Three Case Studies

Composite Options, Part 2

The author puts into practice his comparative analysis of structural composite options presented in Part 1.

by Richard Downs-Honey

We'll move from a hypothetical example of a structural design problem—the selection of cost-effective capping for stiffeners, which we explored in Part 1 (see Professional BoatBuilder *No. 119, page 50)—to three examples.*

First, we'll look at a relatively recent build: Ermis[2]*, a lightweight high-speed custom motoryacht, of carbon infused epoxy. The owner insisted his boat be a single-skin laminate structure, and* not *a sandwich that can delaminate. Given his requirements, we talked with him about his options.*

Another aspect of the planning for this build, whether single skin or sandwich, was the deck. It was infused, and we chose carbon fiber material that was rather special. We'll look at the effect of using very high grades of carbon in producing lightweight parts, given the structural criteria.

Our second case study is a numbers game: a patrol boat design drawn by the LOMOcean office, a New Zealand–based firm. The LOMOcean team has developed a portfolio of 50'–55' (15.2m–16.7m), 50–60-knot boats. We'll examine what happens across a spectrum ranging from hand-laid single-skin chopped-strand-mat/woven-roving, to infused single-skin, to a hand-laid balsa-cored sandwich. Our focus will be the bottom shell and three key factors affecting it: weight, cost, and labor.

Our third case study is of engine girders in a typical 48'/14.6m production powerboat. Again, we'll look at weight and cost. But for this example, we'll see what happens when girders designed to identical structural criteria are built in different markets, namely: the United States, New Zealand, and China—taking into account local material prices and labor rates. We'll compare different versions of a suitable girder: hollow hat-section, one that's infused, some built with csm/wr, some made with double-bias material, some with triax, and—just to keep this interesting—different geometry. Some have constant sections—8"/200mm the whole way—while others are essentially flat in the middle. Moreover, we'll allow for the deadrise change, so the girder is level on the top.

Case Study 1

CHRIS LEWIS

Minimum weight through sandwich construction

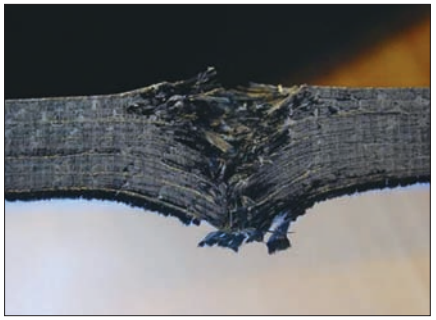
The problem to solve? *Minimum weight.* No doubt about it: this boat had to be lightweight. When you approach such a project, and you know it must be lightweight, you have to ask, What's available to me? Can I build it out of carbon? And if so, can I infuse it?

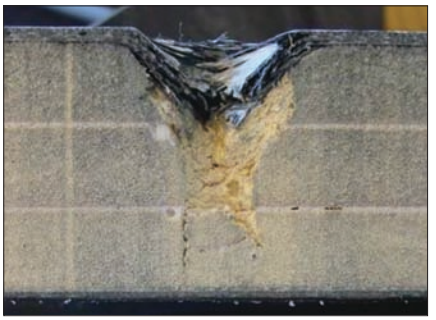
The yard commissioned to build the boat—McMullen & Wing, an excellent New Zealand yard—had never infused anything. But we're the structural engineers, and we tell them they have to infuse. And they do it very well.

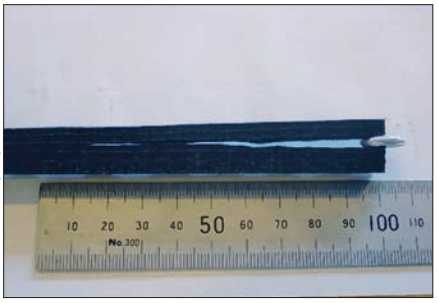
Did we have other constraints? Yes. The owner insisted on single skin. I didn't think you're going to get the lightest structure that way.

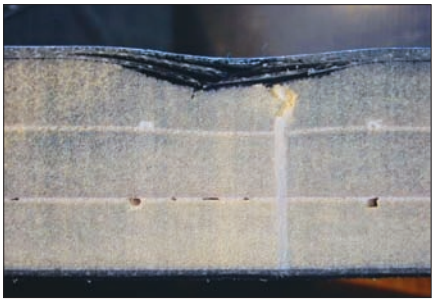
The finished boat didn't quite make the projected 60 knots. But she might do it tomorrow. The owner drives this boat himself, very hard. For certain criteria that you might normally associate with a motoryacht design commission, like noise, he said, "When I'm doing 50 knots, it's noisy, period. I don't want to talk to people then. I don't care. I just want to go fast."

After the boat had been launched, he took the designer, Rob Humphreys, of the United Kingdom, out for a *trip*. Now, Humphreys is a sailboat designer of some repute—Volvo races, Fastnet races. Serious ocean racing. Reportedly, he had never been thrashed in a boat at sea so hard in his life, as he was in









HIGH MODULUS (ALL)

Facing page—*As part of the basic structural-engineering research for the 124′/37.8m Humphreys-designed, lightweight, high-speed custom motoryacht* Ermis[2]*, the author's team at High Modulus in Auckland, New Zealand, impact-tested various single-skin and sandwich options,* ***left,*** *all of which involved carbon fiber skins. Two different shapes of a 35-lb/16-kg weight were dropped from a height of 13′/4m, to evaluate a candidate laminate's surface damage and/or internal damage, in order to arrive at a subjective assessment. In the* ***top pair*** *of photos, sharp impact has penetrated a single-skin laminate, while the sandwich's core absorbed impact energy. In the* ***bottom pair,*** *blunt impact caused hidden interlaminar damage in the single skin, and local core crushing plus outer skin damage in the sandwich.*

Ermis[2] on this trip: a thousand miles in 30 hours. Humphreys said he was crawling around on the floor. Handles came off doors, things fell out of the overhead, and the owner just kept going through the night into big, big seas. Conditions were such that he managed to collect a few minor paint scratches in the bulwarks. The fact that the bulwarks got enough water to move and flex and crack the paint shows you this boat has been proven at sea.

