Pultrusion of Large Structural Sandwich Panels with Integrated Edge Detail and Injected Core

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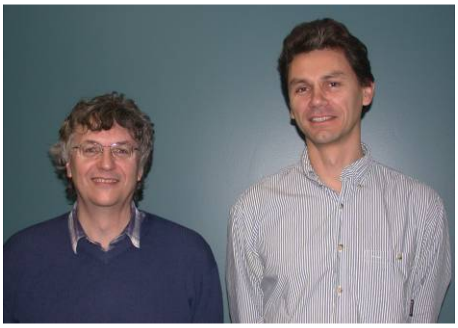

About the Authors

Dr. Jerome Paul Fanucci, KaZaK Founder and President, holds a PhD in Advanced Structures Technology and Composites from the Massachusetts Institute of Technology, and has over 25 years of experience in optimization of high performance composite designs for low cost automated production via pultrusion.

Dr. Pavel Bystricky, currently Director of Advanced Materials at KaZaK, holds a PhD in Materials Science from the Massachusetts Institute of Technology, and has over 15 years experience in developing advanced materials and structures, including metal, ceramic, and polymer composites.

Mr. Mike McAleenan - KaZaK Engineering Manager - has a Boston University MS and 13+ years of commercial and military composite experience. Mike's work history includes design and analysis experience with General Dynamics' subsidiaries Electric Boat and Bath Iron Works, as well as shop floor manufacturing experience working with Mark Lindsay Composites building IOR racing sailboats.

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Abstract

Pultrusion is an extremely cost effective technology for producing structural sandwich panels. However, overall system cost reductions are possible if innovative approaches are taken to further reduce material, machining and assembly costs, providing greater motivation for designers to incorporate pultruded materials into future civil and marine structures. This paper discusses technology development efforts underway at KaZaK to reduce the total installed cost of composite panel systems for the end user. Techniques include pultrusion of very wide structures to reduce the number of costly joints that need to be created in a structure, and the incorporation of highly engineered joints in the pultruded edges of the wide panels to enable cost effective connections that efficiently transfer load across panel-to-panel interfaces. In addition, methods for reducing the cost of sandwich panel core by injection of core material precursor directly into the pultrusion die will be described. Core purchase and machining costs are frequently one of the largest cost elements in a pultruded panel.

KEY WORDS: Pultrusion, Sandwich Panels, Wide Panels, Pultruded Joints, Composite Foam Core, One Step Composite Manufacturing, Fire Resistance, Balsa Replacement

1. Introduction

KaZaK Composites (Woburn, MA) specializes in the development of automated manufacturing technology for advanced composite structures, with particular emphasis on pultrusion. Pultrusion technology represents the only method currently capable of producing composite parts on a continuous basis and of unlimited length.

The process is illustrated schematically in Figure 1, in this case using a resin injection system to impregnate a fabric preform with resin. In the pultrusion process, reinforcing materials in the form of dry unidirectional fibers, cloth, multi-axial stitch bonded materials, braided preforms and specially-produced 2-D and 3-D reinforced materials are continuously pulled from spools or woven using in-line winders and braiders prior to being passed through an optional preheating furnace. Preheating serves to dry the materials and improves resin wet-out. This collation of dry reinforcing material then passes through forming cards, where foam cores can be inserted when making sandwich panels, before entering an approximately one meter long heated steel die. The die compacts the material into the final geometry. Resin is applied to the preform, either by pulling it through a wet-bath or by directly injecting liquid matrix into the die.

Resin injection offers a number of advantages for high performance composite production, although it requires more complex tooling and longer development efforts in some cases. The wet fiber/resin assembly is then cured as it moves through the heated portion of the die. The resin inside the die is exposed to the appropriate temperature and pressure conditions required to achieve a nearly complete cure before the material exits the downstream end of the tool. A pair of hydraulically-activated gripping plates is used to alternately grab and pull the material through the system at a constant speed. Tractor-puller systems are also used for simpler part geometries.

