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ORIGINAL ARTICLE

Development and evaluation of load-bearing fiber reinforced polymer composite panel systems with tongue and groove joints

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Abstract: This paper focuses on recent advances made in design, development, manufacturing, evaluation and modeling of load bearing fiber reinforced polymer (FRP) composite sandwich panel systems including tongue and groove joints. Several processes have been researched in collaboration with industry partners for production of composite panels, including: 1) pultrusion, 2) high temperature resin spread and infusion, 3) vacuum assisted resin transfer molding (VARTM), and 4) compression molding. The advantages and disadvantages of each process are discussed with emphasis on the high temperature resin infusion process. Composite laminates are characterized in terms of strength and stiffness under tension, bending, and shear in relation to longitudinal and transverse fiber orientations. Thermo-mechanical property variations of the FRP composite sandwich panels including joint responses are presented in terms of: 1) production processes, 2) carbon versus E-glass fiber, 3) vinyl ester versus epoxy, and 4) panel and joint design and efficiency including classical lamination theory. The sandwich panels are evaluated at component and full scales under static four point bending loads and further analyzed using classical finite element models for their mechanical responses.

Keywords: Fiber reinforced polymer composite; FRP; sandwich panel; tongue and groove joints; pultrusion; resin infusion; vacuum assisted resin transfer molding; VARTM; compression molding; thermo-mechanical properties; finite element modeling

1 Introduction

Few materials can survive long service life under aggressive waterfront environment, i.e. onslaught of sea waves, impact from vessels, corrosive salts, sand and pebble erosion, high atmospheric humidity, inter-tidal wetting and drying, UV ray effects and marine borers etc. [1-3]. Historically, steel has been the primary structural material used to construct ships. Structure components make up the largest weight group of any ship, typically contributing 35% to 45% of the overall vehicle weight [4], which implies that ship structures have a major influence on the overall characteristics such as displacement, payload, signatures, combat system effectiveness, and life-cycle cost. According to Greene [5], 52 percent of a ship’s manpower is focused on maintenance because of primary construction material being steel requiring constant maintenance to avoid rapid degradation from corrosion. Costs of spare parts and associated downtime to repair corroded structures and hardware severely compromise a ship’s readiness.

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It is desired to develop an alternative to steel for the construction of ship structures [2, 6].

A composite material is a combination of two or more materials (reinforcing elements such as fibers, and binders such as polymer resins), differing in form or composition [7]. The combination of these materials can be designed to result in a material that maximizes structural performance properties. For example, fiber reinforced polymer (FRP) composites are made of thermosetting or thermoplastic resins, and glass, carbon or other types (e.g. Kevlar or natural fiber Flax /Kenaf) of fibers (rovings), mats and/or fabrics. The fiber network is the primary load-bearing component, while the resin helps transfer loads including shear forces through fibers and fabrics and maintains fiber orientation. The resin primarily dictates the manufacturing process and processing conditions, and partially protects the fibers/fabrics from environmental damages such as humidity, temperature fluctuations, and chemicals [8-10].

FRP composites are gaining market acceptance as replacements of traditional materials because of their superior corrosion resistance, excellent thermo-mechanical properties, and high strength-to-weight ratio [11, 12]. Composites also offer many other advantages, including: 1) higher fatigue strength and impact energy absorption capacity; 2) design flexibility; 3) longer service life (over 100 years); 4) lower installation, operation and maintenance costs; 5) non-conductivity; 6) non-toxicity; and 7) consistent batch-to-batch performance. For military applications such as aircrafts, ships and submarines, composite materials offer additional benefits by providing blast-, shock- and fatigue-resistance with reduced magnetic, acoustic and infrared (IR) interferences [4, 13-15].

FRP composite materials and systems have been extensively researched and developed for infrastructure applications for over 30 years [12, 16-19]. For example, numerous FRP highway structures and systems have been developed and are being implemented in West Virginia and many other states in the United States [17]. Among the success stories was the evolution of FRP bridge decks over a period of 10 years, leading to a six-fold increase in ultimate strength and a three-fold decrease in unit cost of FRPs [18]. The significant cost improvement was achieved through the pultrusion process integrated with innovative product design.

This paper presents recent advances in design, development, manufacturing, fabrication, evaluation and modeling of load bearing FRP composite sandwich panel systems including joints [20-23]. Such panel systems have great potential for following applications: 1) decking for ships and marina, 2) bridge and prefab pavement panels for highway structures, 3) housing and other shelters, and 4) protective armors for vehicles and other structures. Each of the above applications represents a huge market opportunity for FRP composites. For example, a study reports that US marina decking industry has an annual market size of $3.4 billion with 5.1 billion board feet of material consumption [24]. A 5% use of composites in lieu of wood would give a projected FRP annual market of $170 million.

A typical sandwich panel can be defined as a three-layer construction, i.e. two thin face sheets (skin) and a thick core, as shown in Fig. 1 [25]. The skin is thin and stiff with high strength; while the core is thick and lightweight. A good sandwich construction requires the core to be strongly bonded to the skin so that the core can transfer loads from one face sheet to the other; thus, the core and skins will act in unison offering greater stiffness than the face sheets alone. Typically, the thickness ratio of core to skin is in the range of 10 to 15 [25]. In the present study, end grain balsa wood was used as core material (thickness ~3 in.), and glass or carbon FRP composite (thickness ~0.25 in.) was used as face sheet material.

Improved structural system response of sandwich and other structural systems is closely tied to reliable and efficient response of joining mechanisms to transfer loads from one composite component to the contiguous component [26-30]. For example, connection integrity plays a crucial role (Achilles heel) in controlling serviceability (deformations, vibrations, fatigue, fracture, chemo- thermo-mechanical responses over ~100 years) and strength distribution and energy dissipation. Therefore, structural systems are designed to fail in members rather than in connections, even though majority of failures are noted in connection zones. Load transfer connections are designed either as adhesive connections or as mechanical connections or even a combination of the two approaches [8-9, 31-32]. The adhesive connections are used widely in the aerospace industry because of reduction in connector weight, lower stress concentrations and smoother aerodynamic surfaces. In this study adhesive connections were made and tested with tongue and groove joining mechanisms along with three layers of external FRP wraps, i.e. two 4’ wide sandwich panels with double lap joint profiles were adhesively bonded to produce 8’ wide panels for joint efficiency evaluations [21,33].

More specifically the objective of present research is to develop lightweight, load-carrying FRP composite sandwich panel systems including joining mechanisms in a cost-effective manner with reference to VARTM- based panels. The composite laminates and sandwich panels produced from different manufacturing processes are characterized both at the coupon and panel levels for their mechanical responses under tension, compression, bending, and shear. In addition, their physical and morphological properties are determined including fiber volume content, panel density, and interfacial bond between resin and fiber. The results are discussed with reference to variations in process, fiber, and resin for quality and cost effectiveness. The mechanical responses of FRP sandwich panels including panels with joints under static loads are also evaluated through Finite Element (FE) modeling using MSC.NASTRAN. FE analysis was carried out at both the bench and full scale panel levels for comparison with experimental data. The effects of different material properties and panel profiles were investigated with attempts to characterize confinement effect of panel edge caps and predict panel failure modes [23].

2 Technical Approach

The novelty of this research lies in demonstrating the applicability of automated pultrusion process for the production of thick FRP sandwich structural panels including joining mechanisms in contrast to the traditional manufacturing method through Vacuum Assisted Resin Transfer Molding process [20-23, 33]. This was successfully accomplished from initial funding, leading to the expansion of the scope of work to include joints and CFRP with three more years of funding as applied research. The research findings were later transferred to shipbuilding industry for scale-up development and eventual field implementation [34]. However, this paper only presents the research activities and findings from the applied research and development phase. It was also of significance that the adhesive connections made from pultruded tongue and groove joining profiles were able to yield near 100% joint efficiency, i.e. failure occurring away from the joints.

The E-glass and vinyl ester resin system through a vacuum-assisted resin transfer molding (VARTM) process emerged as the base-line composite laminate and sandwich panel manufacturing technology in ship building industries [4,35]. One such product manufactured through VARTM process is a composite sandwich panel consisting of a 1/4” thick FRP laminate as face sheets with a 3” thick balsa wood core [36].

The initial goal of the present study was to demonstrate the feasibility of an automated pultrusion process to produce composite sandwich panels. This was accomplished in collaboration with Bedford Reinforced Plastics (BRP) Inc. A total of 1360 sq ft of glass/510A vinyl ester composite structural panels with balsa core was successfully mass-produced and evaluated for thermo-mechanical properties [20].

