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## ***The Elements of Boat Strength Scantling System*** **by Dave Gerr, © 2010 Dave Gerr, CEng FRINA**

It has been over 10 years since *The Elements of Boat Strength* was published in 2000. In all that time and all the many, many boats built to this rule, I have yet to learn of a single structural failure. That's a pretty good record. As *The Elements of Boat Strength* scantling system now has a ten-year history of successful use and is quite simple to apply, it seems a good time to review what the rule is, how it came to be, how it should be applied and how it relates to a few other scantlings. We'll also look at some of the things I'd adjust in *The Elements of Boat Strength* scantling system.

Since almost everything in this system references the "scantling number" (Sn), I'll refer to it as the "Sn scantling system," "Sn system or rule," or the "Sn process." Also—as I'll explain—I have used aspects of this basic system for years before the book's publication.

### **Acceptance of the Sn System and Questions**

A number of naval architects and marine engineers have found the Sn system useful and reliable. *The Elements of Boat Strength* is also used as a text in the U.S. Naval Academy, Dept. of Naval Architecture, Ocean and Marine Engineering. One engineer, said of Sn system:

As a degreed aerospace engineer, I've used the formulas in this book to easily calculate the scantlings for aluminum hulls from 14' to 30' in length, without exhaustive structural calculations or the need for finite element analysis software. Properly applied, you can build your boat with confidence that it will perform safely in the operating limits described. Are there other ways to calculate scantlings? Absolutely! But if you want "rule of thumb" formulas that are reliable when confined within the operating envelope, this is the way to go. I've plugged the equations and operating parameters into an excel spreadsheet that gives me all the scantling dimensions needed when entering the length, width and depth of the hull. Previous reviewers who stated the subject matter is "wide but shallow" didn't understand what they were reading. If you want to design a boat from scratch and will read and digest the material, this book is a bargain.

This does bring us to the most common questions about the Sn system: How can it account for the loads supported by varying spans? How can you simply increase shell thickness by some arbitrary amount for a given speed?

The answers are that the proportions and dimensions of the structure created for each boat by the Sn process build in the required dimensions and regulate span. Additionally, the Sn rule doesn't just increase shell plate thickness with speed. It also decreases frame spacing and increases frame dimensions at the same time, thus accounting for the fact that the forces increase roughly as the square of the speed. We'll take a more detailed look at the actual scantlings in a bit.

### Longitudinal Strength Calculations

In the boating world, many have never even heard of longitudinal strength calculations. Naval architects trained in ship design, however, struggle with these from early on in school and have to demonstrate sufficient longitudinal strength for each and every ship, with good reason.

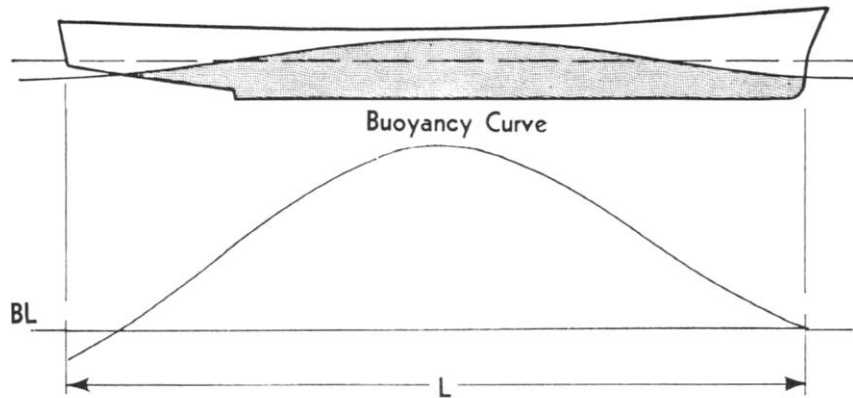


Figure 11-7. Typical Hogging Condition and Buoyancy Curve  
From *Modern Ship Design*, by Thomas C. Gilmer

Visualize a ship at sea in a storm. It could be momentarily lifted up and supported only on its center by a single huge wave. In that case the vessel could snap in half with both the bow and stern twisting down in the empty troughs—extreme hogging. Alternately, the ship could be supported at the bow and the stern by two huge waves, with the middle of the ship unsupported. In this case, the bow and stern would lift and the center of the ship sag down again splitting the vessel in two—extreme sagging. Either occurrence would likely ruin your day! Neither would happen if the ship and sufficient longitudinal strength. In some cases—even at rest in calm water—heavy loads could cause extreme hogging or sagging, which could break a ship.

Those trained in ship design undertake the laborious calculations needed to determine the section properties (moment of inertia and section modulus of the ship), and then analyze the weight distribution over the length of the ship to create beam, bending-moment, and shear diagrams. From these, it can be determined if the section properties of the ship in cross section are sufficient to ensure the longitudinal strength required.

None of this applies to boats. In fact, due to the laws of relativity and similitude, longitudinal strength calculations are trivial for vessels under 60 meters (196 feet). Above this length, longitudinal strength becomes increasingly important, which is one of the reasons that 60 meters is the cut-off length between boat and ship.

*The Elements of Boat Strength* covers only vessels up to 120 feet. Longitudinal strength calculations do not apply.

### The Birth of the Sn System

About twenty years ago, I was discussing an article on engineering wooden boat structures with the editors of *WoodenBoat* magazine. I'd done a great deal of research on this and thought it would be valuable. *WoodenBoat* said go ahead and write something up. To my chagrin, when the editors received the first installment they thought it was too technical for their readers and cancelled the project. As I write this, I've had 417 articles published over a span of 26 years. In all that time, this is the only article that wasn't published. I didn't agree with *WoodenBoat's* reason for not publishing, but they did say they thought it would make an excellent book.