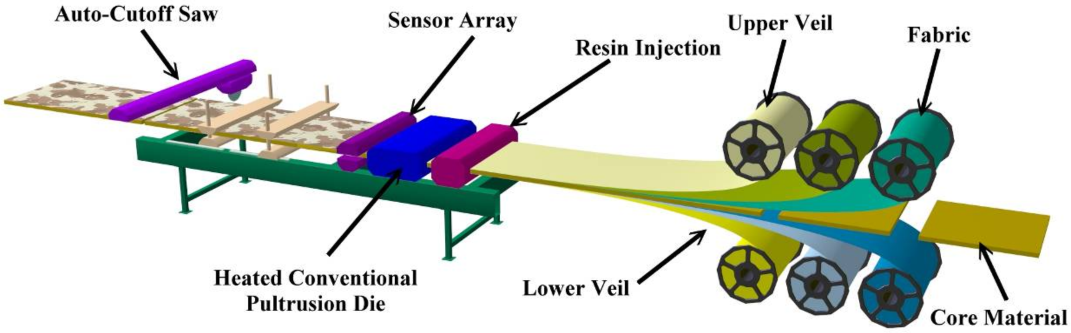

Figure 1 - Schematic of a Typical Pultrusion Line

Pultrusion is the lowest cost method for manufacturing structural composites – labor content of pultruded parts can approach zero on a per pound basis as parts become large. As such, pultrusion is sometimes mistakenly viewed as a "second-class" process. KaZaK specializes in the fabrication of large special purpose pultrusion (Figure 2), and has been demonstrating consistently for over seventeen years that this process can be used for high performance commercial and military applications. Examples include deployable facilities and highly damage-resistant stanchions[1], production of very small cross-section, high performance structures for space applications[2] (KaZaK has produced high precision composite structural pultrusions for the largest item ever deployed from the Space Shuttle, the 200-foot long SRTM boom for the Shuttle Radar Topography Mission), utilization of novel matrix materials, and production of very large, inexpensive 3-meter wide, 30-cm thick structures for piers, trucks and ships.

Figure 2 – KaZaK Operates the largest pultrusion equipment in the world, capable of making panels up to 10-feet wide. The production of 8-foot x 53-foot truck panels is illustrated here.

KaZaK operates the largest pultrusion equipment in the

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[1] J. P. Fanucci and P. Bystricky, "Two Novel Pultrusion-Based Designs for Deployable Facilities and Highly Damage-Resistant Stanchions", Proc. 8th World Pultrusion Conference, 23-24 March 2006, Budapest, Hungary

[2] J.P. Fanucci, J.J. Gorman, P. Bystricky, and T. Heimann, *Pultruded Composites for Space Applications*, Proc. 9th Biennial ASCE Aerospace Division International Conference on Engineering, Construction, and Operations in Challenging Environments, Earth & Space 2004, March 7-10, 2004, Houston, TX, pp. 930-937

world, including an internally designed 10’4” (3.15 meter) wide machine. KaZaK has been involved in multiple development programs related to insertion of large composite pultruded panels into ship ships.

This paper describes some of KaZaK’s advances in pultrusion of structural sandwich panels which have come out of these development programs. First, pultrusion of wide panels with integrated edge details for cost effective connections and efficient panel to panel load transfer will be discussed. KaZaKore, a new and revolutionary structural foam core material which targets replacement of balsa in sandwich panels, will then be introduced. Coupled with novel pultrusion processing technology, KaZaKore will allow manufacturing of stronger finished composite sandwich panels directly from raw materials.

2. Pultrusion of Wide Panels with Integrated Edge Detail

Pultrusion is widely recognized as a low cost composite manufacturing process for making structural composite parts. In most cases, the pultruded part is merely a component in a larger system that can include metal parts as well as composite parts made by other methods such as Vacuum Assisted Resin Transfer Molding (VARTM). The goal of a designer is to develop a finished product with the lowest cost. To achieve this goal, it is necessary to produce component parts as inexpensively as possible, and then, equally importantly, to cost-effectively join them into larger assemblies. Costs associated with assembly can become increasingly important to the finished part price as the cost of the pultruded composite approaches raw material. As pultruded composites begin to be used for the fabrication of very large structures such as bridge decks and ship structures, the cost of assembly and joining pultruded materials becomes an increasingly major cost factor.