Here are the particulars: 124′ (37.8m) overall; meant to do up to 60 knots; three MTU diesels; KaMeWa waterjets made of composite; 130 tons displacement, because the owner wanted to travel transoceanic at 30 knots, so nearly half of those 130 tons is fuel. Structural weight—meaning all the composite that counts: hull, deck, and superstructure—is less than 20 tons. (There weren't many nonstructural items such as tables and chairs.)

The structural design criteria for this example? Minimize the weight of the hull shell and framing. Design and construction to meet Germanischer Lloyd requirements. Ensure high-impact toughness, and durability.

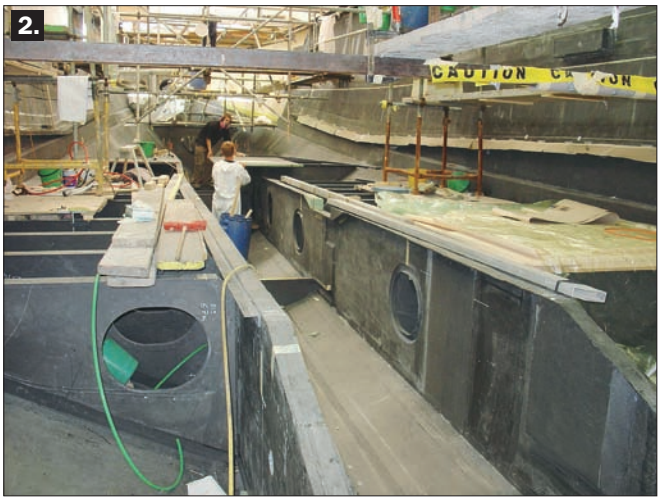
We began by conducting impact tests of various single-skin and sandwich laminates, employing 35-lb (16-kg) weights dropped from a height of 13′ (4m). One weight had a hemispherical round head; the other was sharply pointed. Those tests were to evaluate surface damage, examine a section through each sample to reveal internal damage, and arrive at a *qualitative* judgment as to which laminate was "better."

There's quite a bit of *transverse* framing in the bottom, because, as stated, the boat carries many tons of fuel. So the bottom is basically a double bottom full of fuel—big, deep longitudinal girders, plus a series of transverse frames that serve as fuel baffles and partitions in the tankage area.

The longitudinals were infused off the job, with holes detailed in them for tank access, and set at different heights to cope with things like the engine mounts. Where the taper varies, we of course varied the amount of material and varied the capping. Also, the transition on these longitudinals, from deep, stiff, and strong to not so deep, was done gently, so the hull strakes don't get upset and complain.

Note how the girders are low and wide at the flange, to accommodate the three big diesel engines, 4,000 hp (2,983 kW) each. That configuration makes the girder stronger and reduces stress concentration, so it won't break.

For the main deck, the design criteria called, again, for minimum weight. Here, we had no impact considerations, but the structure was stiffness-and-deflection critical. Not strength; stiffness. The solution for stiffness was a bit of double-bias 400-g carbon, to give us off-axis and torsional rigidity; and then 30mm/1$^{3}/_{16}$″ 5-lb high-temperature PVC foam. The



MCMULLEN & WING (ALL)

The structural-design strategy for Ermis^2 *employed a combination of approaches in the hull bottom:* ***1****—Extensive transverse framing, gaining double duty from the baffles system in the tankage.* ***2****—Full-length longitudinals.* ***3****—Robust engine girders. There were no impact considerations for the upper deck plating; it would be stiffness and deflection critical, with minimum weight.* ***4****—The boat's builder, McMullen & Wing, an Auckland yard proficient in both metal and composite construction, ably infused the deck sections—its first major infusion project.*

laminate either side of that was 370-g (11-oz) high-modulus (440-GPa/64-msi) carbon cloth. Normally you would say, That material is too expensive, even for an owner like this one, who wants to save weight. But, you may find a defense contractor who got their hands smacked and lost some contracts after they'd already purchased the stuff. You can pick these things up occasionally. We did. It wasn't that expensive, so we put it in.

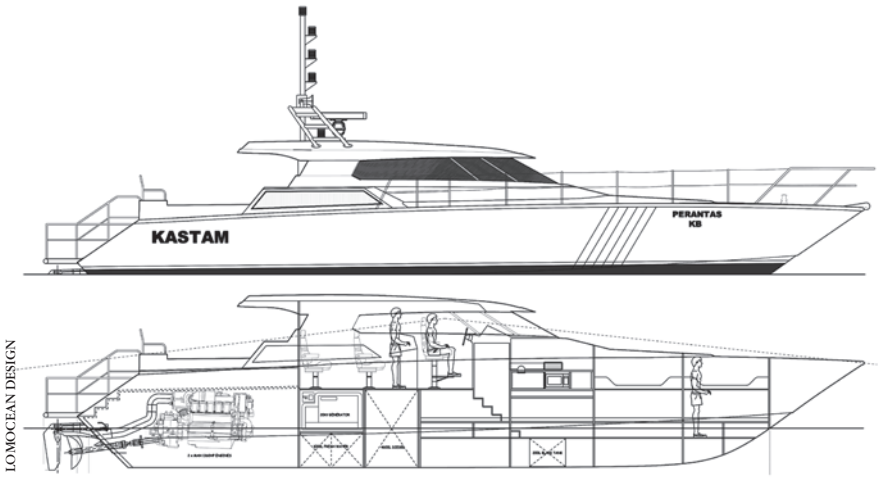
Just to give you an example: the *unsupported* panels for the upper (walking) deck measure 12′ x 6′ (3.7m x 1.8m). We installed stiffeners at 6′ (1.8m) centers. It's important to have very few stiffeners in the decks of motoryachts, because it gives you plenty of clear space to run systems and not have a lot of trouble with penetrations, and labor. Areal weight is 0.9 lbs/sq ft (4.2 kg/m^2) of laminate. If you'd done that in plywood, to get the same stiffness, it would've required 1.5″ (40mm) material and weighed 4.5 lbs/sq ft (22 kg/m^2).

