OPTIMIZED RACING BOAT DESIGN USING UNIQUE HIGH STRENGTH FIBERGLASS

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ABSTRACT

The business of powerboat racing is as competitive as it gets by sporting standards. To be at the head of the pack, boat builders must push the envelope by using stronger and lighter materials. The objective of the work presented in this paper was to investigate the potential of a new, high-performance fiberglass reinforcement designed specifically for use in vinyl ester systems in the powerboat industry. The unique reinforcement is 30% to 50% stronger and 20% to 30% stiffer than traditional E-glass. The powerboat manufacturer saw this improved material as an opportunity to replace a heavier portion of traditional E-glass without sacrificing strength and toughness. Using this approach, he was able to trim weight out of the upper hull portion of the boat, lowering the center of gravity without a loss in hull strength. Such a design resulted in a boat with improved cornering capabilities, the ability to resist barrel rolls in tight turns, and the stability to keep the keel down when flying up to 50 feet in the air between waves during a race. The design was very successful. This is a good example of how to optimize performance by using improved materials.

KEY WORDS: Fiberglass, Applications-Marine, Sandwich Construction

1. INTRODUCTION

The marine industry is a competitive market where manufacturers must differentiate themselves from their competition by innovative designs, attractive products, and superior performance. When designing a high performance boat, the ability to move weight around in the construction allows a designer to maximize the boat's capabilities. It is conceivable to position the center of gravity in a boat at a point well below the water line such that the boat has the ability to take turns at high speeds without rolling in the direction that centrifugal force will tend to pull it. This maneuver, typically termed a barrel roll, slows the boat's ability to right itself when coming out of the turn, and is typically avoided in design. However, as advances are made in topside technology the weight installed on the deck of a speedboat tends to increase. Amenities such as advanced electronics and communication equipment add weight to the control cabin area. The additional weight high above the waterline leads to a top-heavy structure that increases the tendency to barrel roll.

This paper describes a new material that offers equivalent strength and stiffness to traditional marine materials at a reduced weight. One boat manufacturer, Velocity Powerboats by Initial Marine Corporation, has made use of this new technology to move weight from the upper bow of the boat to the hull. In doing so, they were able to increase the distance from the waterline to the vertical center of gravity, and greatly improve the ship's ability to corner at high speeds without barrel rolling.

2. BACKGROUND

The use of foam-core fiberglass sandwich panels is common in the recreational marine industry. It is a material that is comprised of a lightweight, low density, closed cell foam sandwiched between two thin layers of a much stronger and stiffer fiberglass reinforced plastic material. It is essentially a macro-composite material made up of several traditional composite materials. The result is a construction with the high density, high strength material as far from the neutral axis as possible, with the lower density filler material taking up space in the center. For its weight, it has a very high moment of inertia relative to the axis that runs parallel to the sandwich construction. Therefore, it is very good for use in stiff, lightweight structures. Its macro-composite density is also much less than a specific gravity of 1, so it will float even as a flat sheet. These properties make a foam-core sandwich panel ideal for powerboat construction.

The availability of a new glass fiber that has higher tensile and compressive strength and stiffness can be useful for sandwich panel construction. In order to understand how an improvement in the skin mechanical properties will affect the macro-composite mechanical properties and how this can result in overall weight reduction, previous literature can be consulted.

2.1 Sandwich Panel Strength and Stiffness The mechanics of composite sandwich panels has been studied extensively through the application of engineering beam theory. For flexural testing in general, the ultimate strength is the result of a three-way contest between the tensile strength of the bottom surface, the compressive strength of the top surface, and the shear strength. The limiting factor is the one that gives way first. For a foam core sandwich panel the same principles apply; however, because it is a macro-composite (composite skins on a foam core), more considerations must be made.