The work continued to develop carbon and vinyl ester sandwich panels through pultrusion process [21- 23]. A total of 300 sq ft of CFRP panels were produced by BRP and evaluated at West Virginia University Constructed Facilities Center (WVU-CFC). It was established that the sizing incompatibility of carbon with vinyl ester appears to result in less than optimal performance of carbon/vinyl ester composites. Thus, carbon/epoxy system was strongly recommended for further development [22].

Both the pultrusion and VARTM processes with epoxy resin are extremely challenging for mass production because of epoxy’s high viscosity, high temperature cure (177 – 204^{0}C) and other manufacturing adversities. Therefore, the WVU-CFC researchers have collaborated with Fiber-Tech Industries Inc to develop a new vacuum assisted high temperature resin spread and infusion (batch) process that would be viable and yet cost effective for mass production of carbon fabric/epoxy composite sandwich panels. This process appears to present unique advantages over pultrusion and VARTM for large composite sandwich panel production in a cost-effective manner [33].

3 Constituent Materials

Vinyl ester resin: Ashland Derakane 510A-40. It is a grade of brominated epoxy- vinyl ester resin that offers the maximum degree of fire retardancy combined with enhanced chemical resistance and toughness.

Epoxy resin: API FR-7. This resin has been developed by Applied Poleramic Inc. (API, Benicia, CA). FR-7 has low viscosity, high glass transition temperature and toughness and is curable at 71-82^{0}C. For comparison, Shell EPON Resin 9310 epoxy (Resolution Performance Products LLC, Houston, TX) cures at 182-216^{0}C.

E-glass fabric: 40 oz/sq yd quadaxial stitched fabric was supplied by V2 Composites Inc. Each layer of V2 fabric comprises of 33% glass rovings in 0^0 direction, 27% glass rovings in 90^0 direction, and 20% glass rovings each in +/-45^0 direction. 46.6 oz/sq yd quadaxial stitched fabric was supplied by Owens Corning (OC). Each layer of OC fabric comprises of 30% glass rovings each in 0 or 90^0 direction and 20% glass rovings each in +/-45^0 direction (Table 1).

Carbon fabric: Toray T700SC /12K / FOE carbon fabric. T700S is a grade of carbon fiber of highest strength (711 ksi) and standard modulus (33.4 msi). The selected code represents a never twisted carbon fiber of 12000 filaments per tow, with a sizing type designated for vinyl ester and surface-treated at a sizing amount of 0.7%. Carbon 28 oz/sq yd quadaxial distributed fabric was supplied by Saertex USA, LLC. Each layer has 6 oz (21.4%) carbon each in 0 or 90^0 direction and 8 oz (28.6%) carbon each in +/-45^0 direction (Table 1). These fabric architectures were determined in consultation with the sponsor for a specific product to meet the laminate of specific thickness.

Wood core: Baltek D100 rigid end grain balsa. It has a density of approximately 9-10 lbs per cubic ft and was received in the form of non-textured panels of 3” thickness by 24” width by 48” length.

4 Manufacturing of FRP Sandwich Panels through Pultrusion Process

Pultrusion is a process where FRP composites are produced continuously at speeds ranging from a couple of inches to a couple of feet per minute, through a heated die of desired cross-section, i.e., no part length limitation [37,38]. The reinforcements are in continuous forms such as rolls of unidirectional roving, biaxial fabric, or multiaxial fabric, which are properly positioned by a set of creels and guides for subsequent feeding into the resin bath. As the reinforcements are saturated with the resin ("wet-out") in the resin bath and pulled into the forming and curing die, the heat curing of the resin is initiated from the preheated die leading to a rigid profile. Many pultruded profiles such as beam, channel, box, flat sheet are commercially available, but to the authors’ knowledge, it had not been used to produce thick sandwich panels (such as the target 3.5” panel) when this effort was initiated.

Table 1. Constituents and fabric configurations of sandwich panels studied

	Pultruded GFRP	Pultruded CFRP	VARTM GFRP	Infused GFRP
Fabric Layers	6	6	10	5 + 1
Weight (oz/sq yd)	40	28	24	46.6 + 24
Total Weight	240	168	240	257
Type	quadaxial stitched	quadaxial stitched	woven roving	quadaxial + 0/90
Percent 0	33	21.4	30	30
Percent 90	27	21.4	30	30
Percent + 45	20	28.6	20	20
Percent - 45	20	28.6	20	20
Resin	Derekane 510A-40	Derekane 510A-40	Derekane 510A-40	Derekane 510A-40
Core	Baltek D100 ~9.5 pcf	Baltek D100 ~9.5 pcf	Baltek D100 ~9.5 pcf	Baltek D100 ~9.5 pcf

The advantages of pultrusion process include: 1) high fiber content, 2) high cure percent, 3) minimal kinking of fibers/fabrics, 4) rapid processing, 5) low material scrap rate, and 6) good quality control. Its disadvantages may include: 1) improper fiber wet-out, 2) die jamming, 3) die size/geometry limitation, and 4) initial capital investment and die cost [20-21].

The pultrusion of glass fiber reinforced polymer (GFRP) and carbon fiber reinforced polymer (CFRP) composite sandwich panels was accomplished in collaboration with Bedford Reinforced Plastics (BRP) Inc. (Bedford, PA). The target panel consisted of two 1/4” thick GFRP/CFRP laminates (face sheets) sandwiching 3” thick balsa wood core, giving a total thickness of 3.5”. Fabric configurations of quality laminates are detailed in Table 1.

4.1 Pultrusion of GFRP Sandwich Panels

A total of five production runs for GFRP panels were conducted to arrive at quality products of optimal performance. The first run was to produce 1” thick sandwich panels, 300 sq ft; 2nd run was to produce 3.5” thick sandwich panels without joining profiles, 220 sq ft; 3rd run was to explore methods to improve bond between balsa wood and FRP face sheet, 40 sq ft; 4th and 5th runs were to produce 4’ wide 3.5” thick sandwich panels with joining profiles, 400 sq ft each run. A total of 1360 sq ft (over 330 linear feet) of 4’wide GFRP sandwich panels was produced from 5 runs.

Fig. 1. Pultrusion of 4’ wide GFRP panels at BRP

The process development for thick sandwich panel production involved the following major elements: 1) design, selection, evaluation and optimization of fabric configurations (4 generations in collaboration with three fabric suppliers), 2) design and manufacturing of forming die assembly with tongue and groove profiles for joining purposes (4 stages), 3) design and manufacturing of fabric guiding and feeding system (2 stages); 4) design and manufacturing of balsa wood core feeding system, 5) development of high speed resin injection system for better wet-out, 6) evaluation of textured and non-textured balsa core panel, 7) exploration of bond improvement between balsa and FRP face sheet; 8) selection and evaluation of peel-ply for joining areas, 9) development of resin catalyst applicable to pultrusion, 10) optimization of pultrusion process parameters (pull speed, die temperature, resin curing profile) to suit 3.5” panel, 11) procurement of constituent materials including resin, fabric, and balsa, and 12) systematic diagnoses and adjustments in manufacturing process after integration of the above elements.

Pultrusion of complex shapes such as 4’ wide 3.5” thick panels with joining edge profiles has been a challenging task. Difficulty was encountered initially in having perfect joining profiles at both sides of a panel (Figure 1). Then re-tailoring of fabric guidance and feeder system was done in order to properly maintain fabric streams in position and feed into the forming die. Another major technical obstacle was to enhance the bond between balsa and FRP. An indirect bond strength test was developed to quantitatively evaluate three types of panels each using a different adhesive for the bond. An effective adhesive was identified that offers bond strength twice as much as that without applying the adhesive, leading to a failure mode change from adhesive to cohesive. A complex cohesive failure pattern is shown in Figure 2. As a result, an automated pultrusion process was successfully established with a set of well controlled production parameters, yielding GFRP sandwich panels of high quality (Figure 1).

Fig. 2. A cohesive bending failure of sandwich panel showing good bond between balsa and FRP skin

4.2 Pultrusion of CFRP Sandwich Panels

CFRP panels differ from GFRP panels in 1/4" thick CFRP face sheets in lieu of 1/4" thick GFRP face sheets. There were two production runs for CFRP panels. The first run was carried out using a 12" wide forming die instead of 48" wide forming die, thus reducing production and material cost significantly. The objectives of the first run were: 1) to evaluate the processability of new carbon fabric; 2) to test the modified fabric guiding system; 3) to monitor the wettability of carbon fabric; 4) to establish a set of process parameters for carbon composite; 5) to examine the bond between balsa core and carbon laminate; and 6) to address unexpected production issues. Based on mechanical evaluation results of 12" wide x 3.5" thick CFRP panels from 1st run, recommendations and modifications were made for the second run of 4' wide CFRP sandwich panels.

