Exploring the Options

Part 1

In this first of two parts, the author presents a fundamental structural-design problem that is virtually universal among composite boat builders: What materials, and which build method, make the most sense for a given application?

by Richard Downs-Honey

***Editor's Note:** If you've been to IBEX, even if you've been more than once, there's a good chance you missed a seminar presentation by the author, Richard Downs-Honey of High Modulus (Aukland, New Zealand). Not everyone attending IBEX—the annual trade show in South Florida produced by* Professional BoatBuilder *and the National Marine Manufacturers Association—takes advantage of the show's seminar program. Those who do must decide which to attend, given a three-day program of some 50 sessions; and virtually the entire lineup of seminars changes every year, along with many of the speakers.*

So, for those who didn't see the popular Richard D-H, live, we've adapted a seminar of his from IBEX '08—for print. It's not a literal transcription. But it is close to his speaking style—without the New Zealand accent and animated, fast-paced delivery.

Richard had previously presented a technical paper on this very topic, titled "Composite Options," to members of the marine industry in mainland China. The information in that paper is similar to his presentation for IBEX '08, but for publication I prefer our IBEX one—as a "spoken" document. It gives you a sense of the fluidity of Richard's thinking as he takes an audience of boat builders and designers through the kind of structural engineering exercise for which he, and High Modulus, have earned an international reputation in marine composites.

—Paul Lazarus

What I'll talk about here is how you make choices for materials or build processes to meet your criteria. Because in composites, there are many choices, and you have to work out what you need to know in order to choose wisely.

We'll start with a cooking analogy as something we can get our heads around, in terms of choices. Then we'll consider degrees of uncertainty: meaning, it's what you *don't* know that's important.

Designing laminates for boats is the same as making dinner: You have to start by knowing where you're going.

What meal are you preparing? *What sort of boat are you building?*

What's on the menu? *What structural design approach will you use?*

What are the ingredients? *What materials will be chosen?*

How are you going to cook it? *What method will you build with?*

You start by selecting your ingredients. Get stuff that you know, that you can buy, that's available. Then you work out how you're going to cook it. What are you going to do with all those ingredients to create a chicken dinner? What are you going to do with all these composite materials so that you end up with a single-skin/sandwich specification that's production-friendly for a 40′ (12m) powerboat?

I'm here to tell you: It's as simple as cooking dinner. That's all there is to it.

That doesn't mean, though, that everyone comes up with the same solution. In New Zealand, we have what's known as a Kiwi barbecue; our chicken will be grilled—it may be burned—and there'll be peppers and things like that. In Italy, our chicken dinner would be some sort of summer salad, with noodles and fresh herbs. The French will likely create a big red-wine casserole.

So: We're making dinner, it's chicken, we've got the ingredients, and we come up with three different solutions.

Let's explore a boatbuilding example to see which material is better. I've picked an application: *capping*. It's the crown, or top, of a typical hat section stiffener. It might be an engine girder, a deckbeam, or frame. We're going to see what material might be applied there to arrive at the best structural design solution. I'm going to discuss three possible materials and associated processes: sprayed chop and polyester resin; infused 0/90 biaxial and vinyl ester resin; and carbon/epoxy unidirectional pre-preg.

I deliberately picked these materials to demonstrate the thinking behind the issues involved—as opposed to seeking an actual solution. Because the fact is, I wouldn't select any of those materials for capping in a production 40-footer.

We need some criteria. Vibration damping? Marketing hype? Nah. We'll just look at criteria that matter to me: *cost*, including labor; *weight*, including of course the resin; and *stiffness*, because, well, it's going on a stiffener. For most stiffeners, stiffness—modulus times thickness—is critical, particularly deckbeams. If you're making a deckbeam, you've got to make it *as stiff as it needs to be*—which is not necessarily *as strong as it can be*. Not a lot of deckbeams actually break.

So those are our principal criteria: **cost**, **weight**, and **stiffness**.

Here are the things you know: *material properties*. The properties of chopped strand mat, often called sprayed chop, you can look up in a book. Nevertheless, I'm going to base this discussion on actual data, arrived at by way of an exercise we undertook in the Auckland area. We distributed 3′ x 3′ (0.9m x 0.9m) panels to a bunch of local boatbuilders, and asked them to spray out 1 oz, 2 oz, or 3 oz (300 g, 600 g, or 900 g) of chop, and return the panels to us, where we measured and tested each one. We did the same thing again the next week. And the week after, and the week after. So that eventually we got some sort of variation distribution as to what the variable properties might be—as distinct from our making, or the boatbuilders making, a "test sample." And believe it or not, out of all those panels—again, it might've been because they were making panels, not test samples as such—the average fiber content was 35% by weight.

