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Manufacture of Fiber-Reinforced-Foam Composite Structures

ABSTRACT

The paper presents a general introduction to a new class of core material for fiber-reinforced composite sandwich panel construction. The material, soon to enter commercial production, is referred to as a fiber-reinforced-foam (FRF) core and has the trade name TYCORTM. The general design features of TYCOR are described and manufacturing methods are outlined. The manufacture of molded composite sandwich panels using TYCOR is discussed. The engineering properties of TYCOR are compared with other core materials including end-grain balsa and Rohacell. TYCOR is found to provide engineering properties competitive with or superior to other popular core materials. TYCOR works very well in the VARTM molding process, and offers a new approach for the rapid infusion of panels without the need for large quantities of single-use resin distribution media.

INTRODUCTION

Fiber-reinforced composite sandwich construction has been used for decades to make remarkably efficient, lightweight structures. Unfortunately the adoption of composite sandwich construction in commercial and industrial products has been limited due to high costs. Material and processing technologies that can lower manufacturing costs of sandwich structures have the potential to open up vast markets, to the benefit of resin and fiber suppliers as well as the end users who can achieve product improvements through the application of composites.

A new family of sandwich core material has been developed and is nearing commercial production by WebCore Technologies, Inc. (WebCore). The product, named TYCOR™, is referred to as a “fiber-reinforced foam” (FRF) core material. It is composed of closed-cell foam mechanically combined with dry fiber forms. The foam serves primarily as a tooling material to hold and position various structural fiber forms that ultimately become fiber-reinforced polymer (FRP) members once infused with resin during molding. These members take the form of angled struts oriented in truss- or lattice-like webs, or flat continuous webs. A typical molded TYCOR composite architecture is shown in Figure 1.

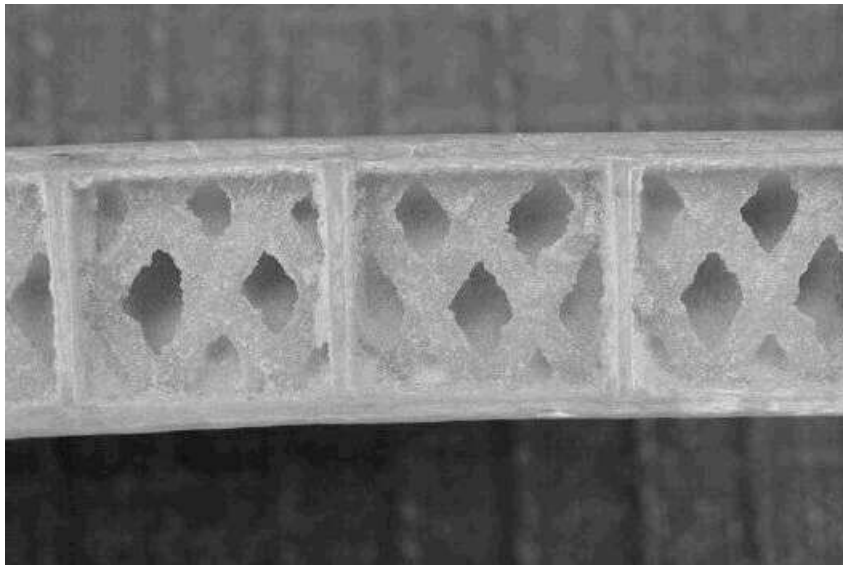


Figure 1. TYCOR panel section with foam removed from core to expose composite elements.

For several reasons, FRF cores hold promise for enabling low-cost FRP panel manufacturing. First, the FRP members within FRF cores dominate the structural properties of the core, so low-cost, low-density foam can be used as the starting material. Second, low-cost fiber forms have been chosen for FRF core designs, and practical methods for incorporating these have been developed. Third, FRF cores work very well with vacuum-assisted resin transfer molding (VARTM) which is rapidly becoming a favored technique for producing large, low-cost composite structures.

TYCOR has been explored for use in numerous applications in industries spanning aerospace, marine, industrial, civil infrastructure, and transportation. As TYCOR nears commercial production, a number of standardized products is undergoing final definition, and engineering properties for these products are being quantified in detail. While competitive performance characteristics are offered by TYCOR (as described in this paper), the generally new and complex architecture of TYCOR requires that: basic mechanisms determining strength and stiffness be characterized; analysis and design methods be developed; inspection, quality control, and quality assurance procedures be established; and molding practices and

process control requirements be established and quantified. Many of these areas are currently under investigation, supported by contracts from the federal and state government agencies and private corporations.