The strength of the panel is dependent upon the mode of failure. There are 7 possible modes of failure for a sandwich panel. They are face tensile yielding, face wrinkling (compression), core shear, core tensile yield, core compressive yield, core indentation, or debonding between core and face[1]. Equations for the predicted failure loading on a sandwich panel for each mode of failure can be derived from engineering beam theory. The weight of the sandwich can easily be formed into an equation based on the dimensions and the density of the constituents. The minimum weight design of the sandwich is such that the skin and the core fail at the same loading, otherwise, one component is overdesigned[2]. Based on this theory, given an optimum design, a thinner, stronger skin material could be substituted in a foam core, FRP skin, sandwich panel without sacrificing macro-composite strength. The weight savings realized in this solution would be the reduced weight of the skins.

The stiffness of the macro-composite sandwich may also be a limiting factor in the design of a powerboat. Analysis of a sandwich for stiffness has also been studied extensively. For a foam core, FRP skin sandwich panel, Gibson has calculated that the optimum design for maximum stiffness and minimum weight occurs when the ratio of the weight of the skins to that of the core is always 1:4, independent of stiffness, span, loading conditions, or materials used[3]. Based on this result, reduction of the skin weight by substituting a lighter, stiffer, stronger fiberglass would need to be coupled with a reduction in foam core weight in order to maintain a panel that is optimized for maximum stiffness and minimum weight.

Based on the aforementioned studies, the design of a composite sandwich panel can be optimized for strength or for stiffness. However it is improbable that the sandwich panel can be designed for maximum strength, maximum stiffness, and minimum weight. The proper course of action would be to decide which is more important to a particular application, stiffness or strength, and optimize the sandwich construction for that property. The alternative property should then be calculated or empirically determined and supplied to the designer as value not to be exceeded in service.

Regardless of the decision whether strength or stiffness is penultimate, the use of a stronger, stiffer, lighter material will reduce the overall weight of the sandwich. For panels optimized for strength, the weight reduction will be equal to the sum of the percentage improvement in strength and density. For panels optimized for stiffness, the weight reduction will be equal to 5 times the weight reduction realized in the skin, because of Gibson's derived 1:4 ratio[3].

2.2 Distinguishing Characteristics of a New High Strength Fiberglass In 2002, a new high strength fiberglass product designed for use in vinyl ester resin systems was introduced to the market. The material, called VeTron™, is manufactured by Advanced Glassfiber Yarns, headquartered in Aiken, South Carolina. *VeTron* is the first high performance glass fiber designed specifically for use in vinyl ester resin systems. It has advantages in composition, sizing, and construction that make it unique.

These new glass fibers are made of a magnesium aluminosilicate glass. This type of glass does not contain the borates typically found in E-glass that lower the melting temperature and temper the glass properties. The exact glass chemistry is considered proprietary in nature, but would be considered as part of the S glass family from a composition standpoint. The softening temperature of this type of glass is about 200° C higher than traditional E-glass, and it is formulated for maximum strength and stiffness. In single filament testing, high strength glass was 30% stronger and had a 15% higher modulus than E-glass[4]. Furthermore, the density of this type of glass (2.46g/cm^3) is about 5% lower than E-glass (2.58g/cm^3.) It is ideally suited for applications where traditional fiberglass is being used, but weight savings are desired. Thus it was selected to be the glass chemistry used in *VeTron*.

During the manufacture of fiberglass, a polymeric sizing is applied. The purpose of sizing is twofold; the sizing protects the glass filaments from abrasion during processing and it promotes adhesion to the matrix material that will be used in the composite. In the sizing specifically designed for *VeTron*, the film formers and lubricants deliver the fiberglass strands through the processing steps to the composite in a protected, integral bundle of filaments. When the strand is saturated with the vinyl ester resin, the film former softens, and the individual filaments are freed from the bundle, allowing them to be encapsulated by the matrix resin. The silane package that is used in the new glass fibers sizing is optimized to promote adhesion to the vinyl ester resins used in the marine market.

The final distinguishing characteristic of the new product is its construction. It is supplied in a catenary-free single-end roving construction, which allows the fibers to align easier in composites that are pultruded, filament wound, or braided. It also makes the fiberglass easy to weave into fabric form, as is typical for the marine industry. The low catenary product makes a fabric that is able to distribute the load evenly among the fibers when stressed. This even stress distribution maximizes the mechanical performance of the fibers, and results in a statistical behavior that is more normal than Weibull-like.