Finished assembly cost can be reduced in several ways. Pultrusion has traditionally addressed the production labor component of composite cost, by automating production as much as possible to remove labor. Labor content of a composite part is closely related to throughput of a pultrusion machine in mass per hour, so larger parts can be far less expensive than smaller parts.

Assume that for a given part the raw material costs are fixed per unit mass of material. Fiber and resin costs are unaffected by the rate at which they move through a pultrusion machine. Therefore, the most direct way to reduce the finished cost of a composite pultruded part is to increase its size. This effectively reduces the labor cost associated with pultrusion. For large panel structures, this means increasing width of the pultruded panel.

For example, the table below illustrates the labor and material costs associated with pultruding a hypothetical bridge deck with a cross section weighing 25 kg/m^2. Costs are shown for pultruding the same panel cross section with widths between 0.5 meter and 3 meters. Even conservatively assuming that crew size needs to increase to make the wider panels, the table shows that there will be little difference in the amount of labor required to pultrude panel sections 1, 2 or 3 meters wide. In all cases, labor is a small percentage of cost compared to direct materials. Wider pultrusions will have an inherently lower cost per unit mass than a narrower pultrusion. In fact, as panel sizes become very large, labor cost becomes an increasingly unimportant contributor to total panel cost.

Raw Material Cost ($/kg)	$5	$5	$5	$5
Panel Width (meters)	0.5	1	2	3
Panel Weight (kg/m2)	25	25	25	25
Panel Weight (kg/m)	12.5	25	50	75
Line Speed (meters/minute)	0.5	0.5	0.5	0.5
Production Rate (kg/hour)	375	750	1500	2250
Raw Material Content ($/hr)	$1,875	$3,750	$7,500	$11,250
Crew cost ($35/hour)				
Crew members required	2	3	4	5
Crew cost ($35/hour)	$ 70	$ 105	$ 140	$ 175
Total Materials + Labor ($/hour)	$ 1,945	$ 3,855	$ 7,640	$ 11,425
Labor Content as % Total	3.6%	2.7%	1.8%	1.5%

The cost savings associated with reduced production labor in wide panel pultrusion, while significant, is frequently not the major cost driver motivating the use of increasingly wide panels. Joining of panels edge to edge can be a major cost. Adhesive cost for long joints is significant, as is the labor associates with joining. Wider panels cut the number of joints in direct proportion to width, while reducing assembly materials and labor in the same proportion.

As part of an ongoing effort, KaZaK has been working to compare the cost of pultruding a set seven different balsa-cored sandwich panel panels compared to the baseline of making the same panels using the VARTM process. For the pultruded composite case, a structure was optimized for fabrication using 10-foot wide pultruded glass and carbon fiber reinforced balsa cored sandwich panels made with integrated joint details built into the panel edges during the pultrusion process. A typical pultruded panel cross section used for this cost comparison is shown in Figure 3a-b. The portion of 10-foot wide panel being held in Figure 3a would weigh more than 400 pounds if fabricated with equivalent bending stiffness in steel. Figure 3b shows the section through an assembled panel to panel bonded joint. These joints are designed to carry the full panel bending load, and also serve as self fixturing assembly aids that provide additional cost reduction. Figures 4a-b show the male and female edge details being pultruded into the 10-foot wide balsa cored sandwich panels used to develop pultrusion versus VARTM cost comparisons. The pultrusion process as illustrated runs at approximately 1 foot per minute, so about 600 square feet of panel are made each hour with at most $150 in loaded labor cost. Thus the labor content of the pultruded panel is approximately 25 cents per square foot in this example.