A book? This was a thought. After *Propeller Handbook*, I wrote *The Nature of Boats* and was discussing new projects with International Marine/McGraw-Hill. I suggested a book on engineering boat structures (not just wooden boats) and sent them my original draft article on

wooden boat engineering. They were enthusiastic. Note the proposed subject: engineering boat structures. This isn't the same as a scantling system. I really wanted to write a book about engineering the structure from first principles.

The fact is I get deep satisfaction from calculating things. When engineering something, I check and check again. One of my favorite writers on structural engineering is Professor J. E. Gordon. He is—among other things—a pioneer in aluminum aircraft structures. Gordon said that he attributes the lack of failure in the structures he'd designed to worry.

Any of you who have engineered critical structures will know the feeling. You check and recheck. I well remember engineering the fin keel for the BOC racer *Holger Danske*. This boat has a 14-foot-deep fin keel with a 5,500-pound ballast torpedo bulb at the bottom. The fin is made entirely of uni-di S-glass, vacuum bagged and post cured. Not only did I design it, but I later helped build it and I sailed the boat as well. (There are a lot of people, by the way, who will say that you can't make a fin keel out of S-glass; modulus too low, they claim. This is just plain not so, as you can see in the photo, but that's another story.)



To add to my concerns about engineering this fin, this design started not long after another BOC boat had lost its keel, killing the skipper. There were also several other keel failures at that time. I had nearly 60 pages of calculations on this fin keel design alone! That's worry for you. And it paid off. The fin never gave the slightest hint of trouble through severe Atlantic storms, groundings, keel wraps, the works.

In any case, the book I originally had in mind was about how to do this sort of detailed engineering of boat structures. So what happened? Why did *The Elements of Boat Strength* end up as a scantling system and not an engineering text? My publisher, that's why. I think they realized what I didn't at first; that only a modest number of tech-heads would really use the engineering text. Most builders, surveyors and many designers would much prefer a simpler and easier-to-use approach. They wanted something that would provide them with reliable results quickly.

The fact is—as much as I enjoy engineering structures—I (like most practical designers and builders) largely used scantling systems of some sort for most of my boats' structural design. The detailed engineering is only applied to special details (or special boats) such as to that extreme fin keel.

There's another reason that scantling systems make good sense, and that's the unknowns in the loads, which we'll discuss shortly.

The upshot was that International Marine talked me into doing a two-part text. Part 1 would be a straightforward scantling system easy to apply to most average boats, for average uses. Part 2 would be the engineering text I'd planned on from the beginning.

Finally, I'd gotten what I wanted. At last I could write my book about boat structures. Be careful what you wish for!

For the few of you who follow this sort of thing, you'll know that Part 2 is yet to see the light of day. Instead of delivery the manuscript for Part 1 in about 18 months, I was five years(!) creating, refining, formalizing and writing up what was originally Part 1 and now is *The Elements of Boat Strength*. Though I've now published five books, nothing has ever compared with the work and research that went into *The Elements of Boat Strength*, neither *Propeller Handbook* nor *Boat Mechanical Systems Handbook*.

One day—maybe—I will really get to write that boat-structure engineering text, but until then, *The Elements of Boat Strength* has proven to serve a very useful purpose.

### **ABYC and the Need for a Scantling Rule**

There's another consideration regarding scantlings. Not many boats are suffering from structural failures due to insufficient structural strength. Certainly, most of us can think of a few such examples, but they are the exception not the rule.

Indeed, most often it's poor details or poor construction practice that lead to failures, not a lack of "beef" in the structure. This is the principal reason that the American Boat & Yacht Council (ABYC) doesn't have a scantling rule. There simply haven't been enough examples of structural failure to justify it.

As a designer, I think scantling rules are important, but keep the above in mind. Most boats of reasonable proportions and good general construction don't break.

### **Importance of Construction Details and Proper Use of Materials**

One of the important features of *The Elements of Boat Strength* is that understanding the materials and proper construction details and methods are integral to the book and to the Sn rule. The fact is that it's just as important (perhaps more so) that such considerations are handled correctly in design and construction.

Proper core-bonding requirements and related laminate specifications, proper secondary bonding and filleting of bulkheads, proper treatment of wood in FRP boat structures are just three examples of the numerous details that are covered as an integral part of the Sn system. In metal construction, rust control, corrosion control, insulation, plate welding thicknesses, welding sequences and many others are integral. Indeed, each scantling material's rule is preceded by chapters on understanding proper and use of the material itself. All this is integral to the Sn process.



### **Loads on a Boat Structure?**

For all of us who find satisfaction in extensive calculations, it's important to remember the old engineering maximum: *garbage in, garbage out*. You can have the most elegant system or program in the world, beautifully conceived and logically consistent, but—if the original data is faulty—the result will be as well.



I can think of few areas in engineering with more uncertainty than the loads experienced by a boat hull in use:

- What are the loads on any boat and in any given condition?
- What direction are the loads applied in?
- How long does the load last?
- How often do they occur?

You can see several photos of boats in waves here. Do you know what the loads are? Can you answer any of these questions with even a remote

degree of certainty?

On higher-speed craft, for example, the critical factor governing loads is the acceleration experienced by the boat. Comparing a group of different standard scantling methods shows a disparity in accelerations on the order of a factor of 3 or more on the same boat using the different methods! This doesn't even consider the variations in resolving the acceleration (g) into loads on the structure, or of sizing the structure to meet these loads.

I am sometimes bemused by those engineers who appear to insist that boat structures should be calculated from first principles, or from a complete application of a class-society rule. I wonder if these engineers are aware of how much uncertainty there is in the assumed loads. I also wonder if they've very heard of Herreshoff's or Nevins rules, among others.