2.3 Mechanical Property Comparison of *VeTron* and E-glass This new product has been used in several composite applications to date. Its mechanical performance has been very good when compared to E-glass. The first comparative data examined comes from Bedford Reinforced Plastics, Inc, where it was substituted for E-glass roving in a pultruded laminate made using roving, E-glass mat, and Interplastics 8182 vinyl ester resin. The E-glass roving was 2400 tex Owens Corning Advantex® roving with 399A sizing. The *VeTron* was substituted at an equivalent glass weight fraction (45.5%.) Because the material processed similar to the E-glass roving, the substitution was very easy, a one-for-one substitution of roving packages. The product was a simple rectangular cross-section of dimensions 6.4 mm x 152 mm. The results are summarized in Table 1.

Table 1. Properties of Pultruded Beams of *VeTron* and E-glass

	E-Glass	*VeTron*	% Improvement
MD flexural strength (Mpa)	437.8	662.6	51
MD flexural modulus (Gpa)	15.0	19.3	29
CD flexural strength (Mpa)	124.0	148.9	20
CD flexural modulus	9.0	9.4	4
Short Beam Shear (Mpa)	31.5	34.1	8
MD tensile strength (Mpa)	356.2	472.3	32
MD tensile modulus (Gpa)	27.0	29.5	9
MD compression strength (Mpa)	240.4	277.2	15
MD compression modulus (Gpa)	22.5	30.4	35
CD compression strength (Mpa)	95.9	102.1	6
CD compression modulus (Gpa)	12.5	12.7	1

These data show that the fiber to matrix bonding capabilities of the *VeTron* are equivalent to slightly better than the 399A sized E-glass, as evidenced by the 8% improvement in short-beam shear. However, the machine direction properties, primarily tensile and flexural strength improvements were significant, and in agreement with the 30% improvement observed in single fiber tensile strengths[5].

In another application, the Naval Surface Warfare Center (NSWC) in West Bethesda, Maryland looked at the properties of an 800g/m^2 fabric made of woven roving. The new material is being considered for many naval applications currently using E-glass where weight savings and strength are necessary. In this study, three materials were compared; *VeTron* (2400 tex), S-2 Glass® roving (365-AA-250), and E-glass roving (225 yield). Each material was woven into a plain-weave fabric, then infused with Dow Derakane 8084 vinyl ester resin using a vacuum assisted resin transfer molding (VARTM) process. The panels were tested at NSWC. These data, part of a project with a larger scope, were cleared for public release in October of 2003. The comparison of tensile and compressive strength and moduli are given in Table 2.

Table 2. Tensile and Compressive Properties of NSWC Panels

Property	E-glass 225 Yield	*S-2 Glass* 365-AA-250	*VeTron* 2400 Tex	Improvement over E-glass
0° Tension to ASTM D638 Type III				
Tensile Strength (Mpa)	379	536	626	65%
Coefficient of Variation	9.8	7.4	4.5	
Tensile Modulus (Gpa)	25.7	27.0	34.0	34%
Coefficient of Variation	4.0	6.0	4.6	
0° Compression to SACMA IR-94 (modified)				
Compressive Strength (Mpa)	409	363	527	29%
Coefficient of Variation	6.8	5.2	6.0	
Compressive Modulus (Gpa)	30.1	28.0	39.0	28%
Coefficient of Variation	6.7	7.0	6.5	

Note that the data in Table 2 are not normalized to a particular volume fraction fiber. In fact, subsequent testing showed that there was some variation in the fiber volume fraction, although the total variation was less than 8%. These data show that the panels made with *VeTron* can support 65% more load than an equivalent cross section of composite panel made using the E-glass woven roving fabric. The improvement in compression was not quite as dramatic at 29%. From these data, and the fact that high strength glass fibers have a 5% lower density than E-glass, one can conclude that the use of *VeTron* in marine composite structures will offer a significant opportunity, in the range of 30% to 50%, to reduce weight without sacrificing strength.