Figure 3a – Single Width of 10-Foot Wide Pultruded Panel Used as Basis for Construction Cost Comparisons

Figure 3b – Detail of Bonded Joint Connecting Parallel Sections of 10-Foot Wide Pultruded Panel

Figure 4a – Male Joint Edge Integrally Pultruded in 10-Foot Wide Sandwich Panel

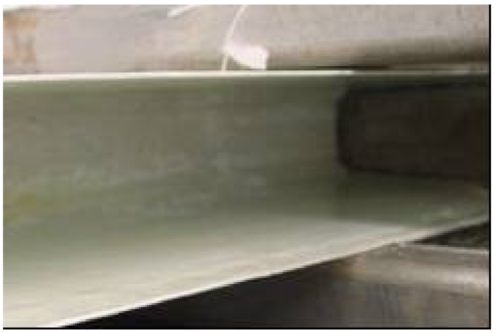

Figure 4b – Female Joint Edge Integrally Pultruded in 10-Foot Wide Sandwich Panel

Figure 5 provides a cost comparison of a set of seven different pultruded panels. Three production scenarios were evaluated, with 1, 2 or 3 sets of each panel type pultruded in a single production setup. The bars on the lower portion of the plot break down the major cost components of the pultruded production run. Notice that the cost of producing the panels is almost entirely driven by raw material cost, with other cost factors like

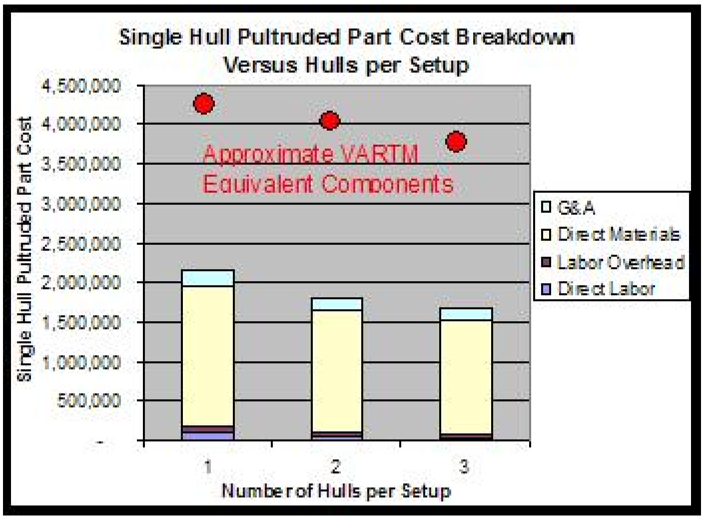

Figure 5 – Cost Comparison of 1, 2 and 3 Sets of Pultruded Versus VARTM Panels. Pultrusion Reduces Cost by 50%.

labor barely appearing in the plots. The tops of each of the three bars represent the total cost of pultruding various quantities of panel in a single setup, with the decrease associated with amortization of the labor and decreased scrap when multiple sets are made at the same time. Price of the illustrated panel set ranges from slightly more than $2 million per ship set when only a single set of panels is made at a time. This price falls to slightly more than $1.6 million when three sets are simultaneously produced. The most important data points in this chart are the three large dots located above each of the bars. These dots represent the cost of making the same set of panels using the VARTM process. The VARTM panel cost in this example is approximately twice the cost of the same set of pultruded panels. Calculated average panel price in this example, which includes a mix of glass and carbon sandwich panels, is about $5 per pound. VARTM panels average more than $10/pound.

