - psi (MPa)	Vertical load - psi (MPa)	Horizontal load (windward/leeward) - psi (MPa)
(a) 1.4D	7.9 (0.054)	0 (0)	1.5 (0.01)	0 (0)
(b) 1.2D + 0.5W + 1.6S	8.4 (0.058)	6.7/7.7 (0.046/0.053)	1.6 (0.011)	6.7/7.7 (0.046/0.053)
(c) 1.2D + 1.0W + 0.5S	7.3 (0.05)	13.4/15.4 (0.092/0.106)	1.4 (0.01)	13.4/15.4 (0.092/0.106)

- Third model (Figure 80b): the F-bracket was also modeled with 11 holes every 12” (304.8 mm). Similarly to the J-bracket, 3 fixed supports on the edge and middle holes were defined to represent the location of the bolts. Vertical and horizontal loads were applied to the structure as per Table 20.

After running the analysis for each model with different load combinations, the maximum deflections and stresses were documented. As previously mentioned in *Section 4.3.2.1*, the maximum allowable deflection for exterior walls according to IBC Table 1604.3 is given by Equation 7. The panel has a span of 101.7” (258.3 cm) and the maximum deflection should therefore be less than $\delta_{\max(\text{panel})} = 0.43$ ” (10.8 mm). The maximum stresses should be smaller than the tensile strength of GFRP: $\sigma_{\max} = 42,786$ psi (295 MPa). Table 21 shows the maximum deflections and stresses in the panel for each load combination used in the first model. It can be seen that the load combination (c) gave the highest values for both parameters. Figure 81 illustrates the deflection and stress distribution in the first model for the mentioned load combination. The highest deflection was 0.068” (1.72 mm), which is 84.2% smaller than the allowable value. The highest stress in the panel was 1,715 psi (11.82 MPa), which is 96% smaller than the allowable value.

The span of the J-bracket and F-bracket between their middle and edge bolts is 60” (152.4 cm). Their maximum deflections should therefore be less than $\delta_{\max(\text{bracket})} = 0.25$ ” (6.35 mm). Table 22 shows the maximum stresses and vertical and horizontal deflections in the J-bracket and F-bracket in the second and third models, respectively. All load combinations and both wind pressure directions were analyzed. For the J-bracket, the load combination (c) with a leeward wind pressure gave the highest values for deflections and stress. Figure 82 illustrates the deflection and stress distribution in the second model for the mentioned load combination.

Table 21. Maximum horizontal deflection and stress in the sandwich panel for each load combination based on FEA results.

Load combination	Max. horizontal deflection - in (mm)	Max. stress - psi (MPa)
(a) 1.4D	0.000214 (0.0053)	38 (0.26)
(b) 1.2D + 0.5W + 1.6S	0.034 (0.86)	860 (5.93)
(c) 1.2D + 1.0W + 0.5S	0.068 (1.72)	1,715 (11.82)

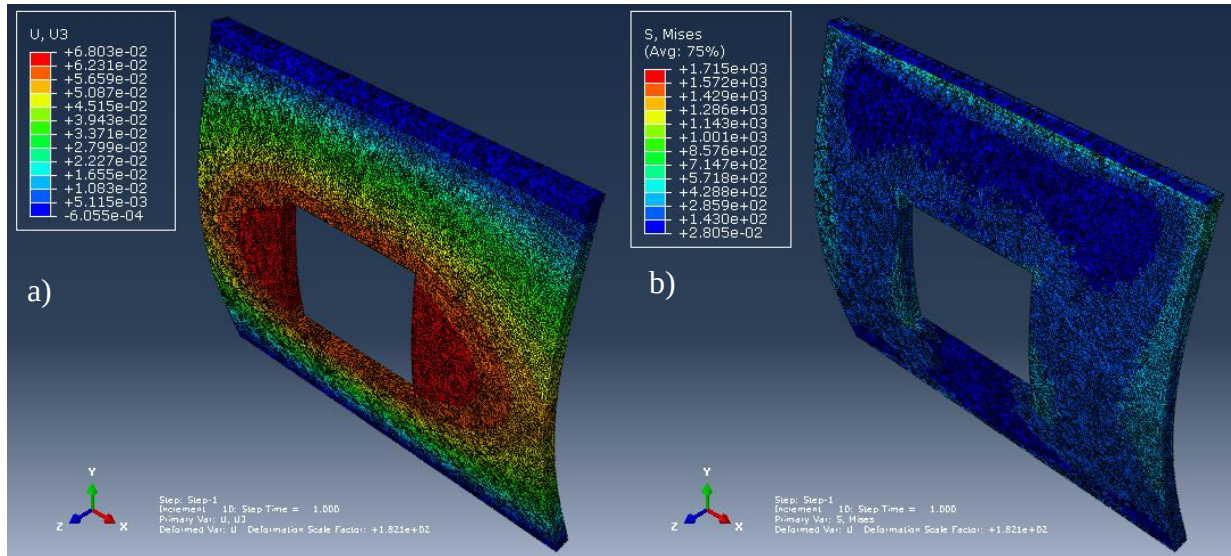


Figure 81. a) Horizontal deflection and b) stress distribution in the sandwich panel for load combination (c) based on FEA results in Abaqus.

Table 22. Maximum stresses and vertical and horizontal deflections in the J-bracket and F-bracket based on FEA results for different load combinations.