3. EXPERIMENTAL

Once the two material testing programs discussed in section 2 of this paper identified the superior mechanical properties of the new high strength fiberglass, it was hoped that an actual marine application would corroborate the weight saving potential. A leading powerboat manufacturer, Velocity Powerboats, owned by Initial Marine Corporation, was approached to try this product out on a 29 foot F-1 class powerboat. Velocity was selected in part because of their familiarity and use of other Advanced Glassfiber Yarns high performance fiberglass products, but also because of their reputation for innovation and quality. The objective of using this high strength fiberglass in the powerboat was to replace some of the heavier fiberglass skin on the upper bow of the boat with a lighter weight *VeTron* fabric, resulting in the same strength at a reduced weight. The weight saved on the top of the boat would be moved to the lower hull, resulting in a lower center of gravity and improved cornering performance.

The upper hull construction was a foam core, fiberglass skin composite. The fiberglass skin was originally made of CDBM 3415 E-glass fabric. This fabric is a Double Bias Mat configuration, with +/-45 fiber bundles stitched to a chopped strand fiberglass mat, shown in Figure 1. The objective was to replace that fabric with one that was about 30% lighter, a DBM2408 fabric made using the *VeTron*.

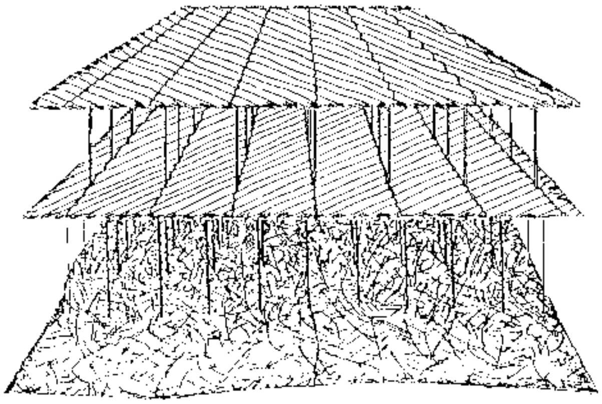

Figure 1. Double Bias Mat Construction

Based on the results presented previously in the mechanical property comparison section, a 30% to 40% lighter *VeTron* fabric was expected to be comparable in strength to its E-glass counterpart. To verify this fact, three sets of foam core sandwich panels were constructed. All of the samples had the same foam core, which was 19mm thick polyvinyl chloride (PVC) foam, with channel grooves to promote rapid infusion of resin for the VARTM. The three fabrics that were examined as skin materials were DBM1708 (E-glass), CDBM3415 (E-glass), and DBM2408 (*VeTron*). All of the fabrics were produced by Owens Corning.

The fabric architecture of all styles is listed in Table 3 below. Note that the DBM1708 and DBM2408 have nearly identical constructions, and that the CDBM3415 has an extra layer of weft strands. The CDBM3415 (E-glass) and the DBM2408 (*VeTron*) were selected because of availability and the 39% weight differential. The DBM1708 fabric was included in this study because it was an available E-glass fabric with a construction that was closer to the DBM2408.

TABLE 3 – Weight Specifics of the Three Fabric Constructions

Fabric Style	Total g/m^2	Warp g/m^2	Weft g/m^2	45° g/m^2	Mat g/m^2
DBM1708	857	0	0	584 (E-glass)	256 (E-glass)
DBM2408	1094	0	0	820 (*VeTron*)	256 (E-glass)
CDBM3415	1526	0	468 (E-glass)	584 (E-glass)	458 (E-glass)

The sandwich cores were laid up with the fabric surfaces and infused with Reichhold's Hydrex® 100 vinyl ester resin using a VARTM process. The initiator, Luperox DDM-9, was added to the resin before the infusion. The panels were allowed to cure under vacuum for 2 hours, and then the vacuum bag film was removed. The panels were sent to an outside lab for mechanical testing.