This paper offers a general introduction to FRF cores and molded panels. Subsequent sections describe the core design features and manufacturing considerations, panel molding characteristics, and the engineering properties of cores in molded panels.

FRF CORE DESIGN AND CONSTRUCTION

To date, a wide range of TYCOR FRF core products have been fabricated and used for molding. The cores have ranged in thickness from ¼-inch to 3-inch. Both glass and carbon fiber reinforcement have been used. There is an on-going product development effort at WebCore to increase product performance through various design innovations, both major and minor. However there are two versions of TYCOR FRF core which retain basic characteristics independent of minor design innovations. These two versions are described in the two following subsections.

Stitched FRF Core

The basic version of TYCOR FRF cores features a uniform-thickness foam board that has been stitched with an untwisted glass fiber roving or carbon fiber tow. The primary purpose of the foam is to serve as a tooling material to hold the fiber in place through the molding process, so this allows the use of light-weight, low-cost closed-cell foams typically in the density range from 2 to 5 lb/ft³.

The stitches are inserted at an angle, typically $\pm 45^\circ$ to $\pm 60^\circ$ with respect to the foam surface plane. Stitches are balanced in the positive and negative angle directions, as is apparent in Figure 1. These stitch rows are generally inserted in both in-plane directions of the foam (x and y), although a single stitch direction has been found to be sufficient for some applications. The $\pm 45^\circ$ angle is best for core shear strength and stiffness. The $\pm 60^\circ$ angle provides a compromise between shear strength and through-thickness tensile and compressive strength.

A tufting method is used for stitching, wherein the roving is pushed through the foam by a special needle, then grabbed to form a loop before the needle is retracted and the next stitch is formed. This produces a stitch on one side of the foam and a loop on the other side. The loops are cut to a short length, typically 1/8-inch to 3/16-inch, so that the final stitch configuration is a series of discontinuous U shaped roving pieces with the two legs extending through the foam.

A second, optional feature of FRF cores is the use of a layer of fabric applied to each foam surface before stitching. This so-called “preattached skin” offers some performance increase for core shear strength and through-thickness tensile strength. The preattached skin could be designed to include the complete skin reinforcement of the panel, in which case the skin would be fully stitched on with all the associated performance advantages relating to damage resistance, skin delamination resistance, etc.. However, the preattached skin is limited in size by the width of the stitching machine, and therefore in large structures the preattached

skin reinforcement can not be fully continuous. If the preattached skin can not be counted as a part of the structural skin, then is a source of extra cost and weight and may not offer a net advantage in strength-to-weight ratio.

Because untwisted roving/tow is the lowest cost form of structural fiber, it provides the greatest potential for minimizing product cost. The development of stitching techniques and stitching machine technology capable of stitching TYCOR with untwisted roving have received continual attention at WebCore for several years. The first volume-capable, automated FRF stitching machine is under final construction at WebCore Technologies and will become fully operational during 2001. The machine features a 50-inch-wide stitch zone with needles spaced at 1 inch.

Hybrid Stitched/Webbed FRF Core

A hybrid version of FRF core features stitching in the x -direction of the core and continuous webs in the y -direction, as visible in Figure 1. The continuous webs are composed of fabric featuring $\pm 45^\circ$ fiber angles. The webs are created by applying fabric to one side of a foam board, sawing the board into strips, then stacking the strips together with the fabric on one side of a strip sandwiched against the adjoining strip. The thickness of the starting foam determines the spacing of the webs, and the cutting width of the foam strips determines the height of the core. The stacked strips are then packed together and stitched in the x -direction as described in the preceding section. Generally a preattached fabric is applied to the top and bottom before stitching to provide integrity to the core, but methods are under development at WebCore for binding foam strips together without the need for preattached skins. A section of hybrid FRF core is shown in Figure 2.



Figure 2. Portion of 3"-thick hybrid TYCOR FRF core.

TYCOR PANEL MANUFACTURING

TYCOR FRF core has been used to make FRF sandwich panels using a variety of molding techniques including resin transfer molding (RTM), pultrusion, vacuum press, and vacuum-assisted resin transfer molding (VARTM). The greatest success has been with VARTM. Numerous FRF panels ranging in size up to 8-ft by 30-ft have been molded using VARTM. Several commercial VARTM molders that have used TYCOR have reported excellent VARTM molding characteristics with TYCOR. The numerous and redundant flow paths through the foam provided by the roving and fabric provide excellent flow from the resin feed side to the tool side (when using a SCRIMP-type process), excellent infusion into all parts of a panel including corners, and excellent wet-out of skins.