Simulation	J-bracket			F-bracket		
	Max. vertical deflection - in (mm)	Max. horizontal deflection - in (mm)	Max. stress - psi (MPa)	Max. vertical deflection - in (mm)	Max. horizontal deflection - in (mm)	Max. stress - psi (MPa)
(a)	0.008 (0.2)	0.014 (0.36)	1,660 (11.4)	0.043 (1.09)	0.018 (0.46)	8,890 (61.3)
(b) windward	0.005 (0.13)	0 (0)	977 (6.7)	0.008 (0.2)	0 (0)	1,651 (11.4)
(b) leeward	0.024 (0.61)	0.342 (8.7)	20,450 (141)	0.05 (1.27)	0.035 (0.89)	5,352 (36.9)
(c) windward	0.005 (0.13)	0 (0)	866 (6)	0.01 (0.25)	0 (0)	2,080 (14.3)
(c) leeward	0.057 (1.45)	0.7 (17.8)	41,530 (286)	0.05 (1.27)	0.049 (1.24)	6,404 (44.2)

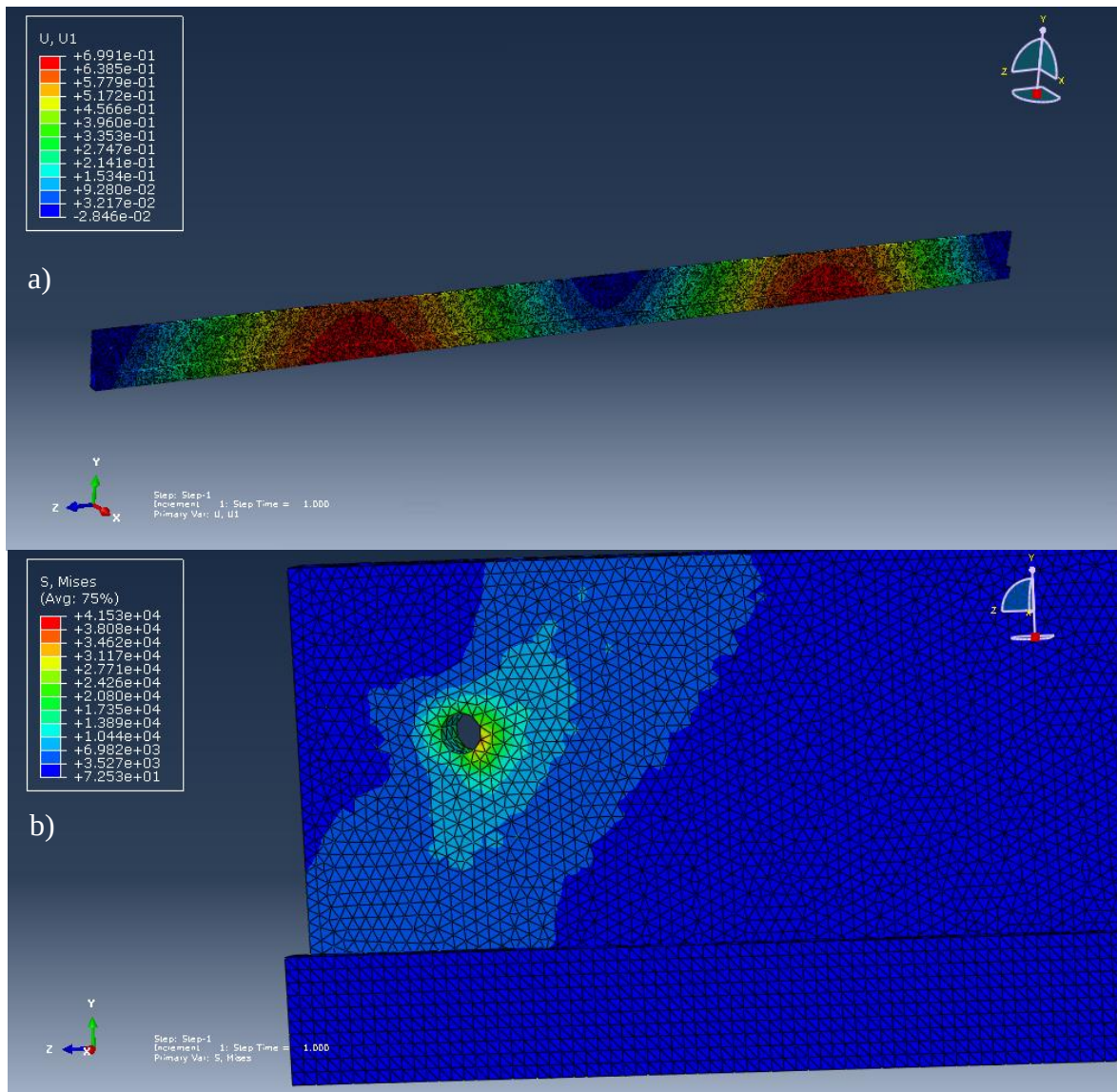


Figure 82. a) Horizontal deflection and b) stress distribution in the J-bracket for the critical load combination (c) leeward.

The vertical deflection was 0.057” (1.45 mm), the horizontal deflection was 0.7” (17.8 mm), and the stress was 41,530 psi (286 MPa). The horizontal deflection, vertical deflection, and stress were therefore 77.2% lower, 180% higher, and 3% lower than the allowable limits, respectively. For the F-bracket, the load combination (c) with a leeward wind pressure gave the highest deflections, but the load combination (a) gave the highest stress value. Figure 83 illustrates the deflection and stress distribution in the third model for the mentioned load combinations. The vertical deflection was 0.05” (1.27 mm), the horizontal deflection was 0.049” (1.24 mm), and the stress was 8,890 psi (61.3 MPa). The vertical deflection, horizontal deflection, and stress were therefore 80%, 80.4%, and 77.7% lower than the allowable maximum values, respectively.

Based on the results, the original dimensions and boundary conditions were deemed acceptable for the sandwich panel and F-bracket. In order to obtain admissible deflection and stress values in the J-bracket, 2 more fixed supports (bolts) were added between the existing ones. The bracket therefore contained 5 bolts in total. The new span of the modified J-bracket became 36” (91.4 cm). The maximum deflections should therefore be less than $\delta_{\max(\text{bracket}_2)} = 0.15”$ (3.81 mm). Table 23 shows the new values for the maximum stress and vertical and horizontal deflections in the modified J-bracket. Figure 84 illustrates the deflection and stress distribution in the second model for the load combination (c) with a leeward wind pressure. The vertical deflection was 0.014” (0.36 mm), the horizontal deflection was 0.11” (2.8 mm), and the stress was 20,280 psi (140 MPa). The vertical deflection, horizontal deflection, and stress were therefore 90.7%, 26.7%, and 52.5% lower than the allowable maximum values, respectively.

In summary, the original dimensions of the panel and brackets were accepted based on FEA results. The minimum number of bolts for the J-bracket and F-bracket should be 5 and 3, respectively. The bolts’ dimensions should be chosen based on the reaction values of the fixed supports.