The experience from pultrusion of GFRP panels was applied to the pultrusion of CFRP panels. In contrast to a smooth 1st run with a rectangular cross section, several process-related difficulties were encountered during the production of 4' wide CFRP sandwich panels with joining edges at the 2nd run.

1) The resin was initially unable to maintain its required level in the wetting bath because of resin leakage through slots of fabric guiding plate. This occurred because carbon fabric was thinner than glass fabric and the space between guiding plates was originally designed for glass fabric instead of carbon fabric of thinner dimension. Two additional pumps were added later to pump the resin back to the bath in order to compensate for leaking resin.

Fig. 3. Pultrusion of 4' wide CFRP panels at BRP

2) Resin injection box was installed closer to the forming die than the first run and the resin inside the box was found setting/curing because of heat conducted from the die. Then the resin injection box had to be removed from the line to clean the cured resin and re-installed afterwards at a position besides the front guiding plate.

3) Pullers were unable to grip dry carbon fabric and thus unable to pull the fabric forward effectively at the beginning of the production. The carbon fabric has a shining surface and the slippage occurred between the pullers and dry fabric. Methods were used to increase the friction for the pullers

to grip the fabric. Once the process was initiated, the puller had no problem in pulling the cured panel. A solution to improve friction for next run of carbon production would be to pre-spray resins over the dry fabric to cure at room temperature before starting to pull.

4) An important observation from both runs was that 510A vinyl resin was not fully staying (adhering) onto carbon fabric surface. This occurred because of a potential sizing incompatibility and poor adhesion between carbon and vinyl ester. To help improve the wet out, the resin was kept pouring onto the surface of top fabric before entering die, even though the fabric was impregnated already thru the wet bath (Figure 4, left photo). The poor wet out resulted in interlaminar failure between layers of carbon fabric under bending (Figure 4, right photo). Therefore, carbon/ epoxy resin system is strongly recommended in lieu of carbon/vinyl ester.

Fig. 4. Poor adhesion between carbon and vinyl ester leading to wet out problem during manufacturing (left) and interlaminar failure (right)

A total of 300 square feet (60 linear feet each of 1' and 4' wide CFRP sandwich panels) was produced. The pultruded panels were cut to 10' x 4' x 3.5" sizes and evaluated by WVU-CFC researchers.

4.3 Joint Design

Pultruded panels have a unique advantage in designing built-in joining profiles for modular construction concept. The joining of composite sandwich panels needs to satisfy the following: 1) panel joints at the sides must have a smooth transition with no exposed edges so that interference with radar signals can be minimized, and 2) joint should not add excessive weight or cost to a panel system. Therefore, a double lap joint was selected and built into the FRP composite sandwich panels after design-analysis determined the overlap length and thickness in terms of required load carrying capacity [27]. A double lap joint is a joint made by placing one adherend (partly above and below) into another, and bonding together the overlapping portions as seen in Figure 5.

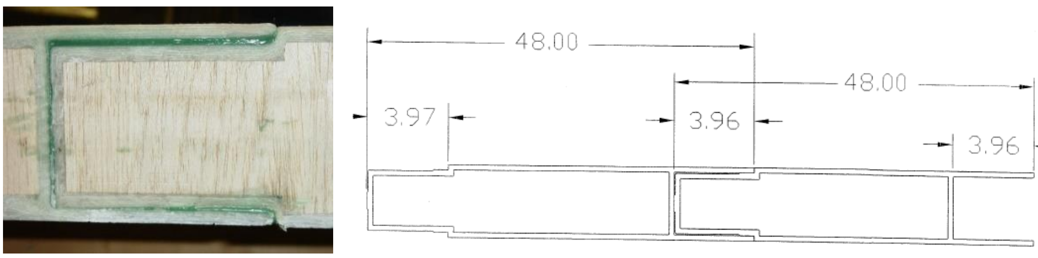


Fig. 5. A double sided lap joint and schematic joining of two 4' wide modular panels (units in inches)

Two 4' wide, 3.5" thick composite sandwich panels were adhesively joined to make 8' wide panels based on the double lap joint concept. The joining profiles were bonded together using structural adhesive that is composed of two component, urethane-based adhesive system and designed to meet the FRP bonding needs. An appropriate joining surface preparation is critical to arrive at the required joint efficiency of the bonded components. To facilitate the surface preparation for adhesive bonding, the joining surfaces in the connection profiles were embedded with a rough peel-ply layer during pultrusion process. A peel-ply is a permeable cloth layer added to the needed surface of FRP shapes during manufacturing that can be peeled off during construction to reveal a fresh, clean, and textured surface ready for adhesive application. In addition to using peel-ply method, a sandblasting method was also used as a supplement method to prepare the joining surface. Then three layers of 24 oz/sq yd biaxial glass fabric as external reinforcement were wrapped over the joint of the joined panel at the top and bottom to achieve near 100% joint efficiency [21].

A total of 60 panel-to-panel joints, in 4 batches, were fabricated with varying parameters including mechanical fastener. One batch of 15 joints were tested under a 4 point bending with a span of 27” (shear dominance) while other three batches of joints were tested under a 4 point bending with a span of 80” (true bending). We arrived at a couple of joint designs and bonding methods leading to near 100% joint efficiency under shear and bending.

5 Manufacturing of FRP Sandwich Panels through High Temperature Resin Spread and Infusion Process

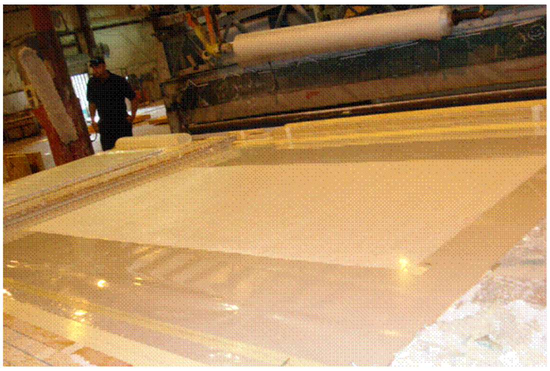
Fiber-Tech Industries, Inc. (Washington Court House, OH) uses a vacuum assisted high temperature resin spread and infusion process to produce fiberglass reinforced plywood panels [33, 39]. This proprietary process has been identified by WVU-CFC researchers to be a viable alternative to produce large glass/vinyl ester or carbon/epoxy sandwich panels of high quality in a cost-effective manner. Major steps of the Fiber-Tech process would include: 1) placing of bottom fabric, 2) spreading of resin for impregnation, 3) placing of core panel, 4) placing of top fabric and spreading resin for impregnation, 5) closing top of oven for curing, and 6) removing of panel, after cure.

This process has the following advantages: 1) 10’ x 60’ platform operation for large panels, 2) high temperature curing (~80 ℃ with current setting), 3) vacuum assisted, 4) almost zero scrap rate, and 5) faster and lower cost than pultrusion and VARTM. In order to arrive at sandwich panels of high quality, the following process improvements are desired: 1) porosity control /void content reduction, 2) optimization of port spacing with enhanced vacuum pressure, 3) fabric tensioning to minimize kinking, and 4) process automation for fabric placement and resin impregnation.

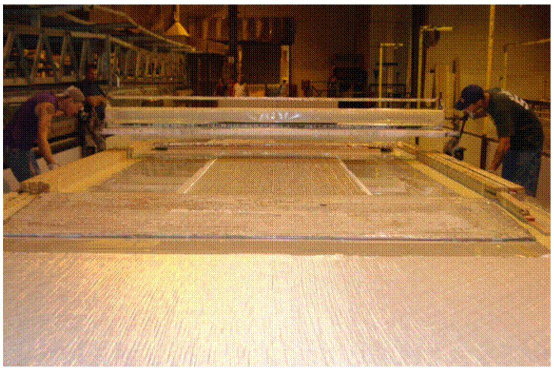
In order to demonstrate the Fiber-Tech process as a new mass production technology for glass/vinyl ester or carbon/epoxy sandwich panels, WVU-CFC team in collaboration with Fiber-Tech Industries Inc has preliminarily resin-infused (with vacuum assistance at high temperature) 80 square feet of E-glass/510A vinyl ester composite sandwich panels with 3” balsa core.