The hybrid TYCOR construction has offered new approaches to VARTM. Because the hybrid is assembled from foam strips there is a convenient opportunity to built resin distribution channels into the core interior. This offers the ability to perform VARTM molding using very small amounts of non-reusable resin distribution media compared to SCRIMP (Seeman Composites Resin Infusion Molding Process). A variety of distribution channel designs has been investigated experimentally. The channels lend themselves to mass production during foam preparation through the use of gang saws. Resin is fed directly into the core interior from tubes punched through the vacuum bag and top face sheet. Using this method, a 190 ft² sandwich panel with a 3"-thick core was fully infused with 700 lb of resin in approximately 10 minutes. Four such panels were made in June, 2001 for a bridge deck panel application. The four panels will be installed on a bridge in Ohio in July, 2001.

The majority of TYCOR panels molded to date have been flat, molded against a single-sided flat tool using the VARTM process. However TYCOR has also been used to mold curved panels. In a proprietary project, a major aerospace company has molded a large structural section representative of the external skin of an air vehicle. The part, which was molded against a single-sided tool, was approximately 6-ft by 15-ft in size and featured compound curvature. The thin TYCOR, fabricated from flat foam stock, was used in the curved mold without the necessity of any pre-curvature treatment. Other relatively thin stitched TYCOR has been fabricated with thermoformable foam, and was heated to impart curvature in the core before molding against a curved tooling surface.

ENGINEERING PROPERTIES OF FRF-CORE SANDWICH PANELS

The discrete reinforcement featured in TYCOR designs allows the tailoring of engineering properties through the selection of stitch advance, stitch row spacing, stitch roving/tow weight, web fabric weight, and web fabric spacing. The greater the amount of fiber reinforcement, the greater the amount of resin pickup during molding which increases the weight and cost of a panel, so there is a predictable tradeoff between engineering properties and weight/cost. WebCore has established nominal standard product designs that are roughly comparable to some popular core

materials to facilitate easy comparison of properties and cost, and to allow easy adoption of TYCOR by potential customers

Strength, Stiffness, and Density

GLASS-FIBER HYBRID TYCOR (TYCOR B)

TYCOR B is a product containing E-glass reinforcement, and is suitable for moderately heavy structural loading. Measured density, strength, and stiffness values for an E-glass reinforced hybrid TYCOR core are compared with end-grain balsa wood properties in Table 1. It is noted that according to a major sandwich panel molder, the as-molded mean balsa core density is significantly higher than the nominal balsa density in products such as Baltek’s Contourkore that feature a grid of balsa blocks on a backing material. There is resin pickup both into the ends of the balsa grains, and between the balsa blocks. Therefore the table includes the effective balsa core density for comparison, and data for 12 - 12.6 lb/ft³ effective core density are presented.

The TYCOR shear strength values are 440 psi and 390 psi in the two material directions. This compares with a value of 432 psi provided in Baltek product literature, and average balsa values of 360 psi and 260 psi in the two material directions reported in MIL-HDBK-23A [1]. It has further been shown that the measured balsa shear strength is a function of core thickness, with the strength decreasing with increased thickness [2]. TYCOR exhibits no such loss of strength with increasing thickness. Furthermore, because it is a directly engineered material, TYCOR does not suffer as great a variability in properties as balsa, even on the basis of a fixed core density for balsa. TYCOR also exhibits significantly greater shear stiffness than balsa. In summary, TYCOR B is competitive or superior to balsa in shear performance.

TABLE 1. CORE PROPERTIES OF TYCOR B AND END-GRAIN BALSA

Core	Core Density (lb/ft ³) Nom./Effctv.	Shear strength YZ (psi)	Shear strength XZ (psi)	Compressive strength Z (psi)	Shear modulus YZ (ksi)	Shear modulus XZ (ksi)
TYCOR ^a	12.6	440	390	1550	38	29
Balsa ^b	9.5/12.5 ^d	432		1870	23.1	
Balsa ^c	9/12 ^d	300	260		20.1	29.7

^aAverage values for TYCOR B HS12 (Hybrid TYCOR, 1"-thick, E-glass reinforcement) measured per ASTM C-273 and ASTM C-365.
^bBaltek Core product literature.
^cAverage values per MIL-HDBK-23A (Ref 1).
^dNominal balsa density, and effective as-molded density for segmented balsa core such as Baltek Contourkore.
Y – Tangent to balsa growth rings; TYCOR continuous web direction.
X – Across balsa growth rings; TYCOR strut-web direction.