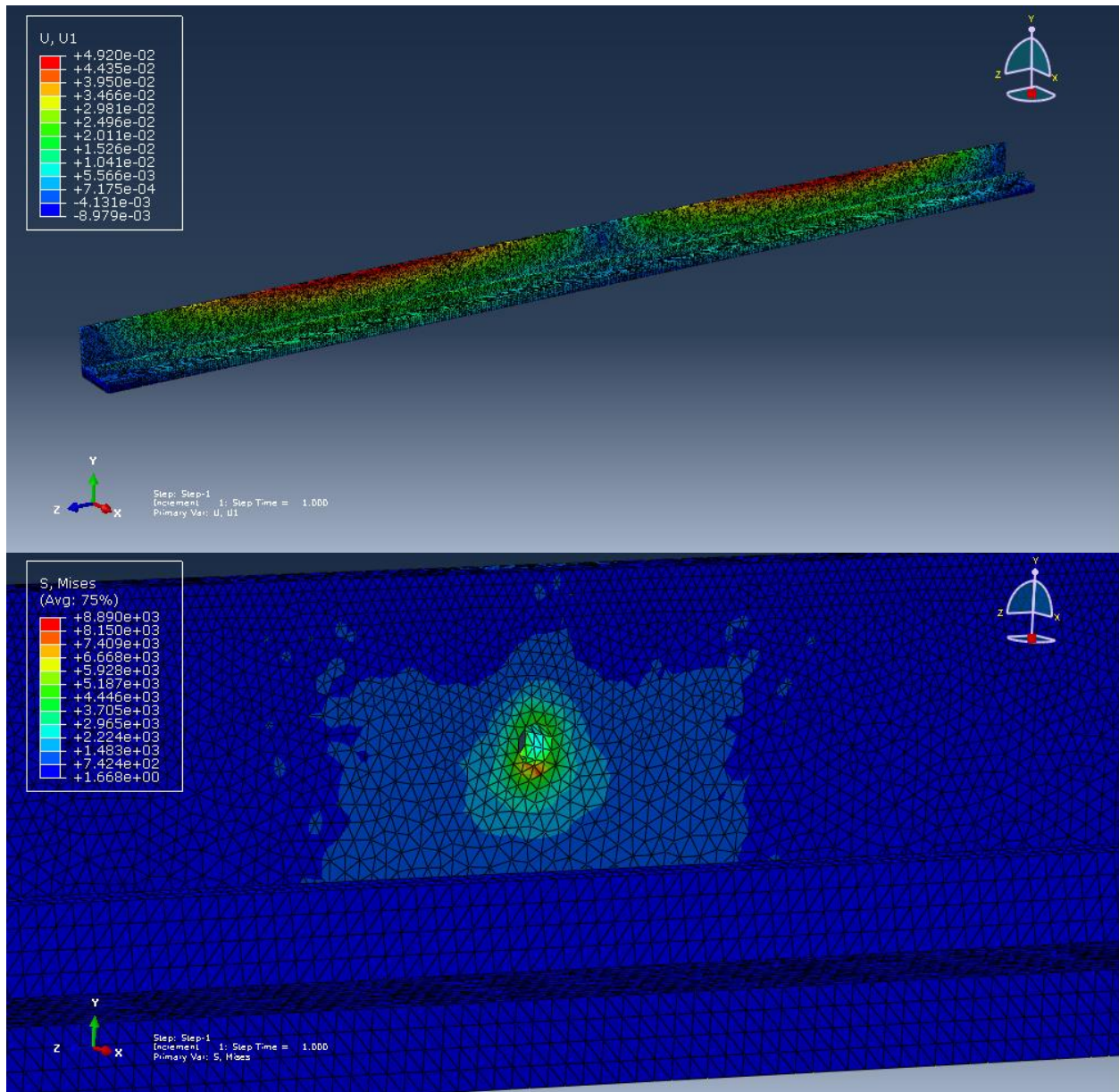


Figure 83. a) Horizontal deflection for the load combination (c) leeward and b) stress distribution for the load combination (a) in the F-bracket.

Table 23. Maximum stress and vertical and horizontal deflections in the modified J-bracket for the load combination (c) leeward after adding 2 fix supports.

Simulation	Modified J-bracket		
	Max. vertical deflection - in (mm)	Max. horizontal deflection - in (mm)	Max. stress - psi (MPa)
(c) leeward	0.014 (0.36)	0.11 (2.8)	20,280 (140)