Now, a lot of shops that spray chop get 33%, or 30%, or even less than that in terms of fiber content. But according to the data *we* got, it's 35%. All right: for a 2-oz/sq-ft (600-g/m^2) laminate, that gives us a thickness of 0.046 inches. (Bear with me: I've converted a lot of these units, and also have a calculator here if I need to think.) The average tensile modulus we got tested out at 1.1 msi. And here's something interesting: the average areal fiber weight was 113% nominal.

On that last item, what it means is, when we asked our cooperating builders to put down 3 oz, they put down 3.4 or so. Granted, there was

COURTESY RICHARD DOWNS-HONEY (BOTH)

The author argues that boatbuilders should analyze competing composites options for a given application in much the same way a cook considers possibilities for a particular meal. Chicken is central to a barbeque, ***top,*** *and an Italian pasta salad; what differentiates them are the cooking method (build process) and accompanying ingredients (construction materials).*

some variation there, and we'll get to that. The biggest variation occurred when the instructions we gave them were as follows: Make this panel at the same time you're doing something else; we don't want you to put your best guy on it and do a perfect job; when you're spraying up, just turn around and spray 3 oz over here, on our panel.

Next, infused 0/90 biaxial. Garry Joliffe, from our firm, conducted some research: He wanted to examine the variation that you get with infused vs. hand-laid materials. So he took one roll of 800-g/m² biax, or 24-oz/sq-yd biax, cut it up, and distributed it to various suppliers, boatbuilders, labs. He asked them to hand-lay a sample, and another sample the following week, and the week after, and the week after.

Then he got different yards to infuse a sample—while staying with the same bag system, the same resin, the same flow medium. Next, he brought all the data together, and looked at the spread of the variation. Because it's infused, the laminate in the latter instance is of course much thinner than sprayed chop. So from Garry's work we get a thickness of 0.024″ per 24-oz/sq-yd material, and a tensile modulus of 4.8 msi. The average areal fiber weight was pretty close to nominal: 101%, or about 1% heavier than we expected.

Finally, we got some pre-preg carbon unidirectional tape. Our firm specifies a great deal of pre-preg carbon uni in New Zealand with spar builders there, so we've accumulated a lot of data on that—weights and thicknesses and other data. For the purposes of this IBEX session, let's stay with 9-oz/sq-yd (300-g/m²) material that's 35% resin content, 65% fiber—by weight, as manufactured, before bleed and cure. This particular pre-preg has a thickness of 0.012″ (0.3mm), and a high tensile modulus: 18 msi. Note that the material is *supposed to be* 300 g/m², but our records show an average of 299 g/m² is the best you get. Admittedly, that's pretty damn close to what you ask for. It's expensive; so of course they wouldn't want to give you too much. Average areal fiber weight is 99.7% nominal.

Which brings us around to *cost assumptions*. See **Figure 1**. At day's end we can distort the hell out of this example by just changing the input data. So I'm being upfront by telling you what *my* cost assumptions are. I can make carbon unidirectional pre-pregs cost-competitive with sprayed chop quite easily: I'll sell you carbon pre-preg at $25/lb and I'll charge you $250/lb for your sprayed rovings.

Figure 1. Cost Assumptions

	Fiber ($/lb)	Resin ($/lb)	Rate (lb/hr)	Labor ($/hr)
Sprayed chop	0.95	1.45	130	20
Infused 0/90 biaxial	1.75	2.20	65	30
Pre-preg carbon uni	25	25	7	40

I'm thinking our glass is around 90¢, 95¢ a pound (it could be 85¢ a pound); biaxial twice that; and pre-preg, $25 a pound. Resin system? Simple hand-laid open-molded polyester: $1.45. Infusion-grade vinyl ester blend, maybe $2.20. Actually, a pre-preg carbon uni system isn't $25/lb; when you buy pre-pregs you buy the fiber and resin together for $25/lb, but I didn't want to try to extract the constituent materials to determine what the fiber and resin are worth. In effect, that's what you pay.