As I've already discussed, I'm a big believer in careful and detailed calculations, but I'm also a believer in understanding the limits of these calculations. In this case, the load data are highly questionable.

### **Advantages and Disadvantages of a Scantling System**

Considering the above, a simple scantling approach makes excellent sense for most average boats. Does it have drawbacks? Yes:

- The structure may be somewhat heavier than needed
- Locations and proportions of components can't be easily adjusted to meet special requirements
- It works only for boats of the size and type covered by the rule

For larger and more complex boats or for boats that are intended for the pinnacle in performance, more detailed analysis should be done to optimize the structure.

For average boats a scantling system approach offers the advantages of:

- Easier application and understanding
- Quick conversion between different construction materials and methods
- Standardized and consistent structure

### **Goals of the Sn Scantling Method**

Given all this, the goal of the Sn scantling method was to create sound and consistent structures, structures that are reasonable in terms of strength, weight and cost and that are easy to build with standard construction methods.

The goal was never to exactly match results for ABS, or Lloyds, or any other specific class rules or scantling system. That would be impossible. Such rules are too vast and intricate to duplicate in some consistent, simpler form. Also, the results from one class rule don't match the result from other rules, or from various methods of engineering from first principles. Thus, it isn't even desirable to try match a specific rule's results. Among other things, there's no reason to say that any one of the many scantling systems around is the one right one, particularly given the unknowns regarding loads. What we do want is a scantling system that gives sensible, consistent results, but not one that specifically emulates the results from another approach.

Keep in mind that surprisingly simple scantling rules can work very well. Sometimes I think that the Sn system is too complicated. A good example is the old rule of thumb for single-skin fiberglass boats, which is:

Basic shell thickness is LOA divided by 1,000

Bottom is 15% thicker

Increase the bottom thickness by another 10% for planing hulls

Deck is 10% thinner than the basic thickness

Have two hull stringers on the bottom

Have one stringer at the turn of the bilge (not needed if a chine hull)

Have two stringers on the topsides

Have 5 stringers on deck

That's it. I can tell you this will make a pretty reliable hull for many average boats. In fact, add in some rules for the stringers, bulkheads, floors and so on and you have a scantling rule. (You can actually find a some of this in *The Nature of Boats*.)

Those who know the Sn scantling rule will see a few similarities to this simple approach buried in it. You can calculate the dickens out of structures, but quite often if the above method will give you results about as good.

Having said this, I wanted the Sn system to be more systematic, comprehensive and detailed and to cover all the standard boatbuilding materials: FRP composite, single-skin and cored; wood traditional and epoxy glued; and steel and aluminum. An approach as basic as the simple fiberglass rule of thumb wouldn't be sufficient.

### **The Scantling Number (Sn)**

Another goal was to come up with an approach that gives a consistent reference or base number and a consistent approach that applied to the same boat design regardless of material and regardless of the system of units (English or metric). This was the genesis of the scantling number (Sn). I wanted users to be able to take a few readily available values and quickly get a reference that could be applied to, say, cored fiberglass, aluminum, and wood-epoxy strip plank. This provides the designer or builder, the ability to easily compare potential structures for the boat at any time even at the very earliest stages.

Originally, I was going to use displacement in tons as the basic reference number. This works well, but it has two drawbacks. One is that there is a slight difference between U.S. and metric tons. More important, you often don't know what a boat will weigh or what it does weigh. The designer or builder would then have to guesstimate displacement. I didn't want to start calculations with a guess. This would require preliminary calculations based on an estimated displacement and subsequent recalcs to match the final designed or as-loaded displacement.

From here, I realized I could use a cubic number based on length, beam and depth of hull to determine the volume of the boat in question. These numbers are known early in the design process and are easy to measure on any boat or on any drawing, and they don't change with loading. Several scantling rules have used a cubic number, and this is a logically consistent approach.

### **What I Would Change About the Sn Calculation**

Throughout the creation of the Sn scantling system, I had simplicity of use in mind. On the Sn calculation I didn't quite get the approach just right. Formula 1-2 says to average out the LOA and WL lengths to get L if the overhang is over 108%. Similarly, formula 1-3 says to average out BOA and BWL when the flare is greater than 112%. In fact, this works well enough. On most boats, you can simply use the LOA and BOA to get L and B for the scantling number (Sn), per formula 1-1.

In fact, my practice is to average out LOA and WL and BOA and BWL on all boats to get L and B for finding Sn. On medium to large boats with small overhangs, the difference is negligible, and I don't have to worry about determining the percent of overhang or flare.

On small boat, however, the resulting smaller scantling number is important:

On our 29-foot example boat (see table below) you get an Sn of 1.33 if you average lengths and beams, but you get an Sn of 1.49 if you don't. If you were selecting, say, plywood topsides plank, each Sn number gives 0.75" and 0.76" respectively and would round to the same 3/4" plank.

If, however, you shrank our example boat to a little 13-foot skiff, the averaged Sn would be 0.119" and 0.14" averaged and not averaged. In this case, the plywood topsides plank would be 0.28" and 0.30". The 0.28" would be rounded to 1/4", but the 0.30" might be rounded to 5/16"—bigger than needed.