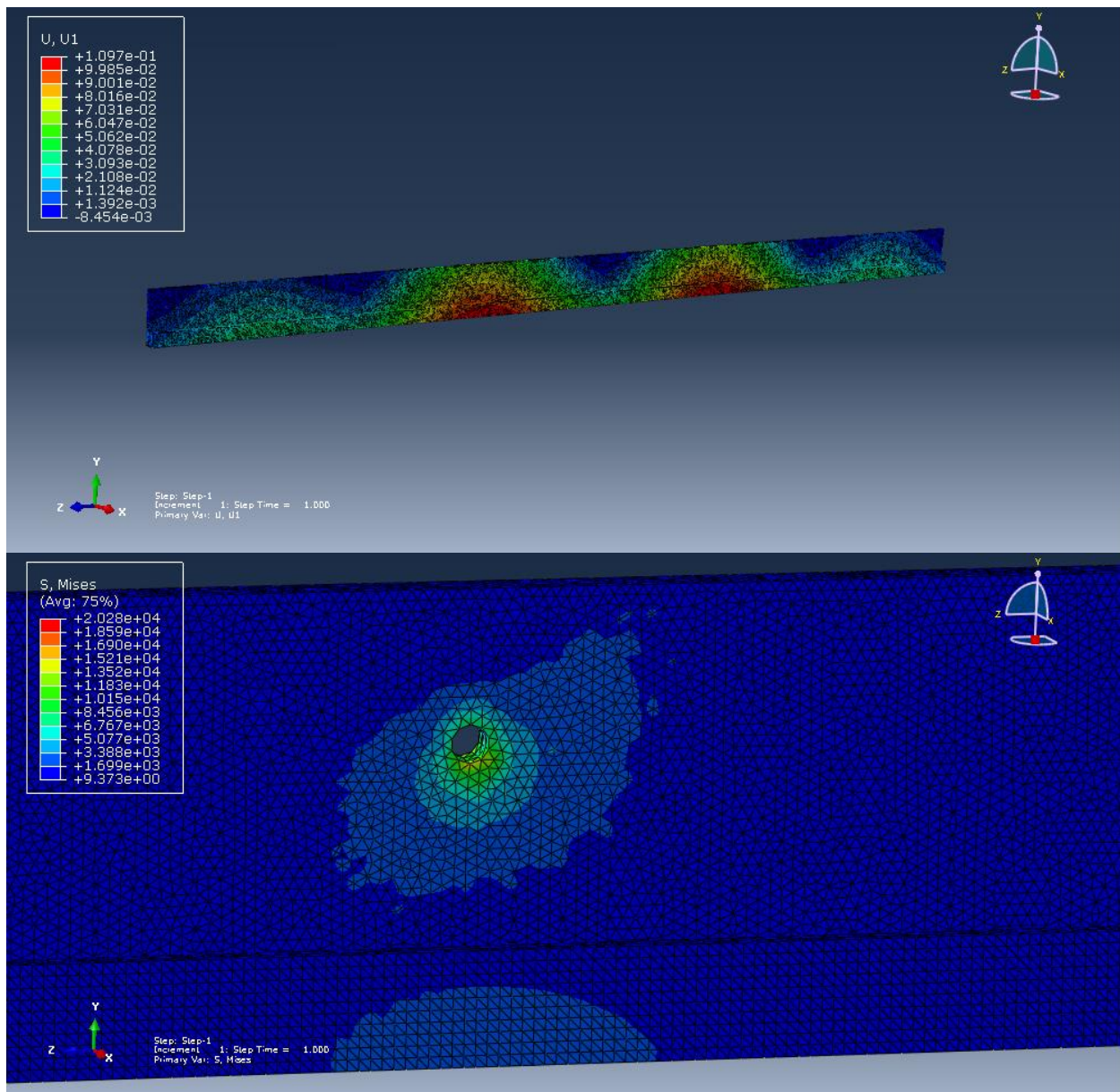


Figure 84. a) Horizontal deflection and b) stress distribution in the modified J-bracket for the critical load combination (c) leeward after adding 2 fixed supports.

4.3.5 UV/moisture testing

In order to check the environmental effects on the finished surface of the cladding panels, 12 GFRP samples were tested under UV and moisture exposure. Stage 1 of testing was conducted on 6 unpainted samples. Figure 85 illustrates clear discoloration in the plain samples where no coating was used. These results were observed after only 3 weeks of testing. 6 other samples were prepared and painted with a ceramic coating. Stage 2 of testing was conducted on them to check if the paint would solve the discoloration problem. Figure 86 shows no sign of color change in the painted samples even after 6 weeks of exposure.

Photodegradation under UV radiation caused yellowing and loss of gloss in the unpainted GFRP surface. The results were similar to the ones reported by Bazli et al. [27] for the GFRP material. Although no visible cracks were observed, the change in color was a problem by itself due to the aesthetic requirements in this project. Therefore, based on the results of the painted samples, the ceramic coating seemed to provide a good solution for UV and moisture resistance. In order to check if microcracks were formed in the GFRP and coating materials during testing, SEM was used on the samples.

Figure 87 illustrates the SEM results for the plain GFRP samples. The unexposed sample was taken as a reference to check the effects of UV and moisture after 3 and 6 weeks of accelerated exposure. The unexposed GFRP sample showed a rough surface and different impurities caused by dust particles and excess resin. After 3 weeks of exposure, it can be seen that glass fibers are clearly visible in the sample. In addition, the surface became smoother and more uniform, having less impurities than the unexposed material. After 6 weeks of exposure, glass fibers became more visible and the amount of impurities was even lower. As Lu et al. [25] mentioned in their study, the irregular (rough) surface of FRP composites became smoother after UV exposure.

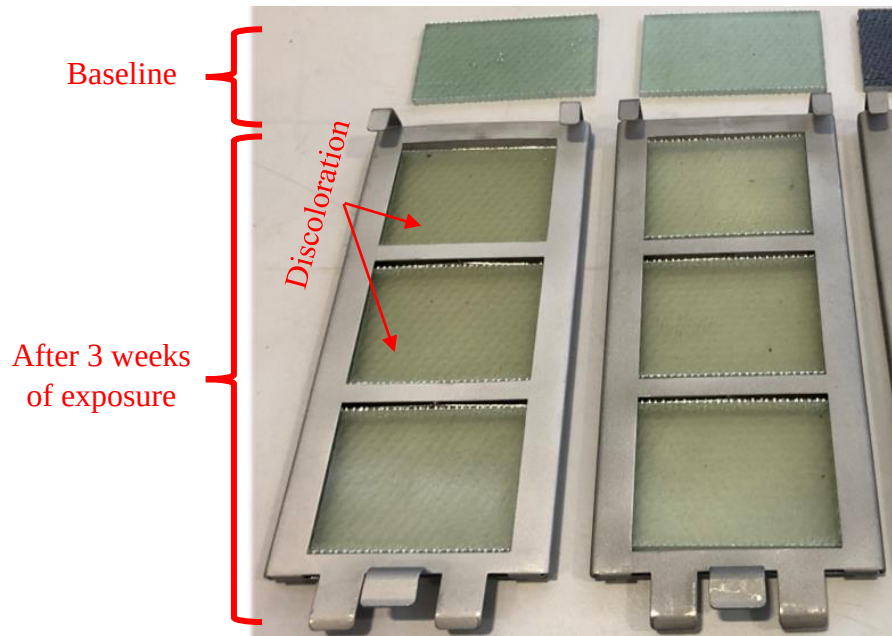


Figure 85. Discoloration of the unpainted GFRP samples after 3 weeks of exposure to accelerated environmental effects (ATSM G155 and ASTM D2565).