Then we get into a topic that may generate some debate; namely, the rate at which you can apply the material to the mold. So I picked some numbers. For sprayed chop I come up with 130 lbs (58.9 kg) of laminate. That's fiber and resin together, per man-hour. *Not per hour of operation*. You might ask: Is that figure real? And what does it mean?

Let's do the math. Say you've got a 30-footer (9m) with 500 sq ft (46.4m²) of surface area. You're going to skin it with 3 oz (900 g) of sprayed chop; you've got a team of three guys. Is it going to take them about an hour, an hour and a half? That's about right. You talk with the gun operators—and the gun manufacturers. They can strip 6 lbs (2.7 kg) of glass a minute at the end of the gun head. You look at it, ask how many people are following behind. Also, is the gun stopping and starting, or is it running continuously? That's how I came up with 130 lbs per hour. What's *your* number? Put it in there. You can change mine if you want. But, as we'll see later, it's not as critical as you might think.

For the infused biaxial I put in 65 lbs (29.4 kg). That figure would depend on the number of layers: you put one layer down, then you have to calculate the time it takes to place the bag on. If you do three layers, you'll have to amortize the cost of the bagging time by the number of plies. My calcs are based on some actual timing and a five-, six-ply laminate.

As for carbon pre-preg, I'm being really conservative. Some of you may be thinking I'd be lucky to get 70 sq ft (6.5m²) in an hour, which is not a lot. You might be able to do that quicker. But I wanted to skew it as badly as I could on the carbon.

What if I changed the labor rates? In a chopper-gun shop, your workers may be costing you $20/hr; whereas, if you get someone to do infusion, he or she is a *technician*; they're costing you $30/hr. Actually, there's an argument to be made for $30/hr people being on the *guns*, because it's more important than what their education level is. But it's pretty hard to find people to do that. And of course, since pre-pregs are expensive, those that apply them must be expensively paid. So I've penned in $40/hr.

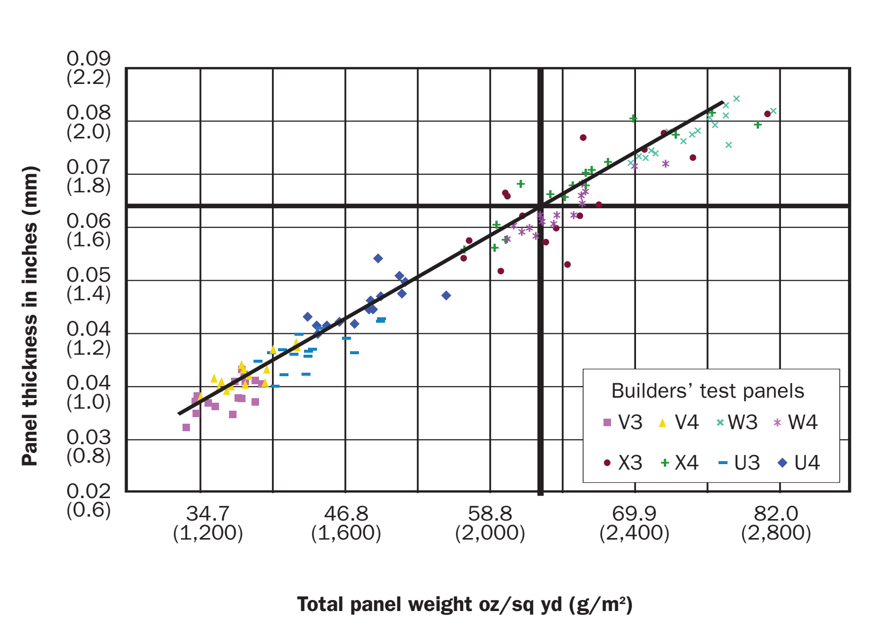
There you go: a whole bunch of cost assumptions that we can argue about.