It bears emphasizing that where stiffness is a criterion but impact resistance is not, *and* you can find a source of cheap carbon, then you can do some pretty lightweight stuff.

CHRIS LEWIS

In 2008, ShowBoats International *magazine cited* Ermis^2 *as the year's most innovative motoryacht under 50m/164′. Three MTU 16V4000 M90-series engines driving through composite KaMeWa waterjets give the mostly carbon boat (with a refreshingly simplified, practical interior) top speeds approaching 60 knots.*

Case Study 2



Options for bottom shell and local transverse stiffeners

For a high-speed paramilitary patrol craft, we've got impact and weight criteria similar to the first case study—but we're dealing with people who make decisions differently than private owners. Certain things must be put on the table for the buyers to decide for or against.

The case boat's particulars are: 55′/17.8m, 16′/4.9m beam, 20-ton displacement, with a sprint speed of 45 knots. For this exercise, we're just going to look at the hull bottom and framing.

Baseline construction is what might be called monolithic fiberglass: chopped strand mat and woven roving, single skin, polyester resin—a typical, conventional laminate. The panel span is 29.5″ x 216.5″ (750mm x 5,500mm). Engine beds are spaced 33.5″/850mm apart. Local transverse stiffeners are on 23.5″–25.5″ (600mm–650mm) centers, so the panels get quite small in the end. Nominal thickness is ¾″/19mm.

But let's consider an *infused* single-skin laminate. Maybe we'll reduce labor by doing a one-shot operation.

Our baseline construction is hand laid, not sprayed up, which means the crew puts mat/roving down, then they put another layer down, and another…and it goes on and on. If we can get them to shoot it in one shot, we get better quality control (provided the infusion process is well understood and practiced), lower void content, higher fiber content, better physical properties; and we might be able to infuse our transverse stiffeners along with the shell laminate, and then install the longitudinals. Using the transversals as flow paths effectively gives you a branch feed. So not all of the structure is infused—just the parts that would fit into a flow strategy.

Let's save some weight by installing multiaxial 0/90 and 0/±45 E-glass reinforcements, and go with a vinyl ester resin. You'll find, with this combination of materials and a single-skin infused laminate, that the properties go through the roof.

Since bending moment capacity is a function of thickness squared, you can double your strength, but you can't halve your thickness. Thus, the drop from a nominal ¾″ to ⅝″ (19mm to 15mm) is about all we can get. But we *have* saved weight—in the frames—with better materials.

The next option to consider is a hand-laid sandwich. We'll install the same polyester-resin/chopped-mat/woven-roving laminate as in our baseline model, with the addition of a low-cost balsa core—two layers of ¾″ material to meet the structural design criteria. That increases panel rigidity, and permits a larger unsupported panel and fewer transverse frames. The net result for this option? Fewer frames mean less material (resin and glass) and therefore less labor and lower cost. However, that saving is offset by the cost of the core; and, there are potential problems with the quality of build. We're still open-molding; you have to vacuum-bag the core in; you must bond the core; and you have to ask yourself just how reliable this system is, compared to single-skin construction.

Bear in mind that regardless of build method, the frames and shell are designed to the same structural criteria. As best we could, we've matched things to make it an apples-to-apples comparison.

Next, we'll try an infused sandwich. Let's do it with a high-performance epoxy resin, put in some linear Airex—R63.140 PVC foam—and get really robust with the skin laminate. Let's make it a thick, stiff, strong shell to reduce the amount of framing. Again, provided the build process is well established, our labor cost will be lower. And, being infused, we've now got a reliable core bond. At the same time, though, we've added a considerable amount of off-mold preparation time. And the bill of materials is quite expensive.

But why stop there? What if we *optimize* the sandwich construction? Now we're moving well away from the baseline model, which essentially says to the laminating crew, You guys really know what you're doing—we're just gonna give you a roll of material, wait for you to finish putting it down, and then we'll give you another roll—to saying, We're spending a lot of money on these better materials. Maybe if we didn't put as much as we needed in some places, it would be cost effective.

So for the optimized sandwich, we'll install the same materials and technology as for the infused sandwich. Except now we've specified six different reinforcements and five different core thicknesses and densities—all of which can fast confuse a general production shop. Nevertheless, if you're willing to pay money to minimize weight, then it might be worth it.

For the optimized sandwich, we took some of the labor-intensive "pre-build" work *away* from the shop floor by pre-cutting materials and pre-arranging patterns, and assembling kits of all the glass and core. When that kit arrives on the shop floor the crew is, in effect, working out of a box.

We've found that this approach can reduce the bill of materials by as much as 20%—and reduce the composite-part weight by 10%, since you now have less material. Even so, an optimized sandwich requires careful planning to ensure accurate CNC cutting of fabrics and core, all of which must

Comparing the Options			
	Weight (kg)	Low cost (U.S.$)	High cost (U.S.$)
Baseline single-skin	3,250	18,000	28,700
Infused single-skin	2,100	13,000	18,700
Hand-laid sandwich	1,750	19,000	26,000
Infused sandwich	1,250	30,000	34,900
Optimized sandwich	1,150	27,500	30,800

be billed into the process. You've reduced direct shop-floor labor by initiating fewer "in-mold" build hours, thereby giving your shop a better utilization of overhead.