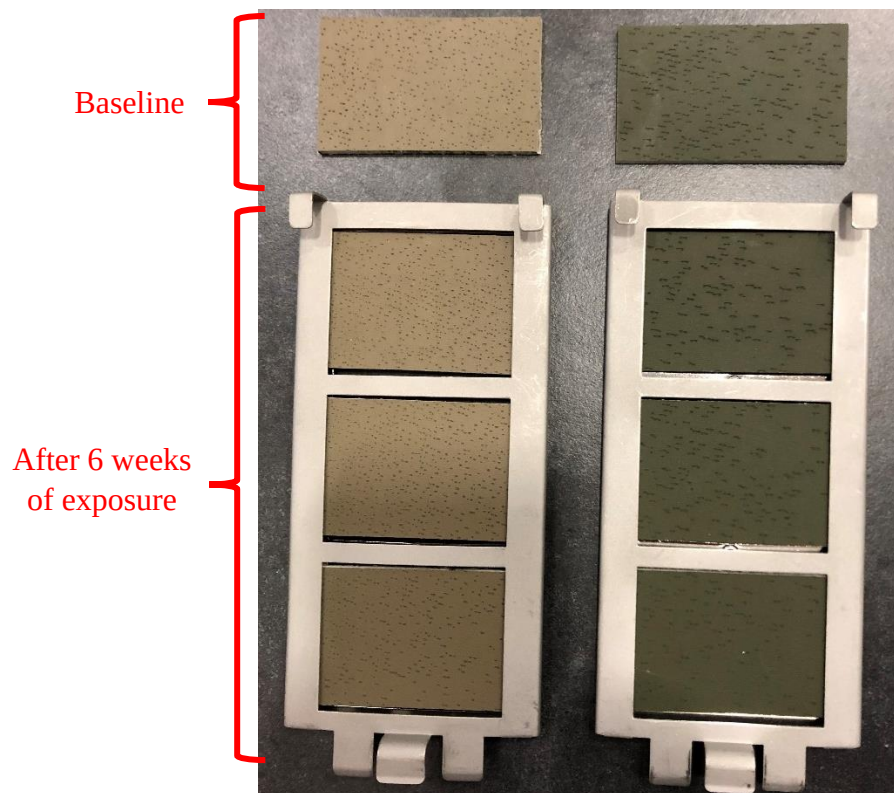


Figure 86. No discoloration in the painted GFRP samples after 6 weeks of exposure to accelerated environmental effects (ATSM G155 and ASTM D2565).

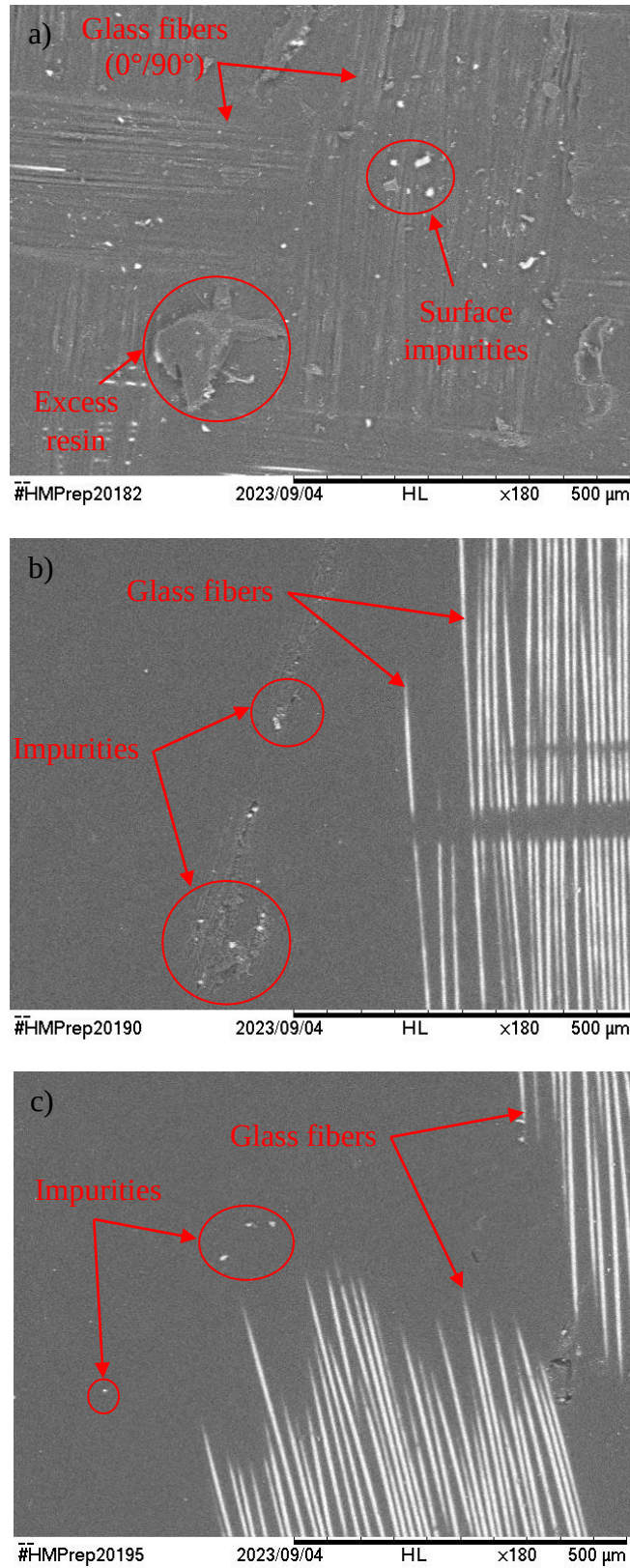


Figure 87. SEM on plain GFRP samples a) without UV exposure, b) after 3 weeks of UV exposure, and c) after 6 weeks of UV exposure.

Due to the degradation of the epoxy resin, the glass fibers present in the plain GFRP samples used in this research were exposed. The loss of surface impurities after testing also suggests that a layer of resin containing them had degraded. Furthermore, the exposed glass fibers after 3 and 6 weeks of testing weren't uniformly distributed over the sample in the SEM images. This could be contributed to the fact that UV radiation may have reflected differently on the unequal surface with varying roughness. The difference in reflection allowed only a fraction of the glass fibers to become exposed.