D*egrees of uncertainty*. So far we've pulled some numbers out of a hat: We know the pricing, we know the properties of the materials, we've picked the rest out of thin air. Let's talk about how no number is really equal to the average. You get somewhere *near* the average. So the first thing you do is check that the distribution of data points you've got is normal. Does it follow a bell curve? As you can see, the data we got on areal fiber weight for sprayed chop was not a normal distribution. Because the data doesn't all fall within the average plus or minus two standard deviations, we've done

Figure 2. Coefficients of Variation

	Areal fiber weight	Weight fraction	Stiffness per unit weight	Labor
Sprayed chop	14.5%*	7%	13%	15%
Infused 0/90 biaxial	1.7%	1.0%	4.5%	10%
Pre-preg carbon uni	0.7%	0.9%	3%	5%

Figure 3. Real Variations in Sprayed Chop



a different analysis to capture the *range* we would expect. But with things like fiber volume on the work that Garry did, along with the data we're getting from pre-preggers on fiber content or resin content, it is much more statistically acceptable.

If you haven't heard the term *coefficient of variation*, it's the standard deviation divided by the mean or the average; just a percentage. Say you've got material with a coefficient of variation of 5%; that means three standard variations capturing 99% of your data will be between 85% and 115% of that average. See **Figure 2**.

My argument is this: Over time, you might well be on the average. But perhaps it would be wise to design for the minimum, or maximum, depending on which way you look at it. As could occur. Because you wouldn't want to say, *On average my boats don't break*.

Back to coefficients of variation. With the exception of the labor column, the rest of my columns come from data I've collected; they're not numbers plucked out of the sky. Those are test data. The sprayed chop's wearing a little asterisk: We adjusted the coefficient of variation for the purposes of analysis, because when we took the coefficient of variation that we'd *measured*, and fit it over the data, the bell curve was out here and the data were in here. So, the data weren't normally distributed. In terms of weight fraction and stiffness per unit weight, those amount to an awful lot of data points; a couple of keystrokes in Excel, and we've got a number out. Now, yours might be different from mine, but this is the variation we got.

Recall that we asked those builders in New Zealand to spray 2 oz of chop. Here's some real variation! See **Figure 3**. The big heavy black line is the expected data point: 2 oz (600 g) of sprayed chop should have a total cured weight of 1,800 g/m², and a thickness of 1.7mm, which is 0.066″. That's where we thought the number would end up. And you can see what we collected for data. The points on this graph are all supposed to be 2 oz of sprayed laminate, with the letters U, V, X, and W representing different builders in the experiment. It was anywhere from…well, there was one bloke here who sprayed up some pretty light panels. His cured panels weighed 1,200 g/m²; someone else was at 2,800 g/m². It's kind of frightening to see that.

We've done that experiment at 1 oz, and 2 oz, and 3 oz; it comes out the same across the range. In fact, the heavier the target panels become, the more variation we get. And as you see here, it wasn't distributed normally with a maximum focused in the middle.

What do we do with the numbers we've gathered so far? We can get a *cost* per square foot by adding up the fiber, resin, labor, and consumables. We can get the *weight* per square foot by adding together the fiber and the resin. Note that the stiffness we're going to be discussing is *not* the modulus, not the msi value. We're capping a stiffener here; we're just interested in basic rigidity. The result, then, is the modulus times the thickness. That removes some variations in fiber content and a few other things.

We can say that as areal fiber weight and resin content vary, so do: cost, weight, modulus, and thickness.

Cost analysis. See **Figure 4**. Here is where you can start to argue whether my deposit rate makes a difference. With sprayed chop, fiber's going to cost you 13¢/sq ft; resin's going to cost you 41¢. It used to be the other way around—when resin was really cheap. You'd put as much in as you could. But now, resin prices are up, glass is down; all of a sudden it doesn't look that attractive. Note that I've indicated "extra" costs; we'll come back to that in a moment. There's 8¢ of labor cost in there.

With the biax, fiber cost is more, but look at how much less the resin is. We know it's more per pound: the fiber content is 70%; there's not a lot of resin in there. To that I've added an "extra" cost: 12¢/sq ft for people running around with vacuum bags and tacky tape and other consumables. Again, that figure might be too much or too little, depending on your operation. But the total cost of the 24-oz infused biaxial is about the same as the 2-oz sprayed chop.