No matter which process is selected in our second case study, it is a fact of business life that material unit prices, depending on who you talk to, will vary considerably; they're infuenced by local market forces, customer volumes, and other factors that necessarily result in a high and low range of numbers for analysis purposes. Since we're conducting a comparative exercise here, I'll give you a number for the hull bottom and framing, which does not include overlaps at the chine or the centerline. And it's not what the boat weighed, just the portion that I looked at. So, regardless of the process selected, I'm making the same assumptions for that area of the boat; the variances are in material wastage.

My labor estimates are just that: *estimates*. We sat down and said, How would you build the boat? Will you have four guys? What exactly will they do on Monday? Gelcoat Monday afternoon? Probably get half a skincoat. What happens Tuesday? Instead of "reading" the problem in terms of x number of pounds of material applied, we put together a schedule for the build. Might be two, three, four weeks long—10 guys doing this, three guys doing that. It was our way of estimating the labor, rather than just saying, Oh, it'll take four days to infuse something. We took into account variations in skill levels and experience, irrespective of the build method. And, we assigned extreme highs and lows in our range of labor rates.

For the optimized sandwich, we included the additional design and CNC-cutting costs to produce the kit sets, but we also placed a value on reduced mold time, and increased throughput. If, say, you've got 10 of these boats to build, and you have to series-build them in a specified time frame, and if you can cycle them smartly in and out of the mold, then maybe you can build more in the same amount of time, or shorten up the build time. That kind of thinking is not often factored in. These days, with the economy down and not a lot of boats to be built, some builders say, It doesn't matter to me; the mold's just gonna sit around if I get the boat out early. Nevertheless, it's something you should bear in mind. Because if you can amortize your fixed-cost overhead over more production by cycling your molds quicker, then it makes commercial sense.

I've charted a comparison of the various build processes just discussed, starting with the baseline method (see **Comparing the Options**, above). Remember: The weight we're considering comprises the weight of the hull shell and framing for the bottom of the boat. Meaning, it's the longitudinals, transversals (or not, if they've been left out because of the sandwich), and the shell, but does not include the chine and the topsides and the rest of it. It's a purely comparative number.

That said, you can see significant weight variation among build methods: The infused optimized sandwich weighs *one-third* what the baseline structure does. And those 4,409 lbs/2,000 kg of saved weight in the bottom could be reliably extrapolated to the rest of the boat's composite structure.

I'll run through the chart, in the order they're presented.

For *baseline single-skin* construction, the cost of materials and labor is between $18,000 and $28,700. It comes down to what you know and what your variances are for weight factors, time factors, and how much you pay for resin.

For *infused single-skin*, you'll remember that we went from ¾″ to ⅝″, so we didn't achieve much savings in shell thickness; we didn't save much weight there either, given the increased fiber content and increased laminate density. But when we take into account the fact that we're infusing the transverse frames and making infused longitudinals, we did manage a one-third reduction in weight. As for material, those costs have actually come down. Remember, this is a well-proven construction system—we understand the learning curve. According to our hours and allied costs, you should be able to build acceptable, comparable components—those not involving cosmetic criteria—for lower costs than with open-molding and however many plies and laydowns it takes to build ¾″ (19mm) of woven roving and mat.

Next, we have a *hand-laid sandwich*. Here, we see a small drop in materials and weight. But the cost has poked up again. Compared to a single-skin laminate, sandwich contruction is half the weight while in the same cost range. That's precisely why people build sandwich boats: they're lighter, and can be cost effective compared to a single skin.

For the *infused sandwich,* we've pulled more weight out again, by moving to a skin characterized by less mat and higher fiber content. And we've gone from balsa to a slightly thinner Airex core. But our bill of materials has rocketed: $30,000 to $35,000 for materials *and* labor.

Finally, we have the *optimized sandwich*, where we started to fine-tune the matter of materials. We pulled the weight down another 10%, and lowered the bill of materials. We've also lowered the build cost, because the labor time to build the structure is down: I opened a kitted box, took out the pre-arranged and pre-marked material, and dropped it in. I didn't have to fit, trim, and cut it.

I'll point out a few other features suggested by this comparison chart. Relative costs are more sensitive to labor-cost variation than they are to material prices. Also, there are different "minimum/optimum" solutions in different markets.

You can look at this chart and say, What am I going to choose? Should I build my patrol boat out of chopped mat and woven roving, open-molded? If performance is a criterion and performance is a function of weight, then you'd say, I don't think so. Well, I

know some builders committed to the baseline course, right now, with a 112′/34m boat, because that's all they know how to do.

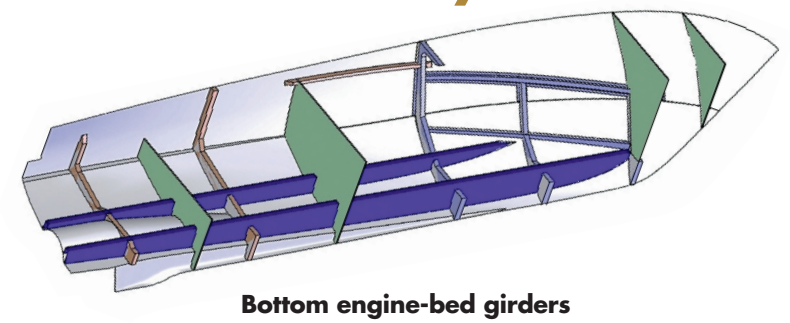
Would you build your patrol boat with a higher-tech optimized sandwich laminate? Maybe, maybe not; it costs more. Does that weight really matter? With single-skin construction, you're condemned to weight in the bottom area. If you take *two* tons out of the bottom shell of a 20-ton boat that does 45 knots, is it going to make a difference in performance?