Fabric configuration for face sheet is also listed in Table 1. It was constructed with 5 layers of 46.6 oz/ sq yd quadaxial fabric and one layer of 24oz/sq yd biaxial fabric. 0/90 fabric was used in order to construct a balanced ply configuration, resulting in a slightly higher total fiber density.

The production of GFRP sandwich panel using high temperature infusion is shown in Figure 6. Figure 6 also shows two finished panels, 40 square feet each. One panel was based on multiple layers of quadaxial fabric in a conventional manner (without stitching), while the other panel was produced with all layers of fabric stitched together in the thickness direction by WVU-CFC researchers. Although extra precaution was taken to ensure good wet-out for stitched fabric construction, delamination occurred between balsa and FRP and poor wet-out existed in some areas. After production, both the high temperature infused composite laminates and sandwich panels were evaluated for their mechanical responses under static loads.



1) Placement of fabric



2) Applying resin for impregnation

3) Placement of core panel 4) Top moving oven in position

5) Finished panel 6) Finished stitched panel

Fig. 6. High temperature resin infusion process and infused panels at Fiber-Tech

6 Manufacturing of FRP Sandwich Panels through VARTM Process

In a VARTM process, dry reinforcements in the form of mat, rovings or fabrics are preshaped and manually oriented into a skeleton of the actual part known as preform [40]. After the preform is inserted into a tool (typically comprised of one mold surface and one bag surface), the resin is injected at low pressure into the closed mold. During resin injection, vacuum is applied to assist infusion of the resin into the fabric and reduce voids. Then the resin cures at room temperature for 12 to 24 hours. Its advantages include low tooling cost, low volatile emission, low void content, and design flexibility for large and complex parts, but it is labor intensive.

Fig. 7. 3.5” VARTM panel (5’ x 5’, provided by NSWC) tested to failure with exposed cracking

Two batches of 3.5” VARTM-made composite sandwich panels were received to generate mechanical property data. First batch of five 5’x 5’ (125 sq ft) VARTM panels were supplied by Naval Surface Warfare Center, Carderock Division (NSWC). One of the NSWC-VARTM panels is shown in

Figure 7. These panels have 1/4" thick GFRP face sheets on top and bottom with 3" thick balsa core. Burn test revealed that the FRP face sheet from NSWC-VARTM panel was composed of 10 layers of E-glass woven rovings of 24 oz/sq yd and having a biaxial fabric array of 0/90, +/-45, 0/90, +/-45, 0/90, 0/90, +/-45, 0/90, +/-45, and 0/90. This batch of panels was made of balsa of density higher than 9.5 pcf.

Fig. 8. 3.5" VARTM panel (4' x 10', provided by NGSS) tested to failure with exposed cracking

Second batch of 200 sq ft of 3.5" thick GFRP panels manufactured through VARTM process were supplied by Northrop Grumman Ship Systems (NGSS), including three (3) 4' x 10' panels and two (2) 5' x 8' joined panels each made by joining two 4' x 5' panels. Upon delivery, per NGSS request, those VARTM panels were kept in the laboratory for at least 4 weeks at room temperature in order for the resin to post cure before test. Figure 8 shows a VARTM panel of size 4' x 10' under a 4 point bending with a span of 100". The GFRP laminate in NGSS-VARTM panel comprised of 10 layers of 24 oz/sq yd woven fabric, giving the same fiber density of total 240 oz per sq yd out of which 30% glass in each of the 0 or 90 direction and 20% glass in each of the +45 /-45 directions.

7. Manufacturing of FRP Laminates through Compression Molding Process

Compression molding is primarily used for thermoplastic resin systems, which uses heat and pressure to form and set the shape of a part [41]. The two halves of the mold, which are mounted in a hydraulic molding ram, are closed after loading thermoplastic pellets in the mold. Molding cycles can range from well under 1 minute to over 40 minutes, depending on the size and cross sectional thickness of the part. The mold is then opened, and the part is removed. Compression molding process involves tooling cost, is limited with the mold/platen size, but it can be used for complex items. In this study, it was used to prepare CFRP laminates with the same fabric configuration as in other processes for baseline values for vinyl ester or epoxy resins as discussed in section 8.2. The wet-out of fabric was achieved in a similar manner to hand lay-up process. Due to the pressure applied, the compression molded laminates usually have a higher fiber volume fraction and lower thickness than other methods.

8 Mechanical Properties of FRP Laminates

8.1 Mechanical Properties of FRP Laminates from Sandwich Panels

Table 2. Fiber volume fraction of FRP laminates

	Unit	Pultruded GFRP	Pultruded CFRP	VARTM GFRP	HT Infused GFRP
Fabric density	oz/sq yd	240	168	240	257
Face sheet thickness	inch	0.250	0.230	0.263	0.281
Fiber content by weight	%	70.5	65.1	63.5	67.7
Fiber content by volume	%	56.5	55.0	48.7	53.3

Composite laminates were first characterized for their fiber volume content because FVF provides a measure for laminate mechanical properties. Unlike GFRP composites whose fiber content could be determined by burn out test (ASTM D2584), CFRPs fiber content was determined by measuring the weights of composite part per unit area and the amount of fiber used. The results are listed in Table 2. The pultruded GFRP panels have higher fiber content than VARTM and high temperature infused samples, and VARTM laminate had the lowest FVF, i.e. 48.7%. Pultruded CFRP composite face sheet has a fiber content of 55.0% by volume in relation to 56.5% for pultruded GFRP. Note that there is a slight variation in fiber density used in different processes.

For mechanical testing, specimens were cut to required sizes from large panels, along the longitudinal and transverse directions. Balsa was removed with the aid of a band saw and then sanded to remove residual wood filings. Tensile property data as shown in Table 3 were generated by testing specimens of dimensions of 1” width x 24” length x 1/4” thickness. The test specimens were bonded with FRP end tabs of length 4” as per ASTM D3039. The tensile moduli were determined from strain gage readings. Bending properties of FRP laminates as shown in Table 4 were generated from testing specimens (5” x 1/2” x 1/4”) under three point bending with 4 inch effective span (ASTM D790). The flexural moduli were determined from load vs. deflection data. LW represents specimen cut along lengthwise direction while CW along crosswise direction. Shadow

Table 3. Tensile properties of FRP laminates

Note: modulus data are obtained from measured strains	Unit	Pultruded GFRP	Pultruded CFRP	VARTM GFRP	HT Infused GFRP
Tensile strength (LW)	ksi	52.17	65.92	43.52	43.96
Tensile strength (CW)	ksi	39.32	49.26	42.98	42.76
Tensile modulus (LW)	msi	3.24	5.25	2.83	3.11
Tensile modulus (CW)	msi	2.91	5.24	2.76	2.71

All coupon level tests of FRP laminates were carried out with six replications as per ASTM standards. The results were found to be consistent with a narrow variation. The strain gages model CEA-06-250UW-350 purchased from Vishay Micro-Measurements Group, Raleigh, NC were extensively used. The coupon mechanical tests were carried out on Instron System model 8501 with a loading capacity of 22.5kips or Baldwin test machine with a loading capacity of 220 kips, while panel testing was conducted on the testing frame using MTS actuator of capacity 110 kips. More details can be found in reference [23].

Table 4. Flexural properties of FRP laminates

Note: modulus data are obtained from measured deflections	Unit	Pultruded GFRP	Pultruded CFRP	VARTM GFRP	HT Infused GFRP
Flexural strength (LW)	ksi	79.6	71.0	57.7	57.0
Flexural strength (CW)	ksi	56.0	50.4	46.7	55.7
Flexural modulus (LW)	msi	3.03	5.29	2.55	2.41
Flexural modulus (CW)	msi	2.20	4.66	2.14	2.39

Pultruded GFRP composite laminates are about 15-20% stronger and stiffer under tension, and about 20-40% stronger and stiffer under bending than VARTM panel. High temperature infused composites have almost the same mechanical properties as VARTM based samples. Pultruded CFRP laminate is 30-40% stronger and 60-70% stiffer than pultruded GFRP under tension, while pultruded CFRP laminate is 75-100% higher in flexural modulus and 12-15% lower in flexural strength than pultruded GFRP under bending. These differences can be related to their variations in fabric density, fiber content, and processing parameters such temperatures which would result in different post-cure behaviors.

Note that the above comparisons are referred with respect to GFRP laminates (sandwich panel face sheets) that consisted of 6 layers of 40 oz per sq yd quadaxial stitched fabric with each layer having 33% glass in 0 direction, 27% in 90 direction, and 20% each in +/-45 directions in relation to CFRP laminates that comprised of 6 layers of 28 oz per sq yd quadaxial stitched fabric with each layer having 21.4% each carbon in 0 and 90 direction, and 28.6% each in +/-45 directions.