Okay. We already *know* pre-preg is

Figure 4. Cost Analysis

	Fiber ($/sq ft)	Resin ($/sq ft)	"Extra" ($/sq ft)	Labor ($/sq ft)	Total ($/sq ft)
Sprayed chop (2 oz/sq ft)	0.13	0.41	Nil	0.08	0.62
0/90 biaxial (24 oz/sq yd)	0.29	0.16	0.12	0.11	0.68
Carbon uni (9 oz/sq yd)	1.53	0.83	0.19	0.58	3.13

Figure 5. Mean/Average Properties	Cost ($/sq ft)	Weight (lb/sq ft)	Stiffness (E x t)
Sprayed chop (2 oz/sq ft)	0.62	0.40	10.1
0/90 biaxial (24 oz/sq yd)	0.68	0.24	20.2
Carbon uni (9 oz/sq yd)	3.13	0.09	37.4

Figure 7. Range of Properties	Cost ($/sq ft)	Weight (lb/sq ft)	Stiffness (E x t)
Sprayed chop (2 oz/sq ft)	0.36–0.94	0.25–0.59	6.3–14.8
0/90 biaxial (24 oz/sq yd)	0.63–0.74	0.23–0.25	18.9–22.2
Carbon uni (9 oz/sq yd)	2.97–3.28	0.091–0.097	35.7–39.1

more expensive. The fiber and resin together are well over $2/sq ft. I've got 19¢ in there for "extra" cost for the vacuum bag, and for having to stick the laminate in an oven to bake it, so there are some heating costs. And that high-paid technician is taking a long time; he's probably 50¢/sq ft in labor on that. At this point, it's looking like a two-horse race between the sprayed chop and the biaxial, with the carbon pre-preg running in the other direction.

M*ean/average properties*. See **Figure 5**. There's our cost—62¢, 68¢, $3.13 per sq ft; and the weight per sq ft. Now we start to think about things. The sprayed chop and biaxial are the same cost, but the chop's a lot heavier. And look how light the pre-preg is. So if weight were a criterion, we might have to reconsider. And of course our laminate does have to perform.

Stiffness, which is E x t, for 2-oz chop comes out at 10. I didn't convert the units; those are 10 whatevers. The biax is twice that. And nearly double again for the carbon uni. Looking at a table like this, which one are you going to choose? The cheapest? The stiffest? The heaviest? What's it going to be?

Well, if we put cost, weight, and stiffness into a type of 3D graph, we get something like **Figure 6**. The red pin is the sprayed chop; along the weight axis, it's the heaviest. On the vertical axis, which is cost, it's about the same value as the blue pin, which is the infused biaxial. The highest pin, of course, is the pre-preg, in terms of cost. And along this line—10, 20, 40—is stiffness. So now we've got a three-dimensional thing with those points floating around, and we're trying to choose one as being better than the other.

Let's examine *properties*. There's going to be some *range* in those properties. We've seen that the shop crew, when asked to put down 2 oz of sprayed chop, might put down more or less. Might be 35% resin content, or it might come in at 33%. And that's going to mess with your pricing. The coefficients of variation now get applied to those means, or averages, to determine what range I can expect in my properties. So **Figure 7** presents the highs and the lows, taking the values we discussed earlier, and applying standard deviations—with a slight twist to the sprayed chop entries, to make sure we didn't go off the scale.

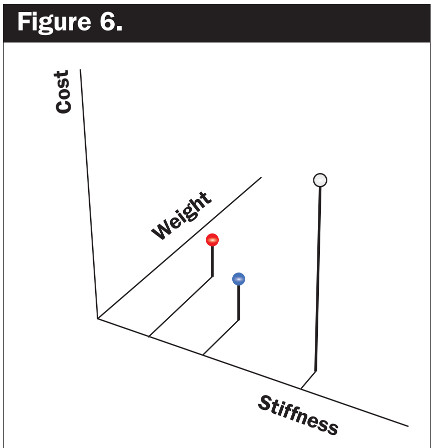
The sprayed chop can cost you anywhere from 36¢/sq ft—if you didn't put enough on, and had no resin, and did it very quickly—to as much as 94¢/sq ft, if the thinking in that shop is "more, better, more, better." You don't get as much variation in cost with the biaxial or the carbon, whether in fiber areal weight or in resin content. If those categories vary, then you'll have a variation in stiffness. So we're going to be somewhere between the numbers shown here.

Just to illustrate what all that does to our previous graph, I've redrawn it in **Figure 8**—taking into account the variation in weight. The range presented by chopped mat is a red horizontal line, or so-called arrow bar, meaning it will weigh somewhere along the line. As for the biaxial, believe it or not, there's a similar but tiny blue horizontal line there, and a barely perceptible one for the carbon.