Clearly, so-called high-tech, optimized construction is expensive. There is, however, a savings in labor by way of CNC pre-cutting; and infusion processing can offset high material unit costs. The question you must ask is: What am I willing to pay for weight reduction? Or, put another way: What price per pound? How much would you pay to save a pound of weight in a patrol boat like this? What's the performance or fuel or engine-size trade-off?

Now you should be able to see why some people are at least *thinking* of building infused patrol boats, likely with sandwich construction and possibly with an optimized laminate—because the old way, the monolithic baseline way, is pretty heavy.

Finally, other factors are often involved, chief among them, even if *you're* convinced but you don't run or own the company: Can you sell a better build method to your boss?

Case Study 3



Bottom engine-bed girders

We'll look at two geometry options, two construction options, three material options, and the comparative costs of all these in three separate markets—the United States, New Zealand, and China.

Geometry options. The first is the simplest: a piece of urethane foam of uniform depth, 8″/200mm, placed down the length of the bottom of the boat. Meaning, you don't have to shape the bottom surface; the foam just goes wherever the hull bottom goes.

Alternatively, we analyze what happens if you opt instead to have a level upper surface; meaning, in places the foam might be 8″ deep, and elsewhere, due to deadrise, it might be as much as 16″/400mm deep. The latter approach can be beneficial, because where it's twice as deep you'll need less material to carry the load. As long as you take that into account in your structural design, and vary the material along the length of the span—which is to say, the laminate itself will vary depending on span and depth—then you can save money by making it deeper.

Naturally, the latter course demands that you put in more urethane; sometimes when you get to a certain depth, the cover laminate that you put over it is no longer a function of strength but simply: stability.

A deep girder is considerably stiffer than a shallow one. Note that we designed the various girder options to the same bending and shear strength. We have *not* designed them to *stiffness* criteria. These are bottom girders, and one set may be stiffer than the next, but they're equivalent in terms of bending load or flexural moment and shear strength of the wall. Comparatively, they're apples to apples.

Construction options. One is an in-situ molding of glass over a polyurethane foam former of 2-lb/ft^3 (30-kg/m^3) density. It has some capping on the top if appropriate, or, in the case of the woven-roving/chopped-mat option, instead of putting unidirectional capping on top, we overlapped the left and right layers to build up thickness. We also overlapped in the triaxial option, still to be discussed.

The second construction option is to make a pre-molded hollow hat-section and tape it to the shell. You could also glue it to the shell with a structural adhesive, but for this exercise, we looked at taping only.

We have two solutions: a horizontal web stiffened with core, or one supported by a shelf. With 12″/305mm of depth, if you put enough material there to carry the load, then it wouldn't be enough to prevent buckling. So those two solutions address the web buckling issue.

Material options. We have three: chopped-strand-mat/woven-roving, lapped on the cap; double-bias (±45) E-glass with unidirectional capping; and, combining the double bias and the uni into a single ply of triaxial, lapped on the top. They're all polyester resin and all hand laid. Just for the hell of it, we infused the triaxial option as well—to evaluate the effect it might have on cost.

All the structural calculations were conducted in a way to ensure apples-to-apples comparisons. Our material costs, however, exclude any wastage—though admittedly it *is* a variable that ought to be taken into account. And, as in our earlier case studies, the labor costs we cite are based on estimated elapsed times for executing various stages of construction—informal time-and-motion studies: how long to fit up a vacuum bag, mold it, take it out, put it in the boat, tape it in; how long to get the PU foam, shape it, fit it in, seal it; laminate one layer, laminate another layer…and so on. That's how we arrived at our numbers.

We applied different *loaded* labor rates, depending on the market. We chose $30/hr as being representative for the States, $22/hr for New Zealand, and $3/hr for China. What we did *not* do was spec the composite-part construction in terms of different efficiencies of labor. We figured the Americans would work just as hard as the Kiwis, and the Chinese wouldn't be slackers either.

Now we can make an informed analysis.

Options Considered				
Label	**Material**	**Type**	**Geometry**	**Process**
A1	csm/wr	In situ over PU foam	200mm deep	Hand-laminating
A2	csm/wr	In situ over PU foam	200–400mm deep	Hand-laminating
A3	csm	Male molded hat, taped in	200–400mm deep	Hand-laminating
B1	db/m/uni	In situ over PU foam	200mm deep	Hand-laminating
B2	db/m/uni	In situ over PU foam	200–400mm deep	Hand-laminating
B3	db/m/uni/foam	Male molded hat, taped in	200–400mm deep	Hand-laminating
C1	triax/uni	In situ over PU foam	200mm deep	Hand-laminating
C2	triax	In situ over PU foam	200–400mm deep	Hand-laminating
C3	triax/foam	Male molded hat, taped in	200–400mm deep	Hand-laminating
C4	triax/foam	Male molded hat, taped in	200–400mm deep	Infusion

Referring to the table **Options Considered**, above, the first three entries, "A1", "A2," and "A3" are made with chopped strand mat and woven roving. Awful stuff.

The next three entries—"B1," "B2," and "B3"—are double bias, or biaxials, with uni capping.

The last three—"C1," "C2," and "C3"—are triaxials. So: "A" for awful, "B" for biax, "C" for clever triax. Some are in situ over PU foam, some are hollow molded, some are constant depth, some are variable depth.

Given this complex matrix, we'll simply skip a couple of items, examine a few, and compare them.

The first question is, Should our girder be of variable depth, or of constant depth? We'll look at that in the U.S. market, and with in-situ PU foam; we won't go into the hollow side of things just yet. And we'll compare the three materials: csm/wr, double bias, and triaxial.

In **Graph 1** we see A, B, and C again. All are polyurethane foam girders. We've got costs on the left, and weights on the right. When you go from csm/wr to biaxial (from A1 to B1 or from A2 to B2), you reduce cost and weight. When you go from biaxial (B1 or B2) to triaxial (C1 or C2), cost and weight go up a bit.