In a proportionate sense of basic fiber properties, property enhancement by switching from glass to carbon fiber appears to be less than satisfactory and this might be attributed to the sizing incompatibility of carbon reinforcements with vinyl ester and resulting fabric wet-out and layer-to-layer adhesion issues [22].

8.2 Carbon/Vinyl ester versus Carbon/Epoxy

It has been extensively identified that carbon fibers available on market are not fully compatible with vinyl ester resins [42-46]. They have no reactive groups capable of reacting with vinyl ester during cure (a free radical process). The sizing incompatibility of carbon reinforcements would highly discount the performance of carbon/vinyl ester composites, including long term performance. The vast majority of carbon fibers are incorporated into epoxy resin systems and the typical carbon fiber surface has several functional chemical groups that can react with epoxy.

Table 5. Carbon/vinyl ester and carbon/epoxy laminates evaluated

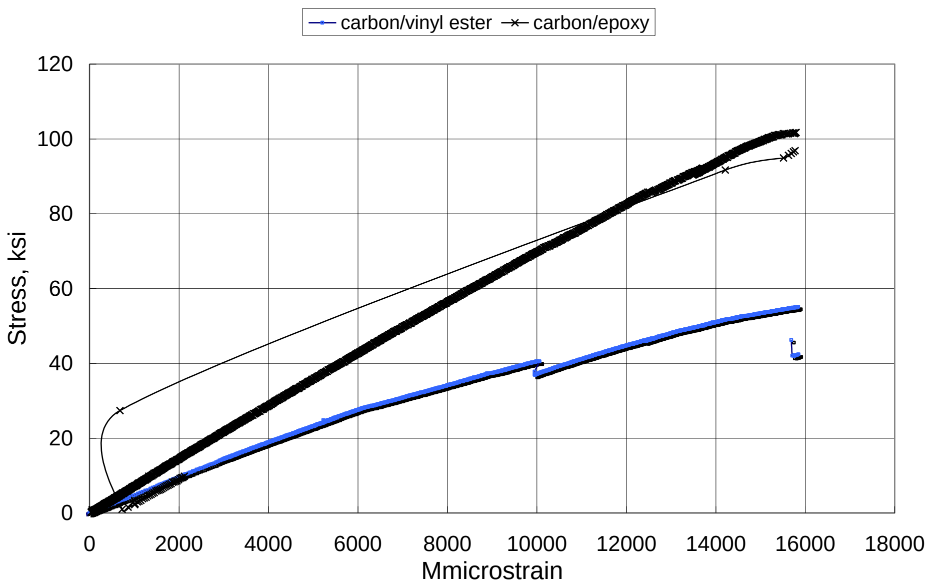
	Production Method	Fiber Content wt%
Carbon/Vinyl Ester (Compression)	Compression at room temp. WVU-CFC	77.5
Carbon/Vinyl Ester (Infusion)	Fiber-Tech Infusion at room temperature	51.0
Carbon/Epoxy (Compression)	Compression at 82^0C, WVU-CFC	76.3
Carbon/Epoxy (Infusion)	Fiber-Tech Infusion at 60^0C	63.0

The above statement was also supported by our data. Carbon/vinyl ester 510A and carbon/epoxy laminates were manufactured through high temperature infusion process (in collaboration with Fiber-Tech Industries Inc) and compression molding process (Table 5). All CFRP laminates had the same fabric configuration. The epoxy resin used in the study was API FR-7 epoxy that has been developed by Applied Poleramic Inc. (API, Benicia, CA). FR-7 has low viscosity, high Tg and toughness and is curable at 71-82 ℃.

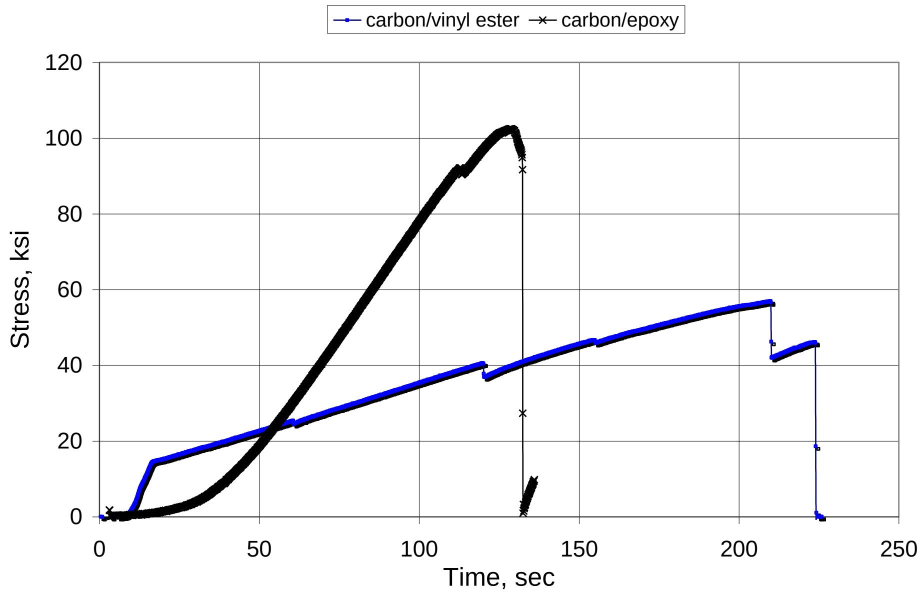
Table 6. Tensile and flexural properties of carbon/vinyl ester and carbon/epoxy laminates

	Tensile strength, ksi	Tensile modulus, msi	Flexural strength, ksi	Flexural modulus, msi
Carbon/Vinyl Ester (Compression)	79.47	6.80	88.51	6.91
Carbon/Vinyl Ester (Infusion)	64.33	4.53	56.17	4.86
Carbon/Epoxy (Compression)	105.92	7.01	98.12	7.30
Carbon/Epoxy (Infusion)	86.20	5.69	83.09	5.08

Typical tensile stress versus strain for carbon/vinyl ester (VE) and carbon/epoxy is shown in Figure 9. Carbon/VE presents a discontinuity at about 40 ksi which does not occur in carbon/epoxy. This discontinuity even becomes more obvious with stress versus time plot. There are two kinks at 40 ksi and 47 ksi for carbon/VE while only one kink at 96 ksi for carbon/epoxy, reflecting debonding of layers of carbon fabric inside the sample. These observations can be witnessed from their failed samples as shown in Figure 10. As seen from Table 6, carbon/epoxy could be 34% stronger and 25% stiffer than carbon/VE under tension.



(a) Carbon/Vinyl Ester vs Carbon/Epoxy: Typical Stress VS Strain @ Tension



(b) Carbon/Vinyl Ester vs Carbon/Epoxy: Typical Stress VS Time @ Tension

Fig. 9. Typical tensile stress vs strain (top) and stress vs time (bottom) for carbon /VE and carbon/epoxy

Fig. 10. Typical failed tension specimens for carbon /VE (left) vs. carbon/epoxy (right)

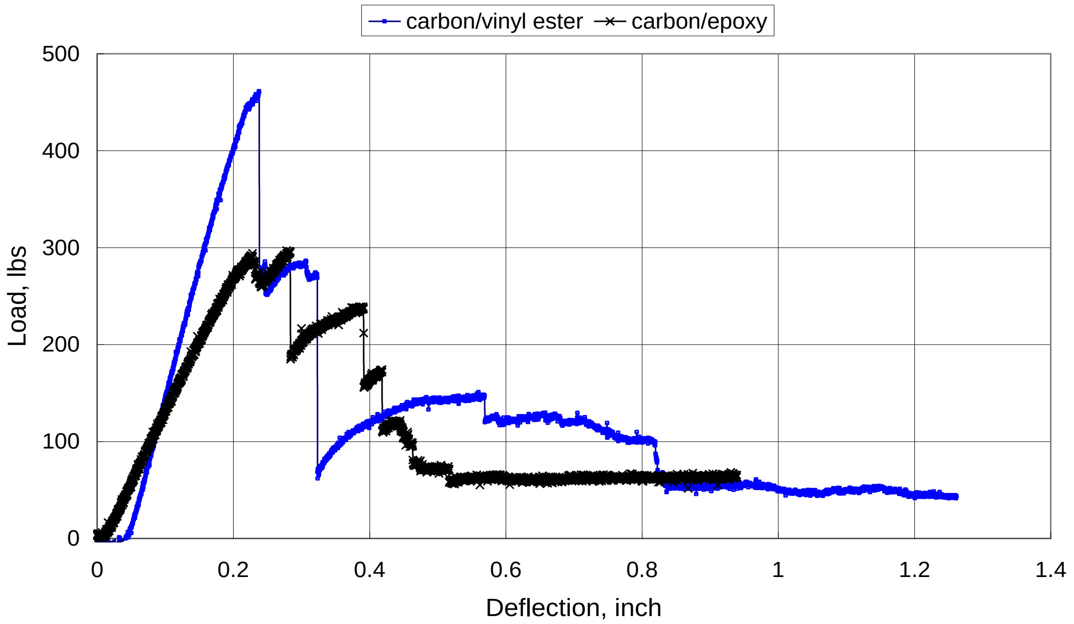


Fig. 11. Typical bending load versus deflection curve for carbon / VE vs. carbon/Epoxy (@ 3Pt Bending)