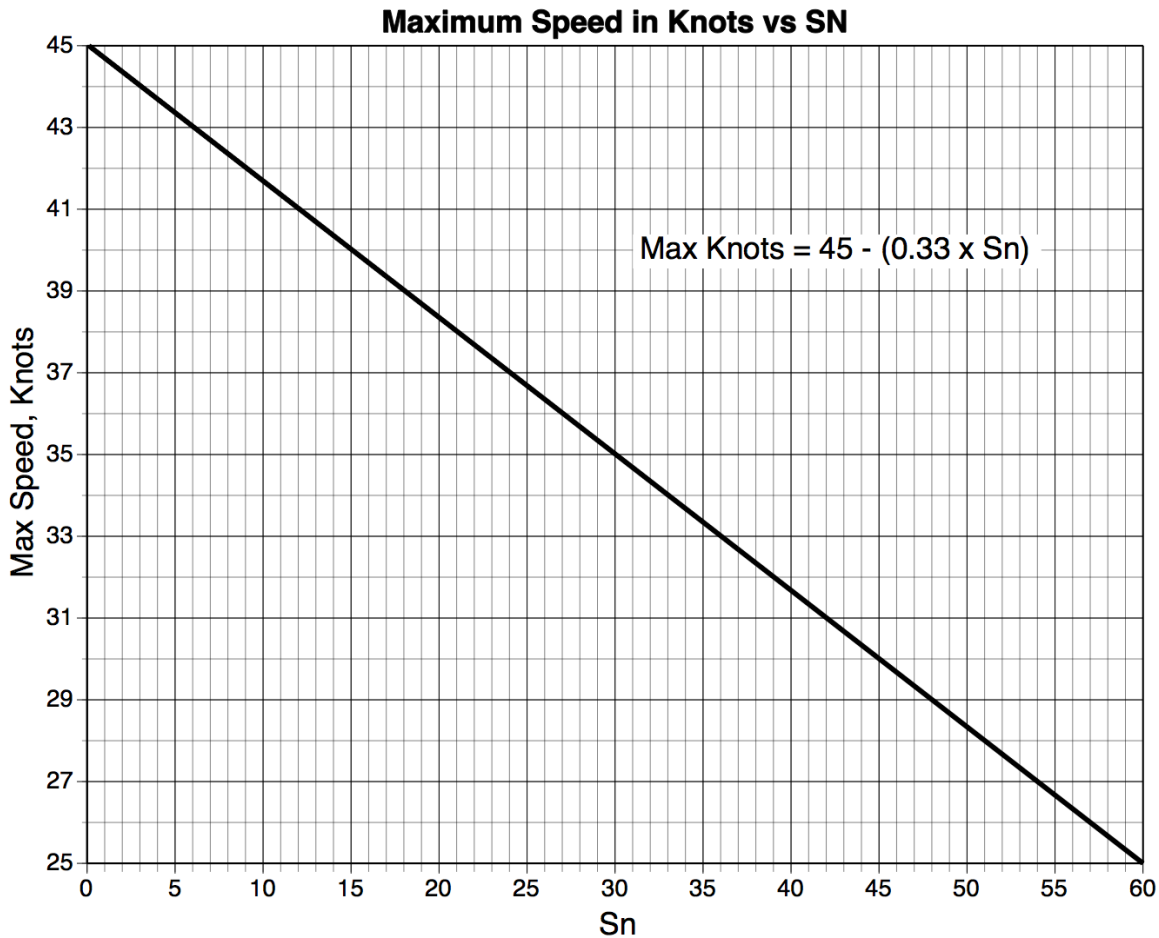
I'd recommend rounding all lengths and beams to get L and B and then be sure to round down on standard plank thicknesses on small boats.

### **Change to Maximum Allowable Boat Speed**

Almost all the changes to the Sn rule that we'll discuss (and in the update/errata document) are fairly minor adjustments or tweaks. The one significant change is to the maximum allowable boat speed. Page 8 of *Elements of Boat Strength* states that the rule covers boats between 10 and 120 feet (3 to 32 meters) and vessels with a maximum speed of 45 knots. This is too simple. The reality is that a 110-foot boat being driven at 45 knots is a complex and sophisticated vessel, probably requiring gas-turbine engines and costing several million dollars. Even a 70-footer going a real 45 knots (52 mph) is a very substantial project.

Though it's rather unlikely that large boat projects with this kind of speed potential will rely solely on the *Elements of Boat Strength* for their scantlings, that is also not really the kind of boats that the Sn rule was aimed at. The rule should limit boat speed relative to displacement or volume, and we already have the volume number in Sn. The chart and formula below describes the maximum boat speed that the Sn scantling rule applies to. Boats operating at higher speed for their Sn number

need use more sophisticated engineering analysis.



What this change is doing is formalizing full planning speeds for smaller boats, but limiting larger boats under the Sn rule, to low planing and semi-planing speeds. If you look at the chart, you'll see that a boat with an Sn of 15 is still covered up to 40 knots. An Sn of 15 is very roughly about a 65 foot (20 m) boat, so this isn't a dramatic a change as it might appear, but larger boats are further limited in speed. An Sn of 40 is limited to 31.8 knots. This is very roughly a 112 feet (34 m) LOA. Given about a 100-foot (30 m) waterline, that's limiting to an SL ratio of 3.2.

**How the Sn Scantling Rule Was Created**

Where does one start to create a scantling rule? With real boats. We've already seen how difficult it is to know what the real loads are on a boat. What we can know with good certainty is the specifications of boats that have been built and have given good service over many years— dimensions, displacement, speed, type of service, material, and scantlings actually built to. These data can be analyzed (regressed) to obtain the desired rules. The data and the results are constantly checked and rechecked against other real-world boats, against basic class rule results and against first principles.

With any such process, the results are not going to and should not match any other specific rules', or methods' results, but the scantlings from the resulting new rule should produce consistently reasonable structures, that meet reliable criteria for strength.

The real boat data available to work with came from:



- My own designs actually built and in service (and from the MacLear & Harris office and from Cape Dory Yachts)
- Boats from other designers for which I had data
- Boat data from the three-volume set of *Fishing Boats of the World*
- Additional wooden boat data from USCG NVIC 16-60, *Scantlings for Wooden Passenger Vessels*

This totaled hundreds of different vessels as a reference database.