The three constructions were tested in accordance with standardized test methods[3]. Typical load-elongation curves in the machine direction are shown in Figure 2. All panel constructions showed a linear response to loading up to >95% of max load. Once failure was initiated, complete collapse was imminent. The failure modes for the specimens were mixed between skin debonding and surface wrinkling. As hoped, the panels made with the *VeTron* material were at least as strong as those made with E-glass roving, even though there was 39% less weight of reinforcing fibers in them. The slope of the curves, which define the stiffness of the panels, increased with amount of skin material, regardless of the skin type.

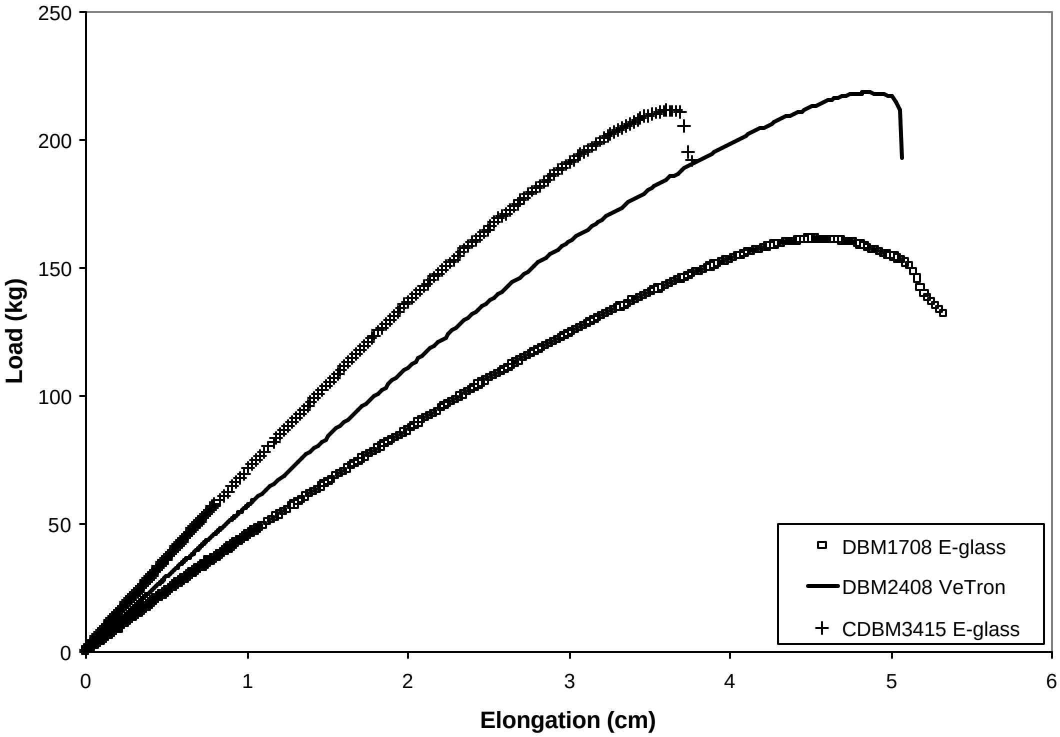

Figure 2. Typical machine direction load/elongation curves for the three panel constructions.

When the panels were tested in the cross direction, the results were similar; however, the additional cross-direction reinforcement in the CDBM3415 overwhelmed the difference in fiber properties. The strength and modulus of the heavier skinned panel was much higher than that of the two panel types that did not have the additional weft layer of reinforcement fibers.