Bending load versus deflection curves in Figure 11 for carbon /VE and carbon/epoxy show the same trend as tensile stress versus strain. Carbon/VE shows abrupt debonding while carbon/epoxy is more ductile and more damage tolerant. Their distinctive failure modes are clearly shown in Figure 12. For infused samples under bending, carbon/epoxy is 48% stronger and 5% stiffer than carbon/VE (Table 6).

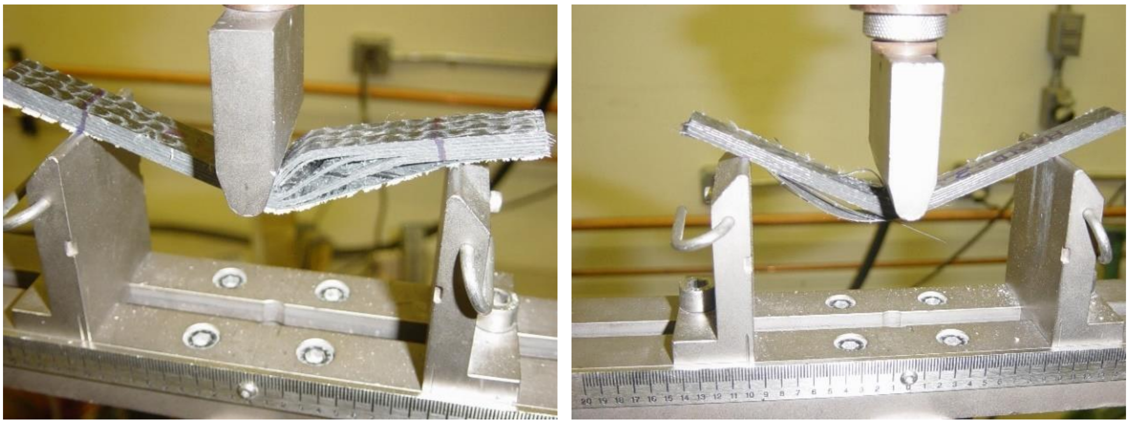


Fig.12. Typical failed bending specimens for carbon /VE (left) vs. carbon/epoxy (right)

This set of mechanical data for carbon/VE and carbon/epoxy clearly identifies that the sizing incompatibility of carbon reinforcement with vinyl ester would discount the performance of carbon/vinyl ester composites in many ways. The poor adhesion between carbon fibers and vinyl ester and between layers of fabric would potentially lead to wet-out problem during composite manufacturing, i.e., high void content leading to lower than expected strength and modulus, and reduced durability.

9 Mechanical Properties of FRP Sandwich Panels

FRP composite sandwich panels were tested at different scales for static bending properties with at least two replications as per ASTM C393. Smaller panels (12"x 36~48", Figure 13) allowed for longitudinal and transverse testing and examining shear response while larger full-scale panels (48"x 120", Figure 14) led to representative structural properties for system construction. Since pultruded panels had edge wraps (end caps) from production process with reference to high temperature infused or VARTM panels, both panels with and without edge wraps were evaluated using smaller panels (Figure 13). For effective use of limited amount of sandwich panels, sectional panels (12"x 96", Figure 15) were also adopted and subjected to pure bending over a span of 80". In addition, results from testing 12"x 96" panels along the pull direction provide a direct comparison with results obtained from the joined (joining two 48" wide sections into 12"x 96") panels for joint efficiency evaluation.

Table 7. Bending properties of 48" x 120" sandwich panels (100" span, 4pt bending)

	Unit	Pultruded GFRP	Pultruded CFRP	VARTM GFRP
Failure load/unit width	lbs/in	1331	1511	1120
Load/defl. slope	lbs/in	15757	23512	14234
Failure strain	micro	5944	3982	6020
Balsa stress at failure	psi	204.7	232.5	172.2
FRP stress at failure	ksi	22.05	25.04	17.63
Modulus from strain	msi	4.06	6.48	2.96
Modulus from deflect.	msi	4.27	6.27	3.06

Smaller scale panel tests were conducted mostly using 12" wide x 36" panels at a span of 27" under 4 point bending and with a load span of one-half of the support span (Figure 13) and span-thickness ratio of 7. Hence it is more like a short beam shear testing where failure will mainly depend on core properties rather than face sheet properties. It was observed that shear failure in balsa core occurred for all panels, independent of fiber type, mass-production method or fiber orientation (longitudinal vs. transverse). Hence both the GFRP and CFRP panels failed at core shear stress of ~ 250psi.

Fig. 13. Four point bending (short beam shear) with a span of 27” for 12” x 36” CFRP sample

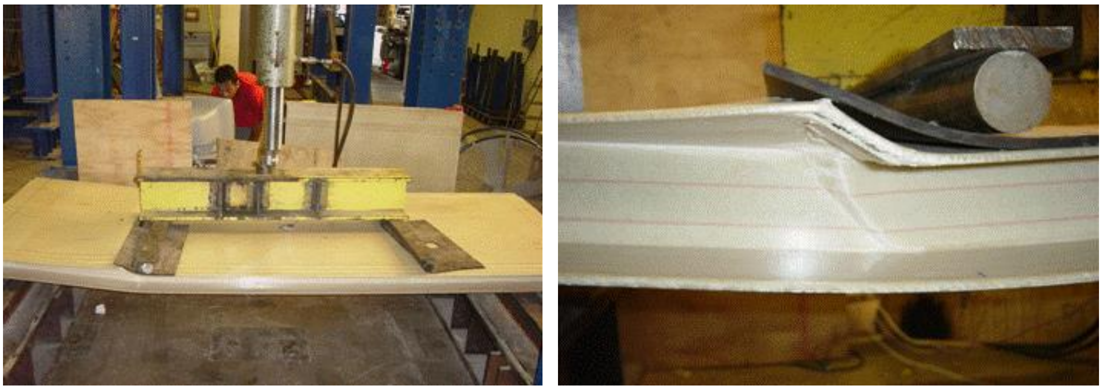


Fig. 14. Four point bending with a span of 100” for 48” x 120” GFRP panel

Fig. 15. Four point bending with a span of 80” for 12” x 96” CFRP panel

Table 8. Bending properties of 12” x 96” sandwich panels (80” span, 4pt bending)

12” x 96” 80” span, 4pt bending	Pultruded GFRP	Pultruded CFRP	VARTM GFRP	HT Infused GFRP
Failure load P lbs/ inch	1378	1414	1261	1130
Failure micro strain	6000 top 5726 bot	3348 top 3448 bot	5695 top 5031 bot	4647 top 4871 bot
Max deflection inch	2.44	1.47	-	1.92
Bending stress ksi	18.63	18.74	15.90	14.98
Bending modulus, msi	3.03	5.40	2.76	3.10
Core shear stress, psi	218.7	217.5	194.1	173.8

Full scale panel tests were conducted using 48” x 120” panels at a span of 100” under 4 point bending with a load span of one-half of the support span (Figure 14). It was observed that failure was initiated by shear failure at balsa core. The mechanical properties of pultruded full scale GFRP and CFRP panels are listed in Table 7 for comparison with VARTM panel. Similarly, sectional (bench scale) panel tests were conducted using 12” x 96” panels at a span of 80” (Figure 15) and their mechanical properties are listed in Table 8. These two types of tests have a span versus thickness ratio of 28 and 22, respectively, indicating true bending with negligible shear contribution. Note that high temperature infused sandwich panel only has bench scale test result because of limited availability of test samples.