Results were checked against:

- Engineering by first principles
- ABS
- Lloyds

Again the goal was not specifically to meet any of the class rules, particularly given the unknowns in loads, but to be close on the majority of the structure.

One of the interesting findings was how strong many real-world boat structures actually are, even without meeting the requirements of class rules. Stiffness and strength in real boats, often are considerably greater than such rules might indicate.

#### **Example Boats to Review the Sn Rule Results**

I'm not going to review the actual scantling calculation process for *The Elements of Boat Strength* Sn rule. They are straightforward enough, but we can take examine several representative example boats and see how they check out. *The Element of Boat Strength* covers such a wide array of materials, sizes and types of boats, that we couldn't possible cover a full sample of possible vessels and materials. To get a representative feel, I've elected to review three example boats, a 29-footer, 74-footer, and a 110-footer. These aren't real boats but examples set up for normal proportions and speeds. We'll take a look at each of them in single-skin fiberglass, and in welded aluminum. The table below gives their characteristics.

These are all selected to be planing or semi-planing hulls as the loads they experience are proportionately higher than displacement boats, and thus are a tougher test of the Sn rule's results. Also, note the speeds. Smaller boats under the Sn rule can easily be moderately high speed, full-planing boats, with SL ratios as high as 7 or 8. As boats get larger, driving them to full planning speeds becomes a more difficult undertaking. Low planing speeds to semi-planing speeds are most appropriate and what the Sn scantling rule was really intended for in such larger craft (as we discussed earlier). The speeds these larger vessels operate at are typical of offshore supply and crew boats in the Gulf of Mexico and the Atlantic.

Following are the Sn rule scantlings for each of these three boats in single-skin FRP and in aluminum. For each, there is a standard midships construction section, a table of the scantlings and drawing of the primary structural members, with their section properties (section modulus and moment of inertia).

**Example Boats**

<b>29 Footer</b>		<b>74 Footer</b>		<b>110 Footer</b>	
LOA, ft.	29.00	LOA, ft.	74.00	LOA, ft.	110.00
DWL, ft.	25.20	DWL, ft.	63.00	DWL, ft.	94.30
DL Ratio	280	DL Ratio	230	DL Ratio	200
Disp., tons	4.48	Disp., tons	57.51	Disp., tons	167.71
Disp., lb.	10,035	Disp., lb.	128,822	Disp., lb.	375,670
SL Ratio (max)	6.0	SL Ratio (max)	3.5	SL Ratio (max)	2.2
Knots (max)	30.1	Knots (max)	27.7	Knots (max)	21.4
MPH (max)	34.6	MPH (max)	31.9	MPH (max)	24.6
HP	300	HP	3,210	HP	6,180
Deadrise, deg.	19.0	Deadrise, deg.	20.0	Deadrise, deg.	23.0
Running Trim, deg.	6.0	Running Trim, deg.	5.5	Running Trim, deg.	5.0
Freeboard, ft.	3.77	Freeboard, ft.	7.95	Freeboard, ft.	7.85
Cp	0.70	Cp	0.65	Cp	0.62
Am, sq.ft.	8.89	Am, sq.ft.	49.15	Am, sq.ft.	100.40
LOA/BOA	3.08	LOA/BOA	3.40	LOA/BOA	4.00
BOA, ft.	9.40	BOA, ft.	21.75	BOA, ft.	27.50
BWL, ft.	8.46	BWL, ft.	20.00	BWL, ft.	25.69
Fb Draft, ft.	1.72	Fb Draft, ft.	4.12	Fb Draft, ft.	6.37
Bottom Girth, ft.	4.43	Bottom Girth, ft.	10.52	Bottom Girth, ft.	13.66
Depth Hull, ft.	5.50	Depth Hull, ft.	12.07	Depth Hull, ft.	14.22
L, ft.	27.10	L, ft.	68.50	L, ft.	102.15
B, ft.	8.93	B, ft.	20.88	B, ft.	26.60
<b>Sn</b>	<b>1.33</b>	<b>Sn</b>	<b>17.26</b>	<b>Sn</b>	<b>38.64</b>

**Sn Scantlings – 29-Foot FRP Single Skin**

Bottom: 0.378”

Topsides: 0.275”

Deck: 0.234”

Engine Bed/Girders Core: 3.5” width & height

Engine Bed/Girders Laminate: 0.243”

Engine Bed/Girders Tabbing Run Out: 2.5”

Topsides & Deck Longitudinals Core: 3.5” wide, 1.75” high

Topsides & Deck Longitudinals Laminate: 0.189”

Topsides & Deck Longitudinals Tabbing Run Out: 2”

Topsides & Deck Longitudinals Spacing: not more than 32” O.C.

Bulkhead and Ring Frame Spacing: 58”

Ring Frames: same as Engine Bed/Girders

Floor Cores: 3.5” thick, 7” min. height

Floor Laminate: 0.567”

Keel Laminate: 0.945” extending 4.25” min. either side of centerline

Chine Reinforcing: 0.132” added inside of bottom and topsides laminate at chine

Chine Reinforcing: extends 4.625” from chine onto bottom and topsides

**Sn Scantlings – 74-Foot FRP Single Skin**

Bottom: 0.874”

Topsides: 0.646”

Deck: 0.549”

Engine Bed/Girders Core: 7.25” width & height

Engine Bed/Girders Laminate: 0.562”