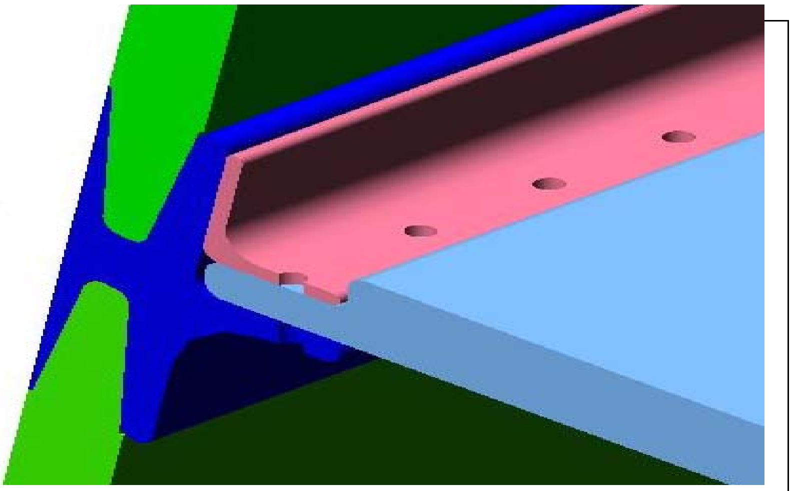

Figure 6 – Typical Example of Pultrusion-Optimized Ship Assembly Based on Large Pultruded Panels with Integrally-Created Joint Details.

This cost study did not include the additional significant cost savings derived for the incorporation of self-aligning joints in the edges of the pultruded panels (for example, like those shown in Figure 6). These details greatly reduce the cost of panel joining, which is a significant cost for the VARTM baseline structure. Studies have projected that the use of this type of integrally jointed pultruded panels can result in a finished composite structure that can be approximately equal in cost to traditionally fabricated steel. If, as expected, these cost projections are supported by planned fabrication of large pultruded demonstration structures, the pultrusion process offers the possibility of breaking the cost paradigm currently restricting the application of composites in large structures, with potentially revolutionary impact on the entire military and commercial construction industry.

<u>3. KaZaKore: Revolutionary Foam Core for Balsa Replacement</u>

In order to cost-effectively improve performance while significantly reducing weight of ship structures, KaZaK is working to develop a high performance, affordable replacement for balsa in pultruded composite sandwich panel structures. The new core material must have very good fire, smoke, and toxicity (FST) performance and more uniform mechanical properties than balsa at comparable densities.

The approach currently used for building ship structures frequently consists of manual lay-up of a balsa core with vinyl ester graphite or glass composite face sheets. These materials are often wet out and consolidated by a vacuum assisted resin transfer molding, a relatively low pressure room temperature cure process that results in serviceable but less than maximum material properties. Ship structures developed with composite sandwich panels employing balsa core material have numerous shortcomings, including the variability of balsa mechanical properties (balsa has variable density and mechanical properties of balsa core composite sandwich panels do not scale with core thickness), the need to machine cores to fit internal details, susceptibility to degradation of the wood product from moisture and insects, and the lack of supply of this natural product. In addition, traditional sandwich panel construction methods based on rigid core materials suffer from added cost associated with forming and handling the large core sheets prior to fabrication of the sandwich panels. The conventional approach of adding reinforcing material to the core surfaces and curing the resulting sandwich for extended periods of time in a batch process also result in relatively slow, costly production rates.

A next generation sandwich panel system must have low raw material costs, equivalent or improved impact, mechanical and FST properties, and be capable of integrating many conventional production steps into a single process to greatly reduce the delivered cost of sandwich panels.

KaZaKore, a proprietary revolutionary syntactic foam core material which targets the technology improvements listed above, is being developed by KaZaK as a balsa replacement for ship and other panel applications.

KaZaKore (Figure 7) is composed of a phenolic resin plus additives which reduce density and improve mechanical and fire performance. An additional area of development is cost reduction through the pultrusion process. As mentioned above, the material throughput of the pultrusion process with minimal labor content translates into a pronounced reduction of direct labor cost in the finished part. However, when using pre-fabricated core to pultrude composite sandwich structures with edge or other details which result in a non-rectangular cross-section, machining of the core to the appropriate shape prior to pultrusion is generally required. KaZaK's goal is to eliminate this additional costly and time consuming machining step by directly integrating the KaZaKore manufacturing process inline with sandwich panel pultrusion.