9.1 Performance and Cost Comparisons

In case of E-glass/Derakane 510A vinyl ester based composite sandwich panels with balsa core, mechanical characterization data revealed that pultruded panels are about 15-20% stronger and stiffer than VARTM panels. Based on the cost analysis, it is concluded that the pultruded panels are 50% cheaper than VARTM based panels, with other parameters (resin, fabric configuration, core material etc) being identical. High temperature infused panels (even produced under a process not yet optimized) performed as well as VARTM panel; but cost about a third of VARTM panels.

Pultruded full scale CFRP panel is about 50-100% stiffer and 10-15% stronger than pultruded GFRP panel. The high strength and high modulus characteristics of carbon fiber have not translated into a proportionate improvement of carbon FRP composites, due to the sizing incompatibility of carbon reinforcements with vinyl ester. Hence, carbon/epoxy is strongly recommended.

It is worth noting that CFRP panels are 15-20% lighter than GFRP panels. The researchers experienced ease of handling of CFRP panels while loading and unloading them before and after testing, in contrast to GFRP panels of the same size. On average, CFRP panel weighed 6.60 lb/sq ft versus 7.80 lb/sq ft for GFRP panel.

10 Panel-to-panel Joint Efficiency

Any joint has to be strong enough in order to transfer loads from one component to another in a structure. Joint efficiency can be determined by comparing the strength and stiffness of a joined panel with that of a jointless panel [12, 26]. Jointed composite sandwich panels were also tested at different scales for static bending properties as per ASTM C393. 12"x 48" jointed panels would allow direct comparison with plain (no joint) panels in the same (transverse) direction (see Figure 13), while 12" x 96" panels with joint made by transversely glue- bonding two 48" wide panels together could only be compared to plain (no-joint) panels cut along the pull direction (see Figure 15). It is much more challenging to achieve 100% joint efficiency under true bending (span to thickness ratio >22) than under "short beam shear" bending (span to thickness ratio ~7).

A total of 60 joints (in 4 batches) were designed, fabricated, and tested to arrive at 100% joint efficiency under shear and bending. A variety of material and design parameters were investigated, including: 1) primer; 2) adhesive; 3) resin; 4) fabric density, 5) ply number, 6) fabric width, 7) stack order, 8) vertical pin, 9) horizontal pin, and 10) mechanical fastener. The test results verified that adhesively bonded joints provide better load transfer mechanism than mechanically fastened systems.

Fig. 16. Joined panels (left, 12" x 96"; right, 5' x 8') of 100% joint efficiency under 4 pt bending

The mechanical properties of jointed pultruded panels are listed in Table 9. Extensive test data have established that 8' wide sandwich panels through adhesive bonding of two 4' wide modular panels (with tongue and groove joint profiles using three layers of 24oz/sq biaxial glass fabric as external reinforcement) resulted in 100% joint efficiency under both shear and bending with failure in balsa core and away from the joint (Figure 16, left photo). Figure 16 (right photo) shows a joined pultruded panel

(5' x 8') under 4 pt bending with a load span of one-half of the support span 80".

Table 9. Properties of joined sandwich panels

	Unit	Pultruded GFRP	VARTM GFRP
Bending at a span of 80" for 12" wide panel sections ("True Bending")			
Failure load/unit width	lbs/in	1378 (no joint) 1433 (joint)	1261 (no joint) 1444 (joint)
Failure strain	micro	5726 (no joint) 6774 (joint)	5695 (no joint) 5916 (joint)
Modulus from load/strain slope	msi	3.03 (no joint) 3.20 (joint)	2.76 (no joint) 3.08 (joint)
Joint efficiency	%	100 (No joint failure)	100 (No joint failure)
Bending at a span of 27" for 12" wide panel sections ("Shear Dominance")			
Failure load/unit width	lbs/in	1613 (no joint) 1674 (joint)	1675 (no joint) 1523 (joint)
Failure strain	micro	1977 (no joint) 2096 (joint)	1912 (no joint) 1424 (joint)
Modulus from load/strain slope	msi	3.47 (no joint) 4.53 (joint)	3.28 (no joint) 3.96 (joint)
Joint efficiency	%	100 (No joint failure)	100 (No joint failure)

11 Finite Element Modeling of FRP Composite Sandwich Panels

The objective of FE analysis is to model and predict sandwich panel response under static loads using MSC.NASRAN software. Data from FEA of GFRP/CFRP sandwich panels were compared with the experimental results. FEA was also conducted to characterize effect of end caps of pultruded panels and even attempt was made to predict panel failure modes, with reference to experimental observations. In addition, FEA modeling of panel-to-panel double lap joint was carried out to predict its response with the eventual goal to optimize joint design for high efficiency.

Table 10. Material properties used for modeling CFRP sandwich panels

	CFRP	Balsa
E11, psi	6.33E6	7652
E22, psi	0.5E6	510176
E33, psi	6.33E6	7652
μ12	0.25	0.02
μ23	0.25	0.02
μ31	0.30	0.30
G12, psi	0.25E6	22800
G23, psi	0.25E6	22800
G31, psi	0.5E6	2550

Different FE models were evaluated for their applicability describing static responses of GFRP composite sandwich panels and the results were compared with experimental counterparts. It was concluded that in order to describe composite sandwich panel response under static load, the candidate model has to accommodate three dimensional nature of geometry and orthotropic nature of material properties. Therefore, 3-D solid model with orthotropic material properties (Refer to Table 10) has been identified to be the model applicable to predict static response of sandwich panels.

For illustration purpose, predictions from 3D orthotropic solid model for CFRP sandwich panel responses are presented herein. A complete presentation of the FE work can be found in [23]. Material properties used for CFRP composite panel modeling are listed in Table 10. FE predictions are compared with experimental results in Table 11 for both the 12"x80" and 40"x100" CFRP panels. In particular, three geometries were simulated for full scale 40" x 100" panel: i) no end caps, ii) with end caps of the same height as 3" balsa core, and iii) with end caps across the entire panel thickness.

Deflections from the model with end caps are slightly smaller than those from the model without end cap. 3D orthotropic solid model also predicts shear stress profile across the thickness for both the small scale and full scale panels within 1% variation from experimental values of 214.40 psi.

3D orthotropic solid model (see Table 11) gives nearly the same values as experimental bending stress under failure load. There is hardly any effect of end caps on bending stress. The model with end caps predicts a bending stress of 22.96 ksi versus 22.99ksi from the model without end caps, in comparison to experimental value of 23.09 ksi. Bending stress profile along the span is represented in Figure 17 while the deflection contours predicted by 3D orthotropic solid model for 40"x100" CFRP panel are shown in Figure 18. The models with end caps and without end caps yield the same bending stress profile within the region of loading as shown in Figure 17.

Table 11 Comparison of model predictions with exp. data for 12"x 80" and 40"x100" CFRP panels

Panel Dimensions		Failure load (lbs)	Centre Deflection (in.)	Bending Stress (ksi)	Core Shear Stress (psi)
12" x 80"	Experimental	13774	1.39	15.29	177.50
	Sandwich beam theory		1.39	15.21	176.58
	3D Orthotropic Solid Model		1.32	15.14	176.21
40" x 100"	Experimental	55745	2.34	23.09	214.40
	Sandwich beam theory		2.38	23.09	214.40
	3D Orthotropic Solid Model w/o caps		2.39	22.99	216.21
	3D Orthotropic Solid Model with 3" caps		2.32	22.96	208.14
	3D Orthotropic Solid Model with 3.5" caps		2.32	22.96	208.14

The investigations reveal that 3D orthotropic solid model is able to capture main features of composite sandwich panel responses under static loads and provide accurate predictions for deflection, bending stress, and shear stress along the span and across the thickness. Nearly 100% match is achieved between model predictions and experimental data. Although the 3D orthotropic solid model appears to under-predict the stiffening effect of end caps of pultruded panels, it does demonstrate the trend that for a panel with joint, adding external layers of fabric wraps over joint area does not affect bending stress and core shear stress, but does stiffen the panel and reduce the overall deflection