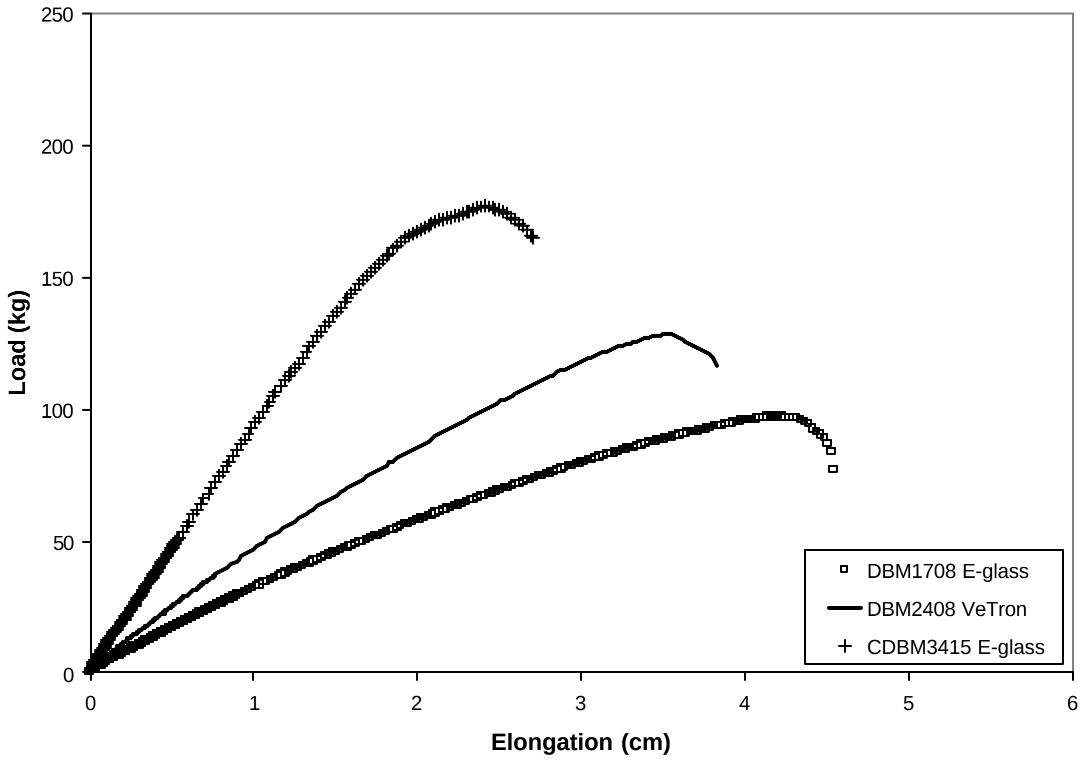

Figure 3. Typical cross direction load/elongation curves for the three panel constructions.

Three samples of each sandwich panel construction were tested in each direction. The results of the testing are given in Table 4 below.

Table 4. Machine and Cross Direction Properties of Sandwich Panels

Property	E-glass DBM1708	*VeTron* DBM2408	E-glass CDBM3415
Machine Direction Flexural			
Strength (Mpa)	25.39	32.18	30.44
Coefficient of Variation	0.5	4.9	0.6
Modulus (Gpa)	2.48	3.16	3.39
Coefficient of Variation	9.6	3.4	3.9
Cross Direction Flexural			
Strength (Mpa)	24.10	28.41	36.96
Coefficient of Variation	4.2	1.3	6.2
Modulus (Gpa)	2.22	2.95	4.99
Coefficient of Variation	1.5	0.5	5.9

4. CONCLUSIONS

The foam core panel construction using the DBM2408 made with *VeTron* was stronger than the CDBM3415 in the machine direction, but not as strong in the cross direction. The E-glass CDBM3415 fabric skins had the highest cross direction mechanical strength; however, it was also the heaviest fabric at 1526g/m2. When normalized for weight, the DBM2408 fabric was the strongest of the sandwich panel constructions.

The modulus of the panels, indicated by the slope of the load/elongation curves, was similar in the machine direction for the DBM2408 and the CDBM3415, even though the DBM2408 fabric was 39% lighter. The stiffest panel measured was the CDBM3415 in the cross direction. However, it is apparent that the same construction made using *VeTron* would be even stiffer.

The objective of this study was to produce a powerboat having improved cornering capabilities. This was achieved by using a novel fiberglass product specifically designed for light-weight marine applications to move some of the weight from the uppermost portion of the boat to the bottom. The 29' F-1 class VR-1 racing boat produced by Velocity of Initial Marine Corporation used this material to produce a boat that won 4 races in 2003.

5. REFERENCES

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