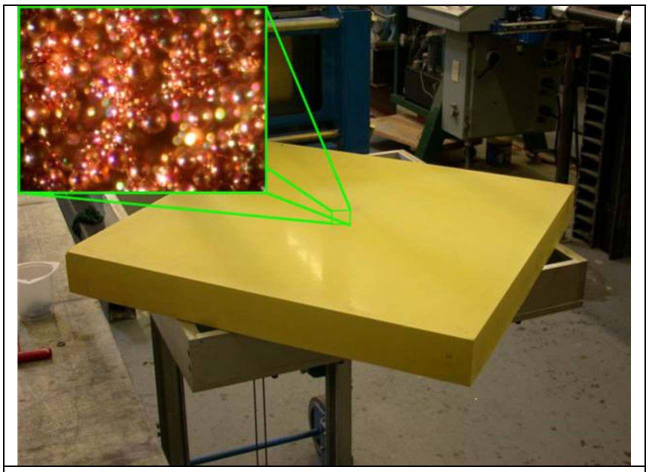

Figure 7 - Large KaZaKore panel and core microstructure (inset)

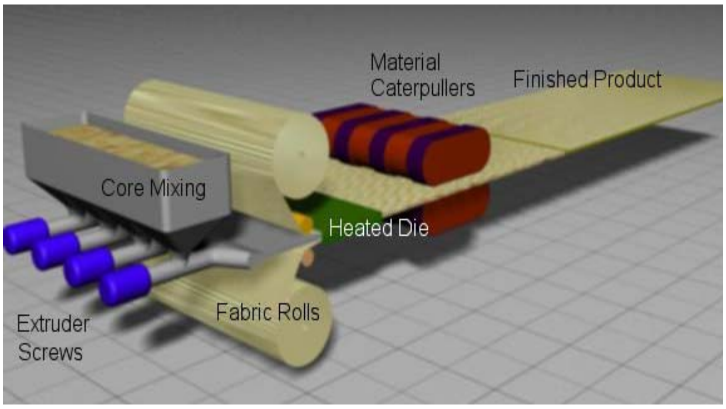

Figure 8 - Schematic of KaZaKore Pultrusion Process

Figure 8 is an illustration of the concept while Figures 9 and 10 show a demonstration of a full scale KaZaKore sandwich panel pultrusion run with co-cured glass fabric/phenolic facesheets. In Figure 3-4, which shows the die exit at the end of the run, notice the abrupt transition zone between solid co-cured sandwich panel to the right and shriveled facesheets only to the left. This transition corresponds to the location where the KaZaKore mix stopped being fed into the machine. This demonstration run is a good illustration of how KaZaKore sandwich panel pultrusion gives the finished product a significant cost advantage over labor intensive, difficult to automate, traditional sandwich panel construction methods. KaZaKore alone (i.e. without facesheets) can also be manufactured continuously by pultrusion. Pultruded KaZaKore cost per board foot is projected to approach one half of the current cost of the balsa core it aims to replace.

Figure 9 - Pultrusion demonstration of KaZaKore panel. Integrated details (molded-in channels visible on the outside edges of the panel) were integrally formed by core material injection, rather than machining the details.

Figure 10 - End of KaZaKore panel pultrusion at die exit shows collapse of the unfilled skins after core injection was terminated.