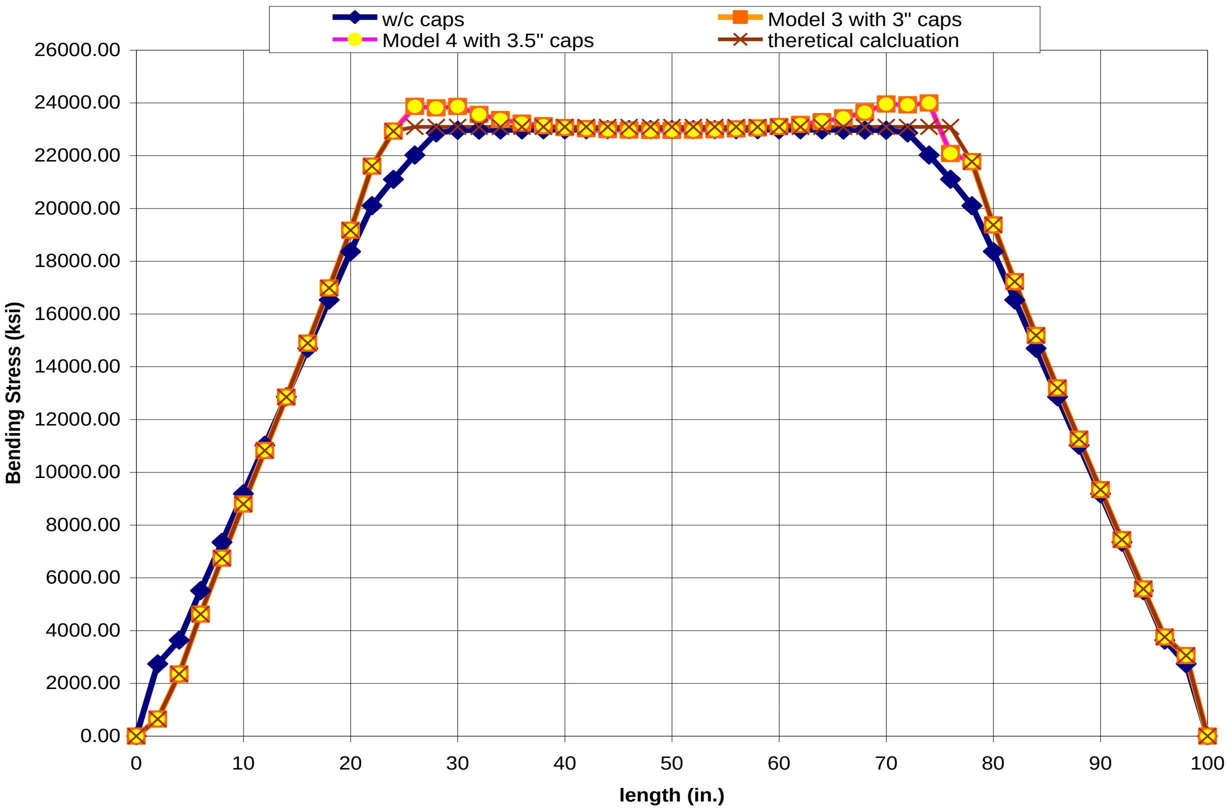


Fig. 17. Predicted bending stress across the span for 40"x100" x3.5" CFRP panel

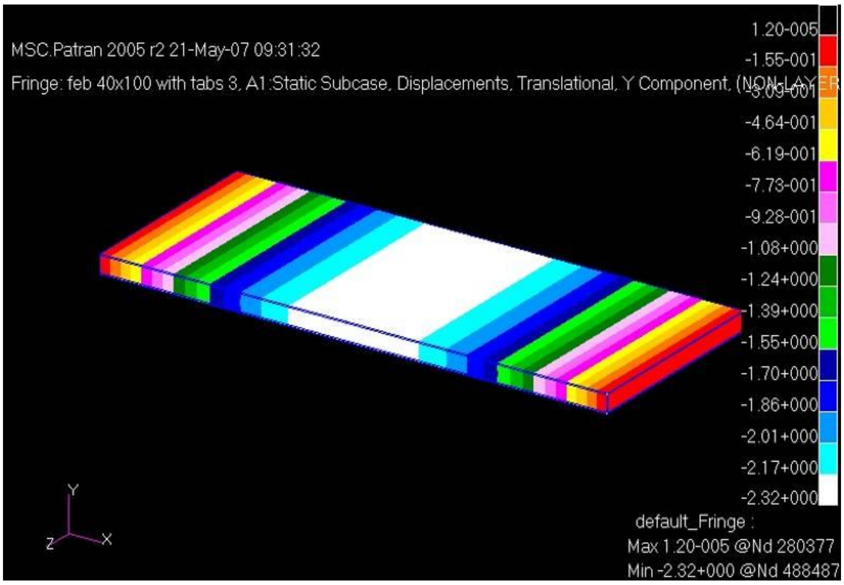


Fig. 18. Deflection contours Predicted by 3D orthotropic solid model for 40”x100” CFRP panel

12 Conclusions

A spectrum of FRP composites and sandwich panels with balsa core have been developed and manufactured through different processes including a new vacuum assisted high temperature resin spread and infusion process. Each production process has its advantages and disadvantages. Pultrusion is a highly automated continuous process and offers high strength structural shapes of high fiber volume content, but requires moderate tooling and capital equipment, limits to constant cross sections and dimensions (height and width) of the forming die. In addition, pultrusion of epoxy resin is extremely challenging. VARTM process requires only one-sided tooling and allows large-scale structural parts to be manufactured. VARTM also offers more structural design flexibility over pultrusion, allowing a product with complex shapes. However, the weakness of VARTM process includes labor intensive, high production cost, limitation with room temperature curing and flow difficulty with epoxy due to its high viscosity. As far as panel production is concerned, the Fiber-Tech process (high temperature resin spread and infusion process) appears to present unique advantages over pultrusion and VARTM for large glass/vinyl ester or carbon/ epoxy sandwich panel production in a cost-effective manner.

Both the composite laminates and full scale panels including tongue and groove joints have been characterized for their mechanical properties. In case of composite laminates, under tension, pultruded GFRP is about 15-20% stiffer and stronger, in pull direction, than VARTM GFRP, while pultruded CFRP is 30-40% stronger and 60-70% stiffer than pultruded GFRP; under bending, pultruded GFRP is about 20-40% stiffer and stronger, in pull direction, than VARTM GFRP, while pultruded CFRP is 75-100% stiffer than pultruded GFRP. In case of glass/vinyl ester sandwich panels, the pultruded panels are consistently about 15-20% stronger and stiffer and 50% lower in cost than VARTM panels. High temperature infused panels (even from a process not yet optimized) show good performance equivalent to VARTM panel, but cost about a third of VARTM panels. These differences may be due to slight variations in fabric density, fiber volume fraction and post-cure behaviors from different processing parameters such as temperatures. Strong bond between balsa wood core and GFRP face sheet is observed. In particular, 100% joint efficiency under shear as well as bending was achieved from the pultruded panels through adhesively joining tongue/ groove edges reinforced with three layers of fabric.

In case of carbon/vinyl ester sandwich panels, pultruded CFRP panel is about 50-100% stiffer than GFRP panel, 10-15% stronger and 15-20 % lighter than pultruded GFRP panel. However, the high performance of carbon fiber has not translated into property improvements of CFRP over GFRP composites, commensurate to cost increases. The lack of improvement in mechanical properties is attributed to carbon fabric sizing incompatible with vinyl ester. This research has verified the long standing sizing issue between vinyl ester resin and carbon fabric. The sizing incompatibility of carbon reinforcements would discount the performance of carbon/vinyl ester composites in many ways. The poor adhesion between carbon fibers and vinyl ester would potentially lead to wet out problem during composite manufacturing, resulting in high void content, and lower than expected strength and modulus, and reduced durability and questionable long term performance. Improvement in wet-out of fabrics and enhancement in the adhesion among the fabric layers have to be addressed in order to ensure success of the quality production of CFRP sandwich panel. Carbon/epoxy is strongly recommended in lieu of carbon/vinyl ester.

A comparative study of different finite element modeling approaches for predicting sandwich panel static response has been carried out. The sandwich panels have been investigated using the models including Sandwich Beam Model, Isotropic Solid Model, Orthotropic Beam Model and Orthotropic Solid Model. Model predictions were compared with analytical and experimental data. 3D orthotropic solid model accommodating three dimensional nature of geometry and orthotropic nature of material properties has been identified to be the model applicable to predict static response of sandwich panels at a great accuracy. The results indicate that the Orthotropic Solid Model is yielding nearly 100% matching from model predictions with experimental results for deflection, bending stress and shear stress.

This work has demonstrated success in automated pultrusion process of E-glass/vinyl ester composite sandwich panels with high degree of consistency in quality. The pultruded panels are proven to be well suited for modular assemblage concept with tongue and groove joint profiles because of their 100% joint efficiency under shear as well as bending and are cost-effective. These technical findings, innovations, and products are readily available for field implementation

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Conflict of Interest

The authors declare no conflict of interest.

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