Engine Bed/Girders Tabbing Run Out: 7.75”  
Topsides & Deck Longitudinals Core: 7” wide, 3.5” high  
Topsides & Deck Longitudinals Laminate: 0.502”  
Topsides & Deck Longitudinals Tabbing Run Out: 5”  
Topsides & Deck Longitudinals Spacing: not more than 32” O.C.  
Bulkhead and Ring Frame Spacing: 80.7”  
Ring Frames: same as Engine Bed/Girders  
Floor Cores: 7.25” thick, 15.5” min. height  
Floor Laminate: 0.661”  
Keel Laminate: 1.311” extending 10” min. either side of centerline  
Chine Reinforcing: 0.306” added inside of bottom and topsides laminate at chine  
Chine Reinforcing: extends 10.75” from chine onto bottom and topsides

### **Sn Scantlings – 110-Foot FRP Single Skin**

Bottom: 1.083”  
Topsides: 0.845”  
Deck: 0.718”  
Engine Bed/Girders Core: 9.5” width & height  
Engine Bed/Girders Laminate: 0.776”  
Engine Bed/Girders Tabbing Run Out: 8.75”  
Topsides & Deck Longitudinals Core: 8.75” wide, 4.5” high  
Topsides & Deck Longitudinals Laminate: 0.681”  
Topsides & Deck Longitudinals Tabbing Run Out: 7”  
Topsides & Deck Longitudinals Spacing: not more than 32” O.C.  
Bulkhead and Ring Frame Spacing: 88”  
Ring Frames: same as Engine Bed/Girders  
Floor Cores: 9.5” thick, 19.5” min. height  
Floor Laminate: 0.776”  
Keel Laminate: 1.624” extending 130” min. either side of centerline  
Chine Reinforcing: 0.379” added inside of bottom and topsides laminate at chine  
Chine Reinforcing: extends 13.5” from chine onto bottom and topsides

### **Sn Scantlings – 29-Foot Aluminum**

Bottom: 0.25”  
Topsides: 0.1875”  
Deck: 0.1875”  
Bottom Longitudinals: Flat Bar 1.375” x 0.25”, spaced 11.375”  
Topsides Longitudinals: Flat Bar 1.25” x 0.25”, spaced 10”  
Deck Longitudinals: Flat Bar 1” x 0.25”, spaced 10”  
Ring Frames: spaced 29”  
Ring Frames Bottom: Web H. 2.875” Web T. 0.25”, Flange W. 2.25”, Flange T. 0.3125”  
Ring Frames Side: Web H. 2.25” Web T. 0.25”, Flange W. 2”, Flange T. 0.25”  
Deck Beams: Web H. 2.125” Web T. 0.25”, Flange W. 1.5”, Flange T. 0.3125”  
Ring Frame Knee Radius: 2.75” min.  
CVK: 3” H. x 0.375” T.  
Floor Height: 1.75” above to of CVK min.  
Engine Bed Girders: Web H. 6.5” Web T. 0.25”, Flange W. 1.875”, Flange T. 0.3125”

**Sn Scantlings – 74-Foot Aluminum**

Bottom: 0.375”

Topsides: 0.3125”

Deck: 0.25”

Bottom Longitudinals: Flat Bar 3.5” x 0.4375”, spaced 15.5”

Topsides Longitudinals: Flat Bar 3.25” x 0.4375”, spaced 14”

Deck Longitudinals: Flat Bar 2” x 0.375”, spaced 12”

Ring Frames: spaced 44”

Ring Frames Bottom: Web H. 8” Web T. 0.4375”, Flange W. 6.25”, Flange T. 0.5”

Ring Frames Side: Web H. 6” Web T. 0.4375”, Flange W. 5.5”, Flange T. 0.4375”

Deck Beams: Web H. 5” Web T. 0.4375”, Flange W. 3.75”, Flange T. 0.5”

Ring Frame Knee Radius: 7.5” min.

CVK: 8.5” H. x 1.25” T.

Floor Height: 5” above to of CVK min.

Engine Bed Girders: Web H. 12.375” Web T. 0.4375”, Flange W. 3.25”, Flange T. 0.5”

Deck Girders: Web H. 8.375” Web T. 0.4375”, Flange W. 6.5”, Flange T. 0.5”

Stanchions: 4” Sched. 40 pipe

**Sn Scantlings – 110-Foot Aluminum**

Bottom: 0.5”

Topsides: 0.375”

Deck: 0.3125”

Bottom Longitudinals: Flat Bar 4.625” x 0.5”, spaced 20”

Topsides Longitudinals: Flat Bar 4.5” x 0.5”, spaced 16”

Deck Longitudinals: Flat Bar 2.5” x 0.375”, spaced 14”

Ring Frames: spaced 53”

Ring Frames Bottom: Web H. 10.25” Web T. 0.5”, Flange W. 8”, Flange T. 0.625”

Ring Frames Side: Web H. 8.5” Web T. 0.5”, Flange W. 7.5”, Flange T. 0.5”

Deck Beams: Web H. 6.25” Web T. 0.5”, Flange W. 4.625”, Flange T. 0.625”

Ring Frame Knee Radius: 10” min.