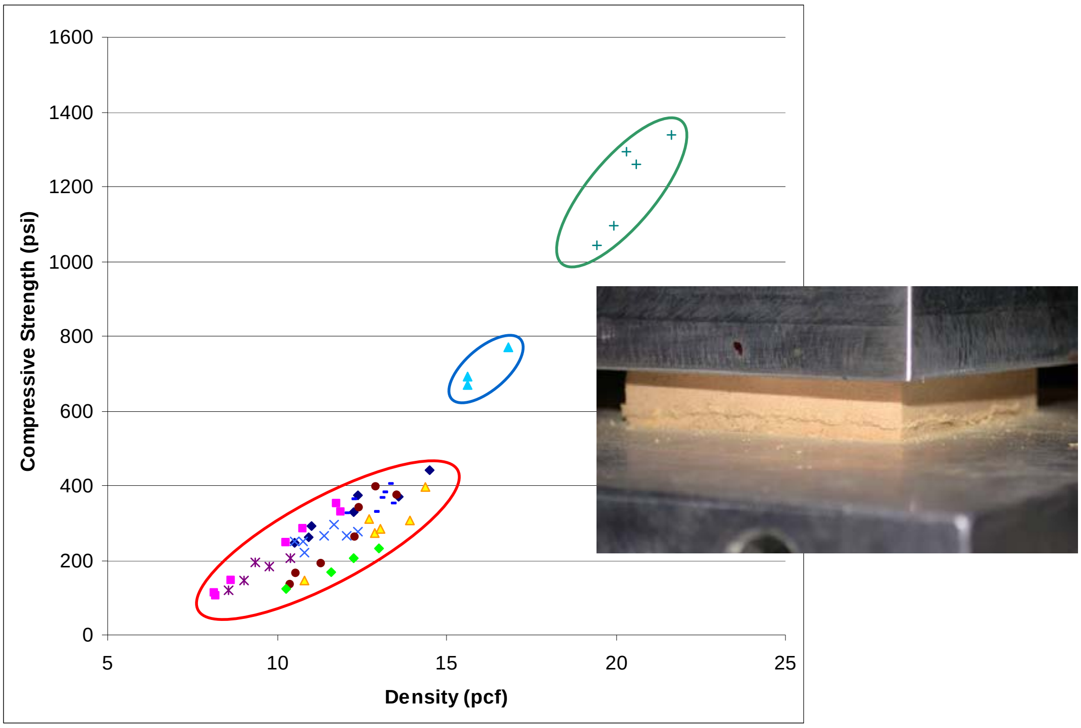

Figure 11 - Preliminary compressive strength of various KaZaKore grades.

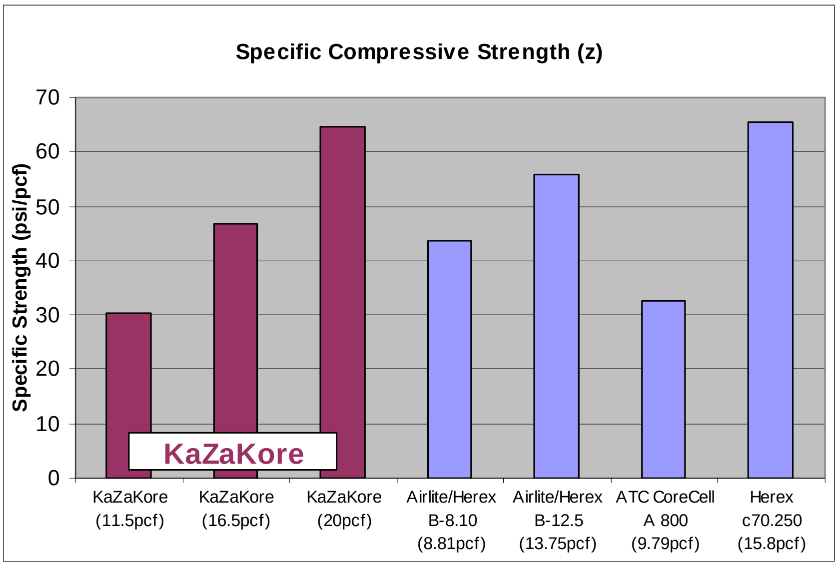

Figure 12 - Measured[3] compressive strength of some commercially available cores compared to preliminary KaZaKore results (KaZaKore is still under development)

Unlike balsa, KaZaKore has uniform properties, is immune to environmental degradation, and is readily available.

When development is completed, KaZaKore will be available in several different grades corresponding to different densities and strengths. Preliminary compressive strength data is presented in Figure 11, illustrating how significant strength improvement can be achieved at the expense of increased density. Figure 12 presents KaZaKore's specific compressive strength compared to commercially available foams being evaluated by the Navy. KaZaKore properties are expected to further improve as composition and processing are optimized.