Continuing with the theme of *range*, if we now express the data as balloons, or jelly beans—**Figure 9**—then the chopped mat data's going to fall somewhere inside that red shape. The chopped mat could be light, heavy, expensive, cheap; it could be less stiff, more stiff. Regardless, it's unlikely you'll find a data point for 2-oz sprayed chop that lives outside that red balloon. It is, as we say, your *envelope of design*. And as you can see, the envelope—on the same scale—for the biaxial, in blue, and the carbon, in gray (with a cross), is much less.

The problem with this picture, though, is that we're looking, as it were, at apples and oranges. The materials give us different *performance*: the sprayed chop, even if

Figure 6.



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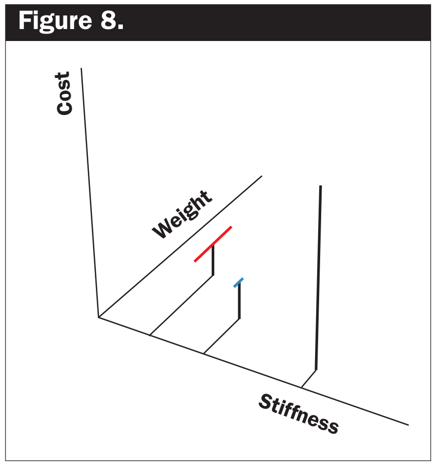

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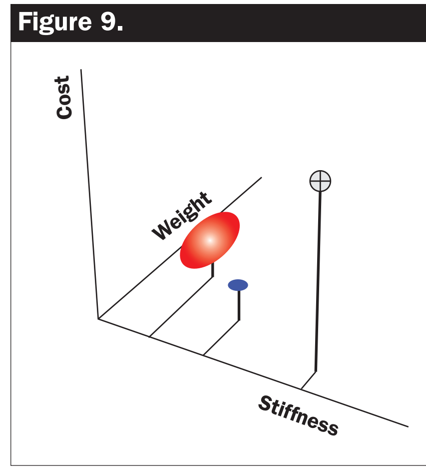


Figure 10.

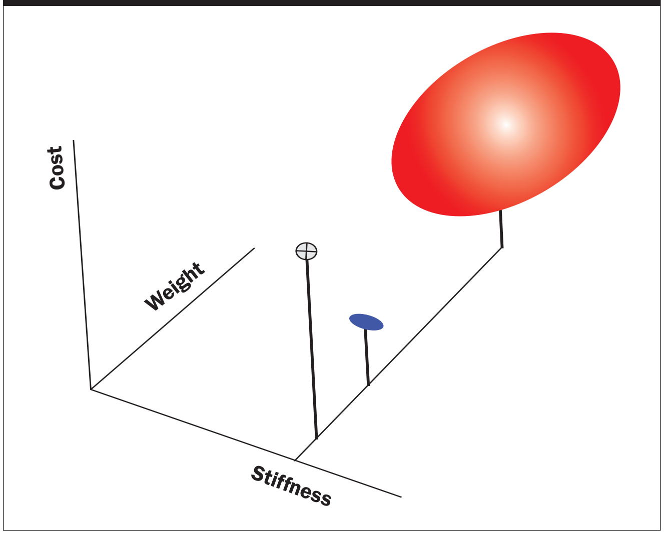
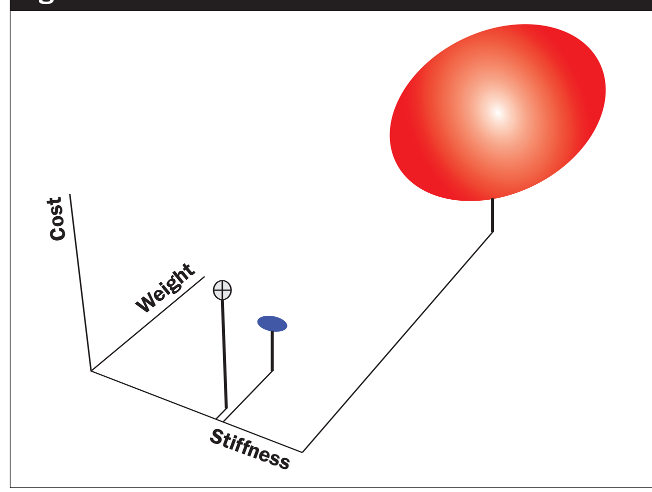


Figure 12. Match Design Minimum

	Cost ($/sq ft)	Weight (lb/sq ft)	Stiffness (E x t)
Sprayed chop (11 oz/sq ft)	2.07 3.71 5.35	1.41 2.26 3.36	**35.7** 57.8 84.3
0/90 biaxial (45 oz/sq yd)	1.08 1.19 1.30	0.45 0.43 0.48	**35.7** 38.7 41.9
Carbon uni (9 oz/sq yd)	2.97 3.13 3.63	0.091 0.094 0.097	**35.7** 37.4 39.1

Figure 13.