Figure 88 illustrates the SEM images for the coated GFRP samples. The unexposed samples showed a rough and uniform surface for both paint colors. After 6 weeks of accelerated UV and moisture exposure, no major differences were seen in the samples coated with the coyote tan color. 2 main observations were made for the o.d. green coated samples after exposure: the surface became smoother and few microcracks were formed.

The results show that the ceramic coating applied to the GFRP samples protected the resin from degrading which could expose the glass fibers and make them prone to cracking. Although some microcracks formed inside the coating, the painted samples did not lose their color after testing for 6 weeks. Ceramic coating was therefore considered an acceptable aesthetic solution for protection against environmental effects.

4.3.6 Fire simulation

Figure 89 illustrates the fire spread along the composite panel after 10 minutes of simulation. The model recreated the setup specified in the ASTM E84 standard. The total distance covered by the flames was 4.4' (134.1 cm) at the end of the analysis. The speed of fire was therefore 0.0073 ft/s (0.0022 m/s).

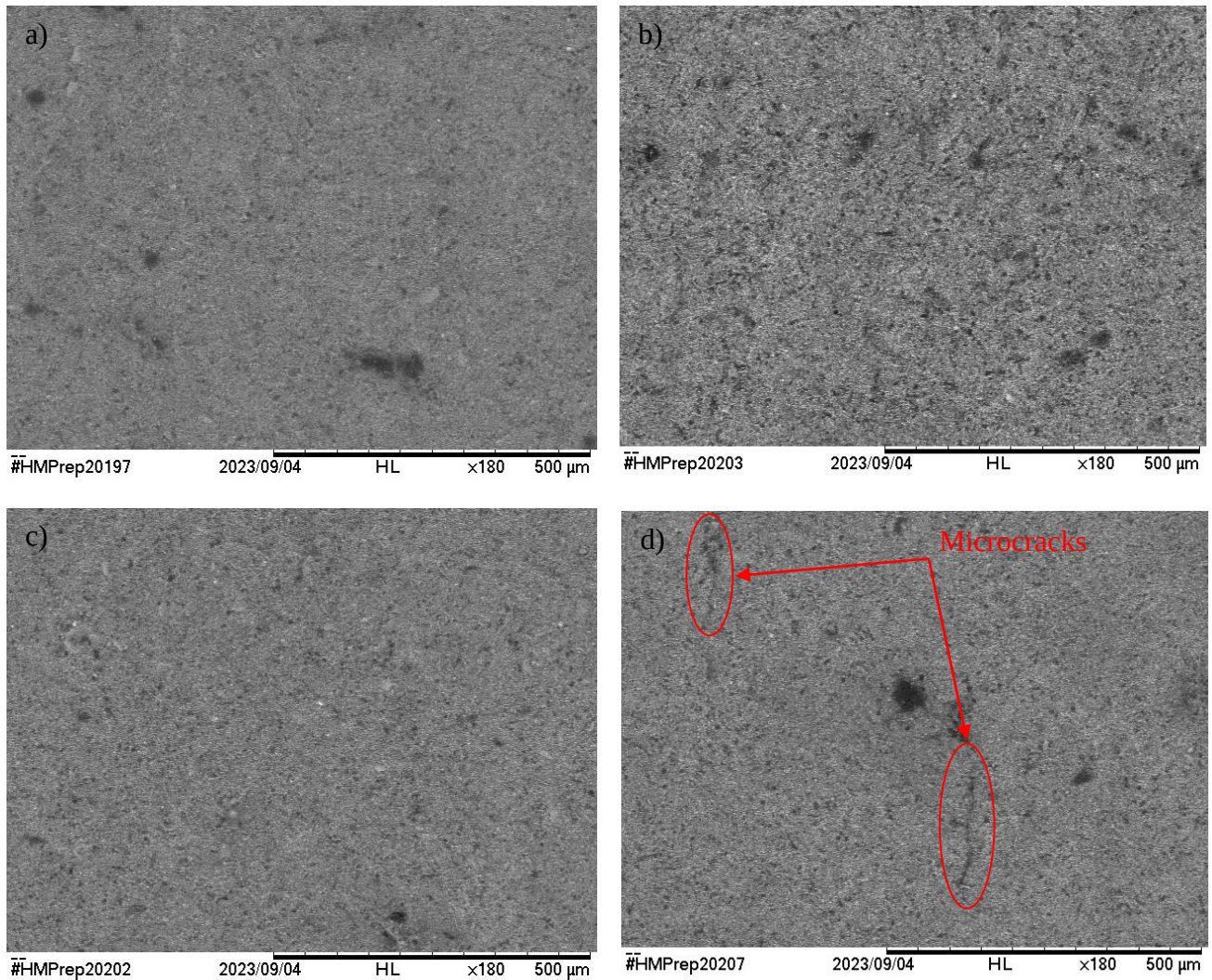


Figure 88. SEM on painted GFRP samples with a) coyote tan ceramic coating without UV exposure, b) o.d. green ceramic coating without UV exposure, c) coyote tan ceramic coating after 6 weeks of UV exposure, and d) o.d. green ceramic coating after 6 weeks of UV exposure.

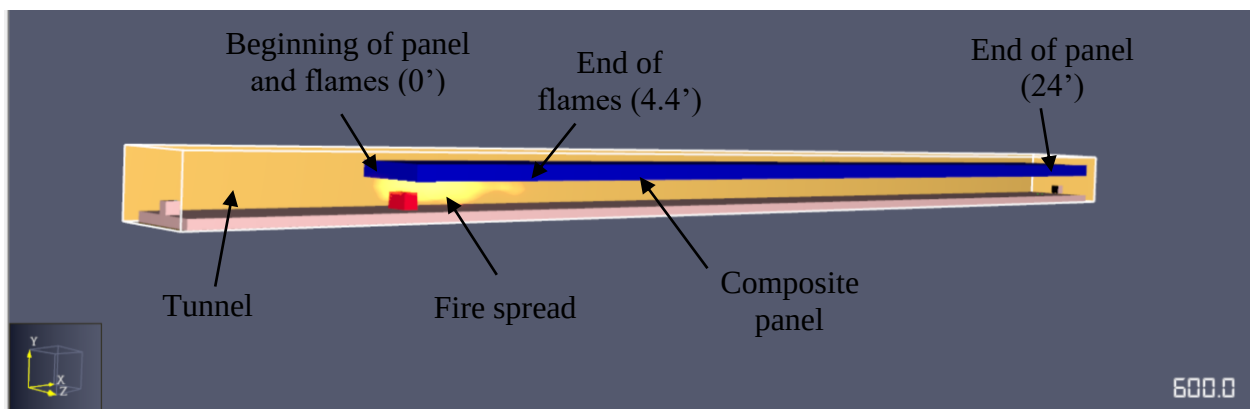


Figure 89. Fire spread along the composite panel after 10 minutes of simulation.