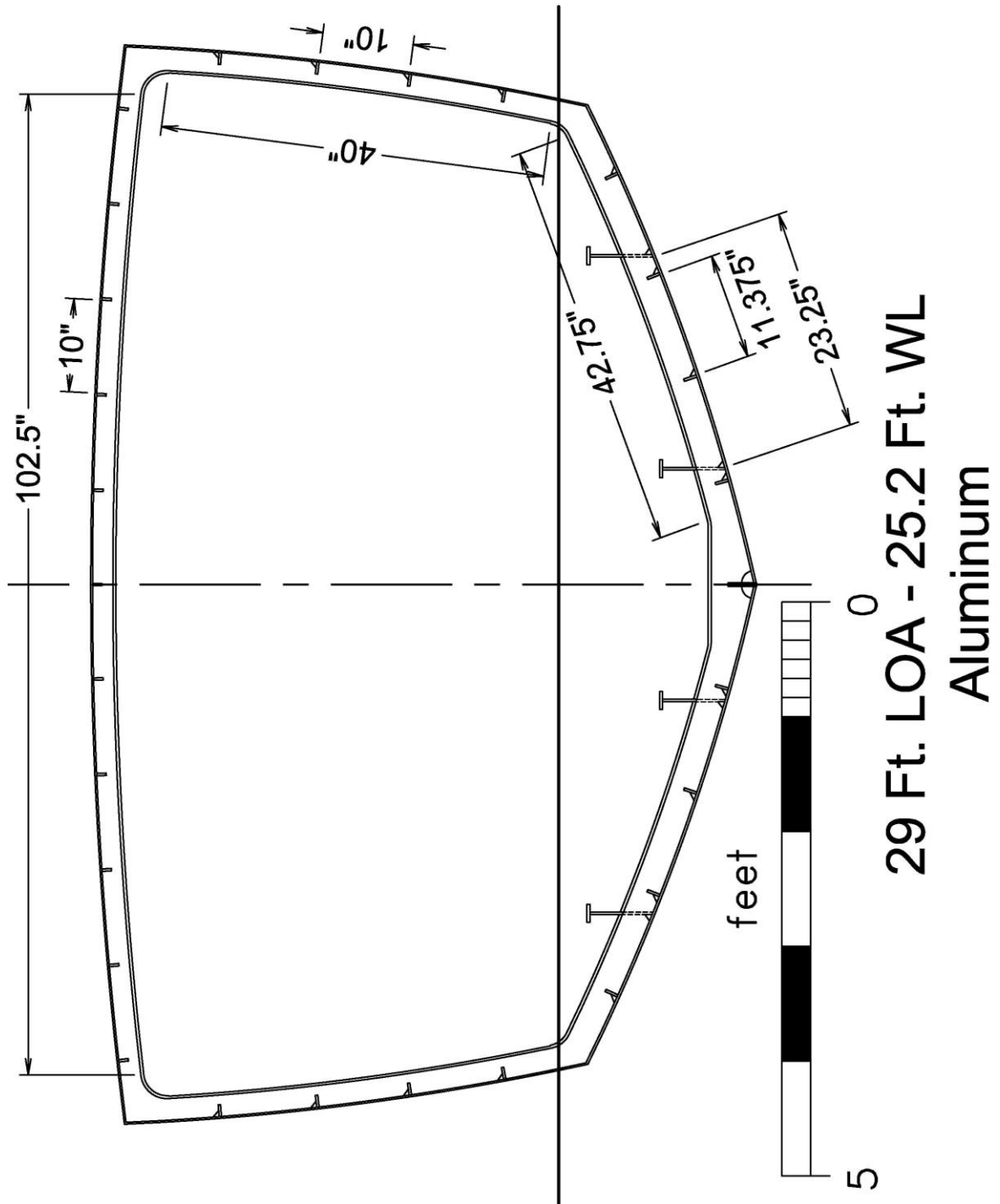
CVK: 12” H. x 1.5” T.

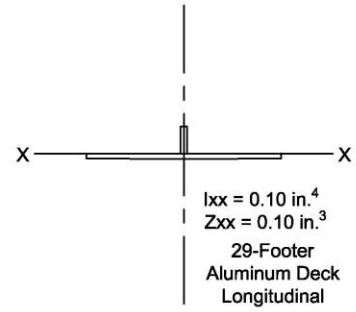
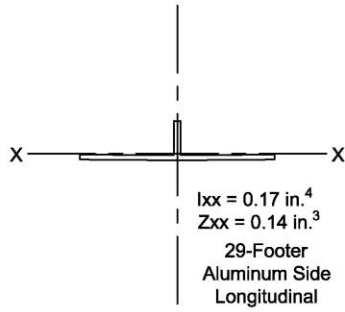
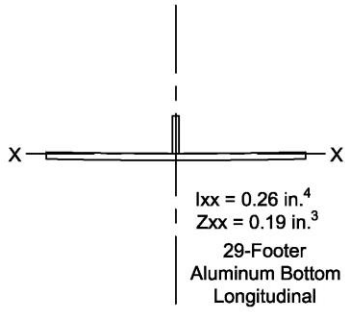
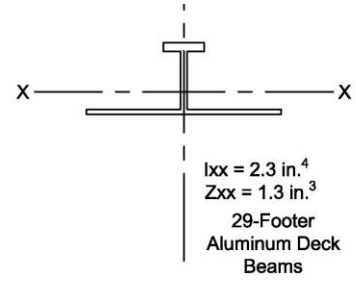
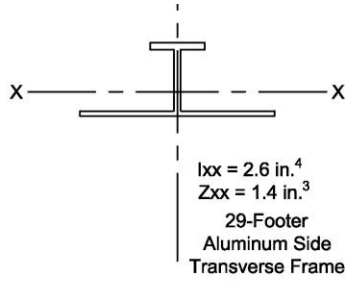
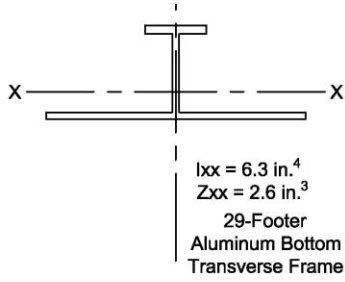
Floor Height: 12” above to of CVK min.