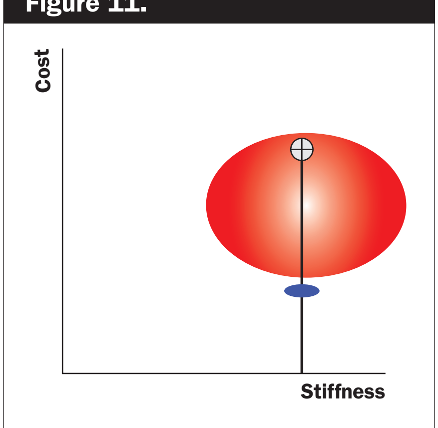


you overspray it, is not as stiff as the biaxial, which has essentially the properties of the carbon uni. When you get right down to it, what we want is minimum weight, minimum cost, and a certain amount of performance. We don't have to have *more* than a certain amount of performance; because once we've got the laminate stiff enough, then it's stiff enough. What's the point in having it twice as stiff? If that were the objective, then you'd just keep doubling things.

Really what we should do is *normalize* according to stiffness. Which means, pick one—in this case, I'll pick the carbon—and adjust the areal weight of the other two until you've got enough material in there so that everything's got the same properties.

We're matching the "average," or "expected" stiffness of carbon uni by increasing the specified weight. Instead of calling that 2 oz/sq ft of sprayed chop, we'll call it 7.4.

Figure 11.



Instead of putting 24 oz/sq yd of biaxial down—to match the properties of the carbon—we'll put down 44 oz/sq yd. The cost and weight increase.

Now, in **Figure 10** they're all in line: They all have the same stiffness. We know the cost of the carbon; the biaxial has moved up, it's become more expensive, because we've got twice the amount of fabric and resin; and the chop's way over here. So, those three options give us the same stiffness.

We can also look at them like this—**Figure 11**, by getting rid of the weight, and just viewing our options in terms of stiffness versus cost.

Without a doubt, 0/90 biaxial infused, insofar as tensile stiffness is concerned—doesn't matter if it's a wee bit overweight, underweight, different fiber content, slow laminator, fast laminator—is going to be cheaper than spraying chop.

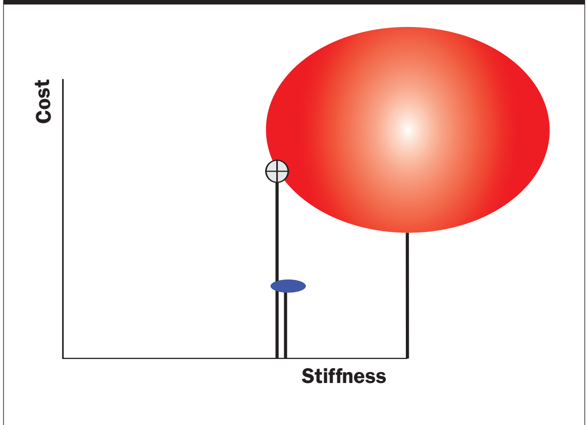
The sprayed chop could be anywhere in there, in that giant jelly bean, from a cost point of view. Indeed, it could even be more expensive than the carbon; or, it could be a lot cheaper than the carbon. Depends on what happens on any given day on the shop floor, doesn't it?

The problem, however, with the analysis above is that we've normalized for average stiffness. So our three options are all going to be, on average, that stiff. But there's a possibility it could be a bit less—in fact it could be a lot less, with the chop. With *your* shop's chop. You ask yourself: Do I want to design and specify so that, on average, my boats don't flex? Or do I want to design and specify that they *absolutely won't flex*, and therefore might be stiffer than need be?