Three of those girder options are at constant depth, three at variable depth. When you go from constant depth to variable depth, the cost doesn't change. But the weight goes down. Less cover laminate is offset by the cost of a little more PU foam.

Putting those foam girders in is time consuming. Maybe we should make them out-of-house, perhaps get a better job of it, and then place them in the boat. What's going to be better—hollow section or PU foam? The PU foam doesn't really do anything for you. You carry it around, waiting for it to soak up water. In **Graph 2**, we're staying with the U.S. market and looking at: variable depth versus standard depth; those three different materials; and the original baseline approach we started with—the 8″ (200mm) csm/wr, the most expensive, and heaviest, thing we could think of building with.

You see how this works. The baseline, A1, is csm/wr, PU foam, in situ, 8″ deep. And as we move across the graph, the next one, A3, is the csm/wr, hollow girder. B3 is the double biax/uni, hollow girder. C3 is a triaxial hollow girder, and C4 is an infused hollow girder.

Notice that the hollow-girder cost stays about the same, whether it's built with csm/wr, double bias, or triax. But the weight certainly comes down, with the infused weight being the lightest. So, a hollow girder saves weight.

We're assuming you're molding the girder on a male mold, outside the boat. Not an expensive, glassed-up mold—just a simple hat-section hollow.

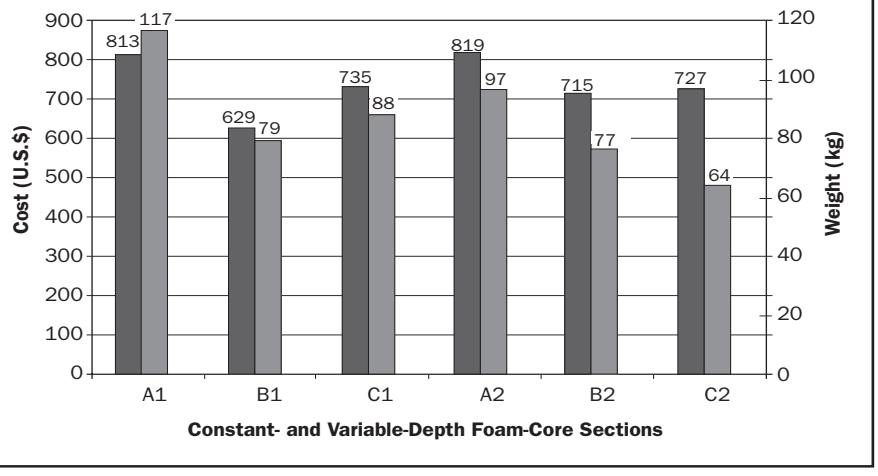
What happens between New Zealand and the U.S. in terms of cost? In **Graph 3**, we're looking at constant-depth versus variable-depth girders. There's a difference between csm/wr, double bias, and triaxial; in general, building our girders in the States, where labor is $30/hr, is cheaper than building them in New Zealand, where labor is $22/hr. So it's *not* about the international exchange rate; you *can* be competitive. The problem is not that New Zealand shops are slow; it's that we Kiwis charge people too much for materials in New Zealand. We're on the other side of the world, it's not a big market—there are only 4 million people. (There are 40 million *sheep*, though; if we can sell *them* something, we'd have a market.) By the time we get resin and glass down there, put it in a warehouse and store it, those materials cost more than Americans pay for the same resin and glass. On that basis, then, the girder is more expensive.

If we look at the in-situ PU foam, Graph 3, whether constant depth or variable depth, when we put PU foam in a new build in New Zealand, and put a lot of labor into it, material costs kill us. We can't compete. We just give up. But our labor costs are less; and if you do a hollow-molded girder, reduction in material costs means labor is more important, and the N.Z.-manufactured girders are cheaper.

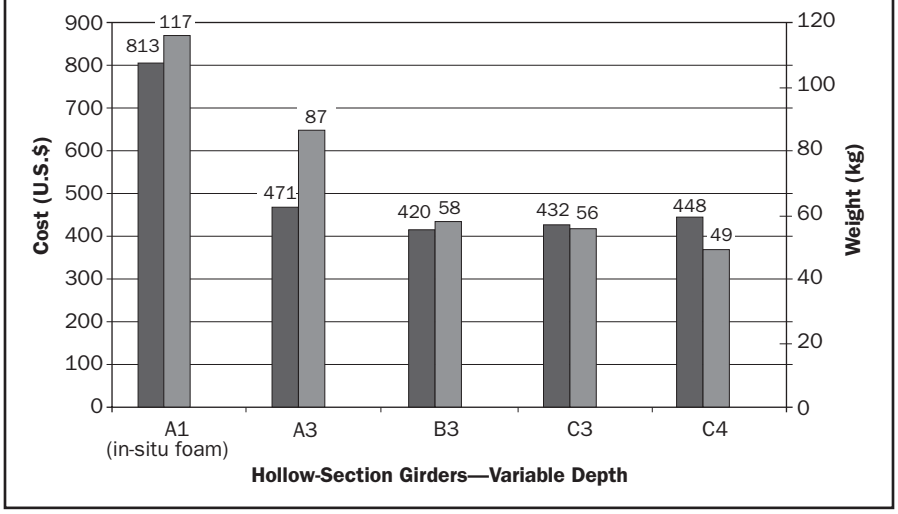
When I did the same analysis again, this time with hollow girders, **Graph 4**, the equation changed. We *can* be competitive, the reason being: we pay too much for PU foam, and too much for resin. If we make a hollow girder, what about labor? There's actually not a lot of difference.