Figure 90 shows the change in temperature at the beginning (0') and end (24') of the panel during the 10 minutes fire spread. Both references started with a 68 °F (20 °C) temperature. After 10 minutes of fire simulation, the beginning of the panel reached a maximum temperature of 374 °F (190 °C), which represents a 850% increase from the initial state. The end of the panel reached a maximum temperature of 169 °F (76 °C), representing a 280% increase from the initial state. Therefore, at the 0' (0 cm) location, the panel reached a 150% higher maximum temperature than the 24' (731.5 cm) location. The results show that, even if the flames didn't reach the end of the composite panel, the temperature increased by 280%. This is due to the flow of heat inside the GFRP and XPS materials.

The flame spread index (FSI) was used to classify the cladding panel according to a fire rating shown in Table 24. The values are given by the ASTM E84 standard, with A being the best class and E the worst. In order to get the desired classification, the FSI was calculated by Equation 8:

$$FSI = \frac{550}{t} \quad \text{(Equation 8)}$$

Where t (minutes) is the time in which flames spread 19.5' (594.4 cm) on the panel. By interpolation, a t of 44.3 minutes was obtained, and the FSI of the composite panel according to the fire simulation is 12.4. Therefore, the cladding panel has a class A rating according to the fire model. However, the results need to be validated by an actual tunnel test according to ASTM E84.

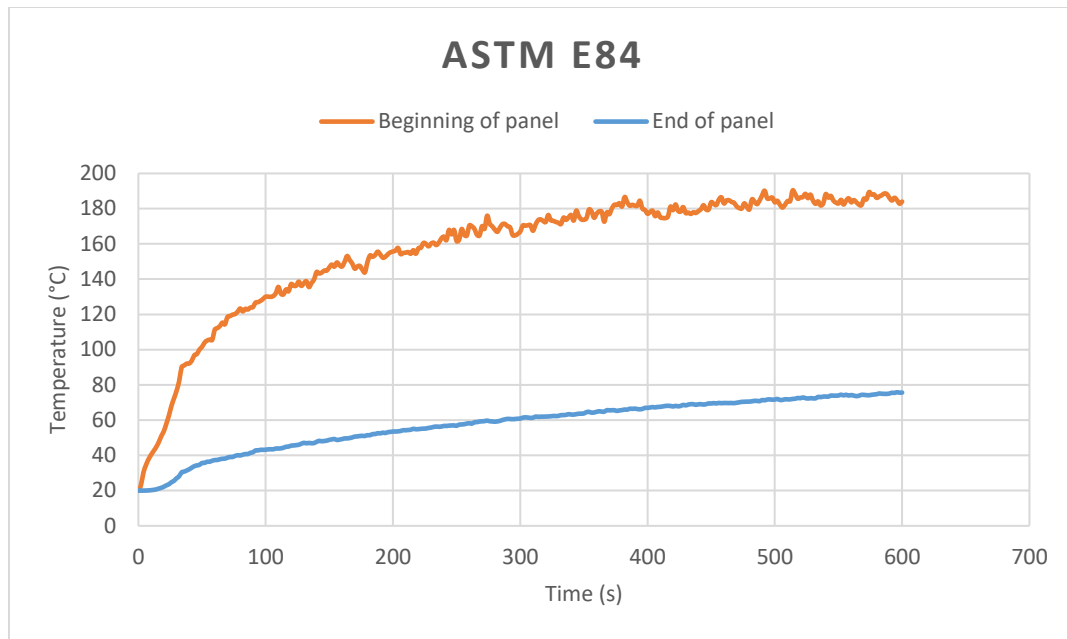


Figure 90. Temperature vs Time change in the beginning (0') and end (24') of panel during the fire simulation according to ASTM E84.

Table 24. Fire rating classifications based on the FSI according to ASTM E84.

Class	FSI
A	0 - 25
B	26 - 75
C	76 - 200
D	200 - 500
E	> 500

CHAPTER 5:

CONCLUSIONS AND FUTURE WORK

In this research, cladding sandwich panels were designed and tested to serve as an exterior retrofitting application. The goal was to improve the energy efficiency of several buildings located in Knoxville, TN. DOE's BTO and ORNL managed the project, while UT's FCMF, IACMI, and DB Technologies were in charge of research and manufacturing. The sandwich structures were composed of GFRP/epoxy skins and a polymeric foam core. VARTM was used as a primary manufacturing technique due to the large size of the panels. The work was divided into 2 main parts: XPS and PU foams were first compared as core materials by a series of lab-scale thermal and mechanical tests. The second part contained all concepts, testing, and simulation related to the current application of the modular cladding panels.

Based on the results, several conclusions were drawn:

- The VARTM process gave a consistent resin content by weight (between 31.0% and 36.3%) for GFRP plates and XPS sandwich panels having a maximum of 1 vertical GFRP joint. However, this percentage increased for the Prisma sandwich panel (39.4%). The difference was caused by the presence of 3 inclined GFRP joints that absorbed more resins than vertical joints. According to ASTM C271, the Prisma panel had a density of 2.89 lb/ft² (14.1 Kg/m²), which was 35% higher than the 2.14 lb/ft² (10.4 Kg/m²) density of the XPS panel. The XPS sandwich panel was therefore the lighter structure.
- The thermal resistance per inch of material (R-value/in) at a 75 °F (24 °C) mean temperature was compared for different panels (ASTM C518). XPS foam had an R-value/in of 4.9 h.ft².°F/Btu (0.86 K.m²/W), which was 1,189% higher than the 0.38 h.ft².°F/Btu (0.07 K.m²/W) R-value/in of GFRP. Therefore, the XPS foam provided most

of the thermal resistance of any XPS/GFRP sandwich structure. Another comparison involved an XPS sandwich panel without joints and a Prisma panel with 3 joints. The Prisma panel had an R-value/in of 3.66 h.ft².°F/Btu (0.64 K.m²/W), which was 17.9% lower than the 4.46 h.ft².°F/Btu (0.79 K.m²/W) R-value/in of the XPS panel. This difference was caused by the low thermal resistance of the GFRP material present inside the web. Thermal bridging was therefore the result of heat transfer through the GFRP joint. The XPS sandwich panel was therefore the better insulation structure.