In which case, we would be normalizing by *the design minimum*. You'd have to increase the specified weight of the sprayed chop from 2 oz/sq ft to 11.4 oz/sq ft, (600 g/m^2 to 3,420 g/m^2), or the biaxial from 24 oz/sq yd to 45 oz/sq yd, so the minimum property that you could expect—given the variation in fiber content and everything else—is not less than the minimum you'd have of the others that you're comparing.

Therefore, in order to match the design minimum, which is the "minimum" expected stiffness of carbon uni—**Figure 12**—the sprayed-chop laminate's average stiffness would have to be higher. This table shows the range, and average, performance. The bold upper left numbers in the third column are the minimum stiffness results, and the areal weight has been adjusted so these are all the same. The average (middle number) and

Figure 14.



maximum (lower right corner) vary as the materials vary in consistency.

That requirement, then, yields the 3D graph in **Figure 13**. In order to be sure the sprayed chop (on the right-hand side) has sufficient stiffness, we had to increase the *average* stiffness. And with it, you can see we increased both the weight *and* the cost.

Now, if we view our material options from end on—**Figure 14**—we see that from a *cost* perspective, the biaxial's the cheapest. Note that they've all got the same minimum stiffness.

Look at the small gray carbon circle. If we specify 9 oz/sq yd, we get a minimum stiffness performance that is the same as if we specified 11 oz of sprayed chop. It is going to be more expensive than the biaxial, but there are many points in the red sprayed-chop bubble that are more expensive than the carbon pre-preg. Not all, but most, of the volume of the red balloon is higher up the cost axis than the carbon. And I reckon, in reviewing these graphs, that you would be hard-pressed to argue that sprayed chop is more cost effective than carbon pre-preg.

You need to know what your variation is in your process, and what your parameters are, before you can make any decisions about what is good or bad.

As I said when we started here, you wouldn't use sprayed chop for capping stiffeners. You wouldn't use carbon unidirectional pre-preg for capping, either, especially if you're open-molding with polyester. And you wouldn't use infused 0/90 biaxial, because what you really want for that sort of application is infused unidirectional (or double bias on the web). None of the materials we've been talking about is ideal for capping.

But I selected them precisely because what I wanted to illustrate is an understanding of the *variations* involved—assuming you're designing to certainties, designing for what you need to know. If, however, you're employing materials whose variations you *don't* know, then you could be all over the place.

You might say, in response: I'll take that up in my safety margin; I'll account for the variation there.

Which is fine—provided you have

a design methodology that has different safety margins for different processes and different materials. Many builders don't.

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All right. Show of hands: Who now believes you can build parts out of carbon unis for less money than sprayed chop? Wow: I've convinced a couple of people! Are you guys carbon fiber suppliers?

Who believes they know how much their construction is costing them, and what the variation is on the shop floor? In infusion, pre-preg, or sprayed chop.

Well, you've got *my* data. But please go and get some of your own data. High Modulus, as a materials distributor in New Zealand and Australia, receives goods that we first analyze and then send out to customers; there's every chance that one of those suppliers is going to put the wrong stuff in the box, or something like that. And we'll get caught. So every time a pallet or container load arrives, we open the box, we take a sample out, and check to make sure it *is* a biaxial and not a double bias. And we weigh it. And we record the areal weight. And the guys in the warehouse follow accept/reject criteria. We gather data. We have graphs. We know which suppliers are reliable, and which suppliers are habitually overweight. I've got to tell you: I haven't found too many production yards that do that sort of incoming QA on their reinforcements on a regular basis. They may rush down to the lab and do all sorts of tests on the resin, but they take the 2415 off the truck and *assume* it's 2415. And they buy it by the pound.

Say you're a fiberglass weaver. And the boss says, "We're going to increase our sales by 5% this year." So you go to the machine and wind it up, and make the next batch 5% heavier. The builder will order a hundred pounds. The builder's guys say, "We ran out." So they order some more—not realizing they're *using* more material than they thought, not wasting more.

So I really urge you to get some data on what you *think* your variations might be. Because without that analysis, you really cannot make some of these decisions that we've run through today.

[Three case studies will be presented in the next issue of the magazine: discussing structural design and materials selection for a 124' (37.8m) performance motoryacht; comparing build methods for a 50' (15m) patrol boat; and finding the most cost-effective approach for adding an engine girder and bottom longitudinal to a 40'–50' (12m–15m) production powerboat—Ed.] PBB

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