All right. What happens if we go to China, where labor is $3/hr? What if I told you I could get biaxials there for

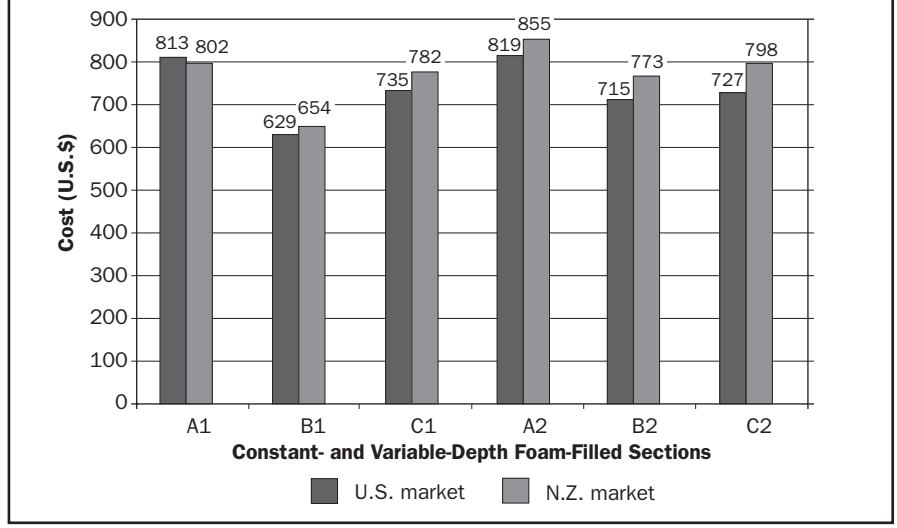
Graph 1. In-Situ Girders / U.S. Market



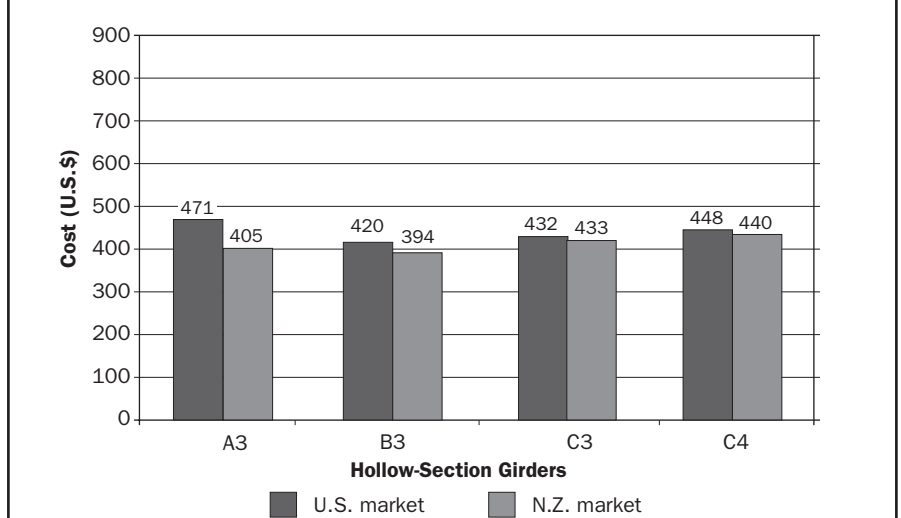
Graph 2. Hollow-Section Girders / U.S. Market



Graph 3. In-Situ Girders / U.S. Market vs. N.Z. Market



Graph 4. Hollow-Section Girders / U.S. Market vs. N.Z. Market



less than a dollar a pound? Granted, some composite materials in China are really expensive: PVC foam and balsa core, for example. But there are also some really low-cost reinforcements. So China is not merely an area of low-cost labor. If we were talking about a Nomex carbon sandwich, you'd have to import all the carbon and pay dearly; it would cost you more than building it here. But if you're in China and sourcing locally, and they haven't had to freight it in… Well, freight becomes a large part of the cost when they move a finished product over here.

Let's have a closer look at China in **Graph 5**. I've broken it down so you can see material and labor costs. No surprises there. We go from $800 for the baseline csm/wr version, down to $350. Everywhere you look, it's cheaper in China. And it's because the material costs have dropped, and labor costs have seemingly disappeared. But it's not all…*labor*. Here's the really frightening thing: What would happen if they got in step with the world economy and decided they needed some inflation in labor, and the labor went from $3/hr to $6/hr? The cost would go up only a tiny bit.

You'll remember first, that this is an in-situ girder, and second, that we concluded it's a lot cheaper to build with biaxial or triaxial; woven roving and chopped mat and resin just didn't make sense. In China, we don't necessarily arrive at the same conclusion. There, the differential between one material and another isn't as significant. In fact, chopped mat and woven roving in China *can* be cost effective. They don't pay much for their woven roving: I saw some there for about 60¢ a pound! It was a 12-oz reinforcement, a beautiful material.

It's the same for hollow girders in **Graph 6**. But now the csm/wr option *is* cheaper than the double bias, triax, and infused ones. And the difference between them isn't as significant, even though you're using more expensive materials.

After studying a dense comparison chart and multiple column graphs, what conclusions can we reach from our third case study?

First: *Construction*. A hollow hat-section is lighter and less expensive than molding over a PU former.

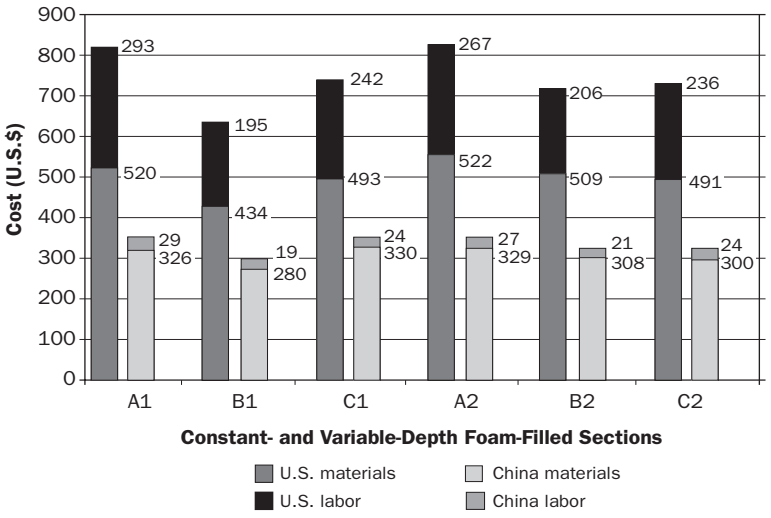
People often ignore the cost of foam, and discount the labor involved to shape and fit a foam former. (Granted, you can buy so-called preforms, which would make a difference, but I did not pursue that option for this exercise; it's too complicated.) There is also the increased difficulty of laminating in situ. Hand-laminating over a stiffener in a boat is going to take a lot longer than standing at a bench with a mold and making something.