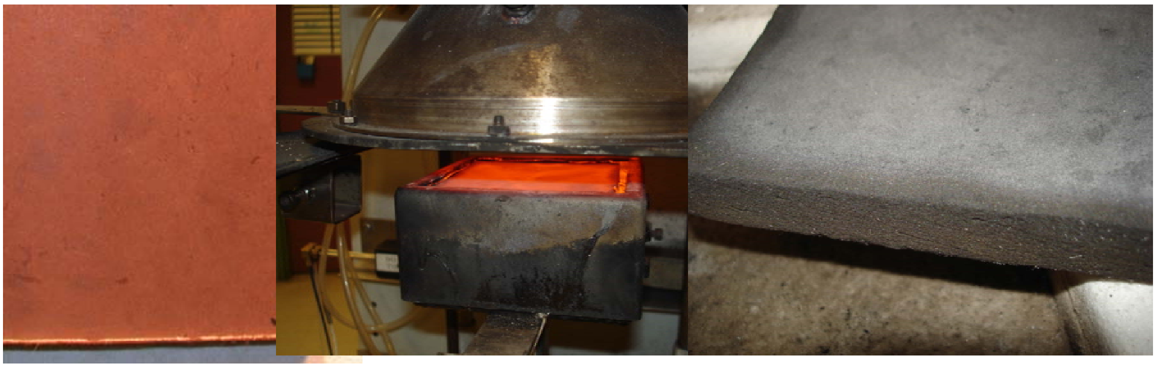

Figure 13 - Cone calorimetry (ASTM E-1354) fire, smoke, and toxicity testing. KaZaKore sample is shown before, during, and after testing.

KaZaKore fire, smoke, and toxicity (FST) properties are very good. As shown in Table 1, KaZaKore has passed MIL-STD-2031 ignitability and heat release tests (Fire & Toxicity Qualification for Composite Materials in Submarines). In addition, with a built-in fire resistant surface veil, KaZaKore has passed the stringent UL-1709 Fire Resistance test (Figure 14). In this test, a 2000°F flame source is applied

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[3] Bob Matteson, "Core Materials Characterization", Composite High Speed Vessel (CHSV) Report, NSWCCD, October 1, 2006.

to one face of the sample which must survive for a minimum of 30 minutes with a temperature rise of no more than 250°F on its opposite face. The part must then survive a 50 psi water blast.

Table 1: KaZaKore passes MIL-STD-2031

Fire Test (Mil-Std-2031 Requirements)	KaZaKore
Time to Ignition (Minimum: 90s)	108
Peak HRR (Maximum: 100kW/m²)	35
Average HRR (Maximum: 100kW/m²)	28

Figure 14 - UL-1709 Fire Resistance Test

4. Conclusions

Pultrusion is a widely recognized method for producing low cost composite hardware, and has become a well-accepted production methodology for making commercial composite structures. KaZaK Composites has been working to further improve the cost-savings that can be achieved in pultruded composite structures by advancing technology in two areas. First, we have reduced the labor content per unit mass of pultruded structures by simply making larger panels. With approximately the same amount of labor, a larger panel translates to smaller specific labor content. Cost effectiveness and structural performance can be further enhanced by pultruded large structural panels with integrated joining details. Traditionally, cost and weight associated with the assembly of large panel structures from smaller panels can represent a large fraction of finished part cost. Wider panels with structurally efficient joints lowers labor associated with post-pultrusion operations on a pultruded structure, enhancing cost-effectiveness of the finished product.

Pultrusion of Large Structural Sandwich Panels with Integrated Edge Detail and Injected Core

Reducing the cost of core materials in large sandwich panels is being addressed by the development of an injectable syntactic core precursor material that creates a finished core in line with the pultrusion process from wet resin and other constituents, rather than using precut balsa or foam boards. Significant cost savings are derived both from reduced raw material costs, and by the elimination of pre-pultrusion core machining costs associated with shaping cores for optimized joint strength and assembly convenience.

Work reported here, specifically the combination of very large pultruded panels with integrated joint details, as well as an injectable core material replacement for balsa or foam, has been projected to result in an ability for large composite assembled structures to compete directly with conventional fabricated steel cost in some applications.