- 4 mechanical tests were conducted to compare the structural performance of XPS and Prisma sandwich structures. A 3-point bending test (ASTM D7249) resulted in a failure by delamination in both structures. The delamination was followed by a shear crack in the foam core in the XPS samples only. They also had a 43.8% higher elastic modulus, 40% higher failure load, and a 15.8% lower failure displacement than the Prisma samples. A 4-point bending test (ASTM C393) resulted in a failure by cracking of the top and bottom facesheet in the XPS and Prisma samples, respectively. The XPS sandwich structures had a 23.8% higher peak load and 28.2% lower total deflection than the Prisma sandwich structures. However, they both showed an equal modulus in the elastic zone. An LVI test (ASTM D7136 and ASTM D7766) resulted in the Prisma samples exhibiting greater deformation compared to the localized damage propagation found in the XPS samples. XPS panels had a 9.6% higher force, 1.1% lower absorbed energy, and 6.4% lower displacement than Prisma panels. Finally, an FTT test (ASTM D7291) resulted in failure by shear cracking of the foam in the XPS samples, and delamination between skin and foam in the Prisma samples. The latter panels also failed for a 32% lower load and had a 40.3% lower elastic modulus than the XPS panels. The 4 tests gave similar results: the XPS

samples exhibited a brittle behavior while the Prisma samples exhibited a ductile one. SEM was carried out on the 2 types of foams and showed that XPS had a lower void content than PU. The difference in foam structures resulted in difference in behavior under the applied loads. Although it demonstrated a brittle failure, the XPS sandwich panel was the stronger structure.

- Tensile testing (ASTM D3039) on GFRP samples gave an elastic modulus of 3,191 Ksi (22 GPa), a tensile strength of 42,786 psi (295 MPa), and a Poisson's ratio of 0.165.
- After choosing the XPS foam as a core material for the cladding panels, flexural tests were conducted on a 4 x 8 ft² (121.92 x 243.84 cm²) sandwich structure. FEA models were developed to compare the deflection values between testing and simulation. Less than 4% variation was noted between experimental and numerical data. The FEA models were therefore validated.
- Multiple concepts regarding the design and installation of panels and connections on the existing buildings were studied and modeled. Easy manufacturing and installation, along with the possibility to remove a single panel for maintenance, were key requirements in the project. The final concept included J-brackets and F-brackets fixed by bolts to the existing RC slabs. The sandwich panel, containing an L-shaped bracket on the top side, would be installed on the fixed brackets. Caps would then be placed on top of the panels to resist uplifting. Rubber gaskets would be placed along the panel edges to eliminate any water infiltration.
- In order to design the panels and connections, 3 FEA models were created. The first model contained the largest sandwich panel, having 123.9 x 101.7 x 4.24 in³ (314.71 x 258.32 x

10.74 cm³) as dimensions. The second and third models contained the J-bracket and F-bracket, respectively. 3 load combinations composed of dead, wind, and snow loads were used according to the ASCE-7 standard. The panel had a 84.2% lower maximum deflection and 96% lower maximum stress than the allowable values given by the IBC and tensile test. Similarly, the J-bracket had a 90.7% lower vertical deflection, 26.7% lower horizontal deflection, and 52.5% lower stress than the allowable values. Finally, the F-bracket had a 80% lower vertical deflection, 80.4% lower horizontal deflection, and 77.7% lower stress than the allowable values. Based on the FEA results, a minimum of 3 and 5 bolts should be used to fix the F-bracket and J-bracket, respectively.

- Plain and coated GFRP samples were tested under UV and moisture exposure (ATSM G155 and ASTM D2565). Photodegradation in the plain samples caused discoloration after 3 weeks, while the coated samples showed no signs of discoloration, even after 6 weeks of exposure. Further investigation using SEM showed that the resin degraded in the plain samples. The results showed that the ceramic coating applied to the GFRP samples protected the resin from degrading which could expose the glass fibers and make them prone to cracking.
- Fire modeling was conducted on the composite panel according to the ASTM E84 standard. The results gave an FSI of 12.4, which classified the panel with a fire rating A.

The research and multiple tests conducted in this study contributed to the advancement of the ongoing cladding project. However, several tasks are still needed to ensure that the panels abide by the project's requirements. The expansion bolts, that will be used to fix the brackets to the existing RC slabs, should be designed. Their dimensions should be chosen according to the support reactions from the FEA models and the American Concrete Institute (ACI) and The Masonry

Society (TMS) standards' requirements. Furthermore, fire testing according to ASTM E84 should be conducted to compare the results with the fire simulation. Optimizing the connections by varying their dimensions in the FEA models could be beneficial in terms of saving material and reducing the project cost. Finally, adding color pigments inside the resin could eliminate the step of applying ceramic coating. Considering the mentioned possibility would also require testing the new resin system under UV and moisture exposure.

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VITA

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Marc Al Ghazal graduated from the Lebanese University in 2016 with a Bachelor's degree in Civil Engineering. He worked as a Civil Site Engineer for Eldo Steel in Lebanon for 1 year. His duties were to calculate project budgets, supervise steel structures' assembly in the factory, and manage teams during site work. He then worked as a Structural Design Engineer for 4 years for Civil Minds and Ammerha in Lebanon. His duties were to design reinforced concrete and steel structures based on FEA modeling and building standards. He also created structural execution drawings and supervised site works. In Spring 2022, he started his Master's degree in Structural Engineering at the University of Tennessee, Knoxville in the United States. He also worked as a Graduate Research Assistant at the Fibers and Composites Manufacturing Facility and graduated in Fall 2023.