CARBON-FIBER TYCOR (TYCOR A)

TYCOR A is a product containing carbon fiber stitching, designed for high strength-to-weight and stiffness-to-weight as required in typical aerospace vehicle applications. Tests of ½”-thick TYCOR A molded panels were performed by a major aerospace corporation in year 2000 as part of an air vehicle development program. Also tested were panels made with ½” thick Rohacell 200WF foam core. The results are presented in Table 2. Also included in the table are in-house test results measured recently for a new TYCOR design (Design No. 1-7) made with a lighter weight carbon tow and a more dense stitch pattern.

The older TYCOR design is comparable to the Rohacell in shear properties, superior in through-thickness compressive strength, and inferior in through-thickness tensile strength. The new TYCOR test design (No. 1-7) exhibited significant improvements to all strength properties, and significantly surpasses Rohacell 200WF in performance except in through-thickness tensile strength. Numerous design variations were recently tested in an effort to optimize the strength-to-weight of TYCOR A, and currently WebCore is in the process of down-selecting favorable designs and performing more extensive property measurements. Nonetheless, TYCOR A appears to be competitive with Rohacell in structural performance.

TABLE 2. CORE PROPERTIES OF TYCOR A AND ROHACELL 200WF

Core	Density (lb/ft ³)	Shear strength (psi)	Shear modulus (ksi)	Compressive strength Z (psi)	Tensile strength Z (psi)
TYCOR A12 ¹	13	330	27	1620	340
Rohacell 200WF ²	12.8	350	24	1090	820
TYCOR 1-7 ³	13.8	590	57	1990	560
¹ Average values for TYCOR A12 (TYCOR, ½”-thick, carbon-fiber reinforcement) measured per ASTM C-273, ASTM C-365, ASTM C-297, independent test source. ² Measured values for ½” thick Rohacell per ASTM 273, independent test source. ³ Average values for TYCOR A Design # 1-7 (TYCOR, ½”-thick, carbon-fiber reinforcement) in-house testing per ASTM C-273, ASTM C-365, ASTM C-297.					

Impact Performance

Because of the discrete reinforcement members comprising a molded TYCOR panel core, TYCOR has been found to perform excellently at limiting the extent of damage in locally impacted panels. In dropping-weight impact tests of TYCOR panels, damage to the skin and core tend to remain localized around the impact location. In contrast, balsa core and many foam core panels tend to suffer large-zone delamination between the core and skin. In tests performed at the Naval Surface Warfare Center, 3-ft × 4-ft sandwich panels were tested in edgewise compression before and after a standardized impact. TYCOR core and balsa core panels with identical skin designs were tested. The initial strengths of the TYCOR

and balsa panels were nearly identical. After impact, the TYCOR panel retained 90% of its strength, whereas the balsa-core panel retained only about 40% of its strength.

SUMMARY

TYCOR fiber-reinforced foam (FRF) cores for composite sandwich construction represent a new class of sandwich core material. Because TYCOR features a composite foam/fiber construction, there are many possible design variations. While product development is a constant thrust at WebCore with a focus on continual performance improvement and product optimization, WebCore is on the verge of beginning commercial production of a standard set of FRF products.

Standardized sandwich panel tests performed on molded TYCOR sandwich panels have shown that TYCOR designs can generally match or surpass the structural performance of common structural core materials such as end-grain balsa and Rohacell foam. TYCOR works very well in VARTM molding processes, and the fabrication process for hybrid stitched/webbed TYCOR offers new possibilities for direct resin infusion of panels through channels in the core without the need for one-time-use resin distribution media required in the SCRIMP process. Large composite panels (190 ft²) have been molded using this approach, with full infusion achieved in a matter of minutes.

TYCOR will soon enter commercial production with the promise of offering attractive product characteristics for customers already using conventional core materials. As WebCore produces standardized FRF products, the company will continue to optimize the design of TYCOR FRF cores, support the development of VARTM molding technology using TYCOR, and advance the understanding of fundamental mechanisms that determine the performance of molded TYCOR panels as necessary to provide reliable analysis and design tools for TYCOR.

REFERENCES

1. MIK-HDBK-23A Structural Sandwich Composites, United States Department of Defense, 30 December 1968.
2. Kilborn, Chris, "Balsa Wood Core Material Design Values," presented at SAMPE 2000, Long Beach Convention Center, Long Beach, CA, May 21-25, 2000.