Second: *Materials.* We've seen that an engineered multiaxial specification can be less expensive than the supposedly "cheaper" csm/wr baseline in all the markets we considered. It's simple: You put less fiber down and less resin on, so you don't pay as much. And that's because you've got the fibers going in the direction you want. The in-plane shear strength of a double bias, what you put on the web, is about two, two-and-a-half times that of a woven roving. So, less weight of fiber and resin is required, and fewer layers of material, thereby reducing labor.

Third: *Infusion* is a viable option. It can yield an overall cost similar to the hand-laid girder, along with a slightly lighter but more consistent and reliable product. If I were setting up to do this sort of thing, and the labor costs were down, I'd probably plan on molding my girders, and infusing them outside the boat. As opposed to doing what almost everybody does, which is get in there with a block of urethane foam and a bucket and brush and some chopped mat and woven roving.

Last: What can we conclude about the *market* differences? You've got to do a total cost analysis of labor and materials first. It's very important, because that's the only way to reveal

Graph 5. In-Situ Girders / U.S. Market vs. China Market



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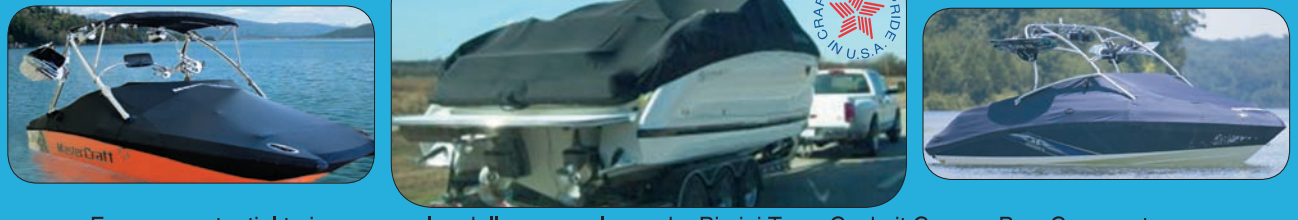

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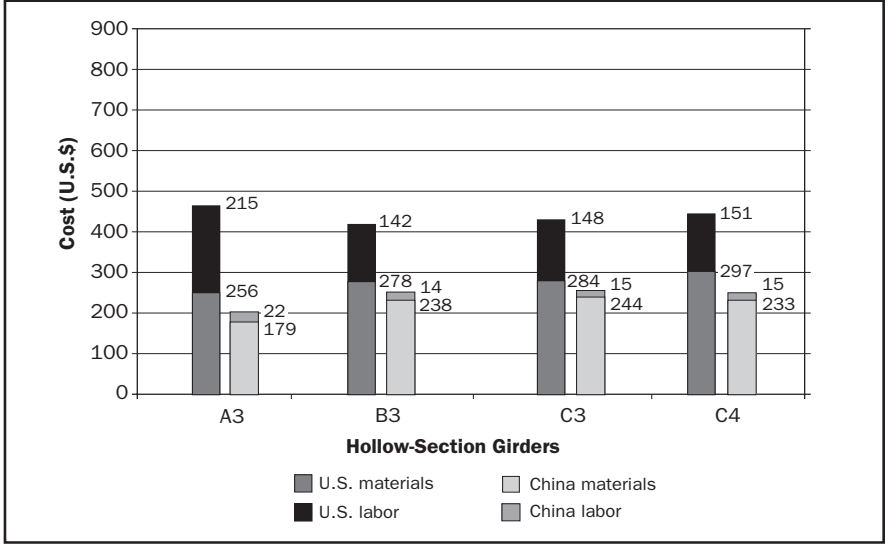
Graph 6. Hollow-Section Girders / U.S. Market vs. China Market



things that are not readily self-evident. We've seen, for example, that a reduced labor rate in New Zealand is offset by higher material costs. And the influence of the cost of labor or materials varies across markets, and must be interpreted with care.

I've presented an array of solutions to the girder problem, everything from constant to variable depth; from in situ to pre-molded, infused, and hand laid; from awful stuff to double bias and triaxial; and how these materials and methods manifest themselves among three major players in the marine marketplace—the U.S., New Zealand, and China.

Look at the *range* of possibilities: build an in-situ girder in the States out of chopped mat and woven roving, and you'd spend about $800 for a product that will weigh in at about 265 lbs/120 kg. Or you can get that girder made in China, with an infused triaxial, for about a third of that cost, for a product whose finished weight is just 110 lbs/50 kg.

Bottom line: You'll be able to choose which criteria we've looked at to best meet your needs—provided, of course, that you thoroughly explore the options. PBB

About the Author: *Richard Downs-Honey is a co-owner of High Modulus—headquartered in Auckland, New Zealand—which specializes in composite technology, materials, and structural engineering for the international marine market. It was with High Modulus that he started his composites-engineering career, 30 years ago. This article, along with the companion piece in the previous issue of PBB, was adapted from a seminar presentation Richard made at IBEX '08, in Miami Beach.*

A case study in Restoration

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