Engine Bed Girders: Web H. 15.625” Web T. 0.5”, Flange W. 4”, Flange T. 0.625”

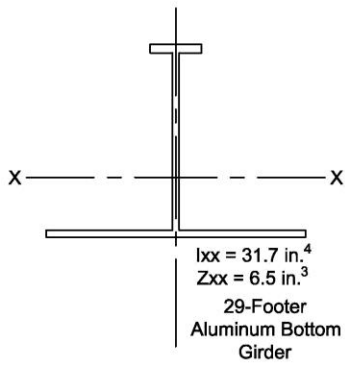
Deck Girders: Web H. 11.25” Web T. 0.5”, Flange W. 9”, Flange T. 0.625”

Stanchions: 5” Sched. 40  
pipe

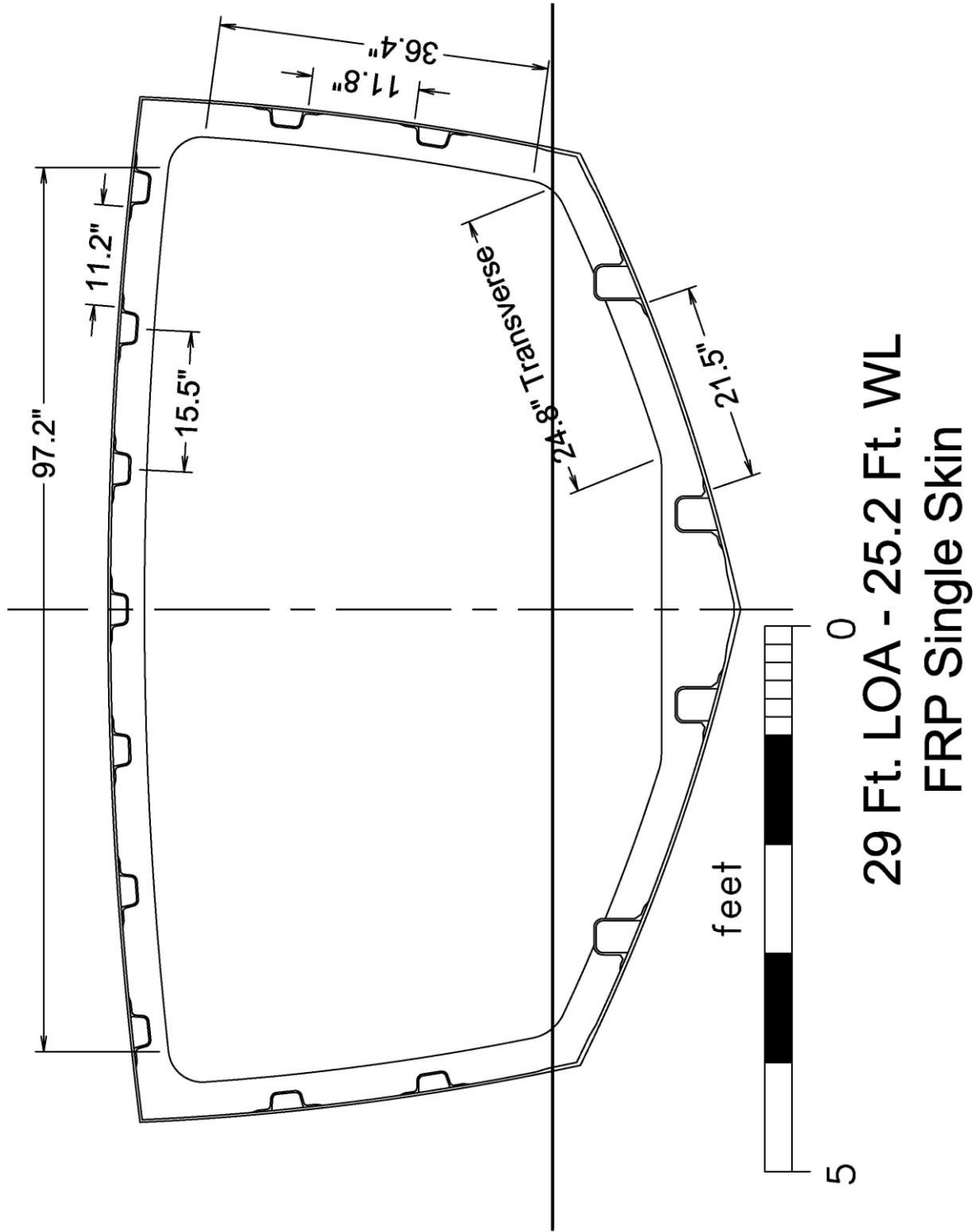


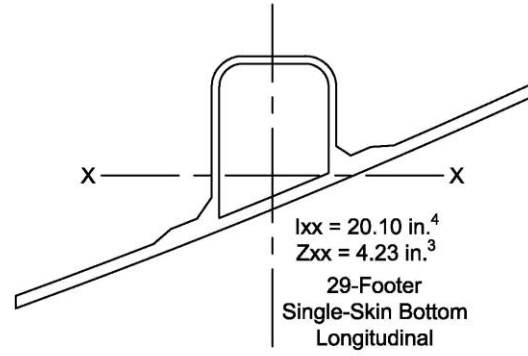
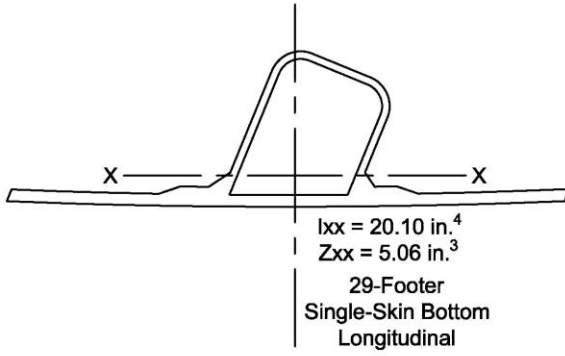


Effective Shell Plate = 38t

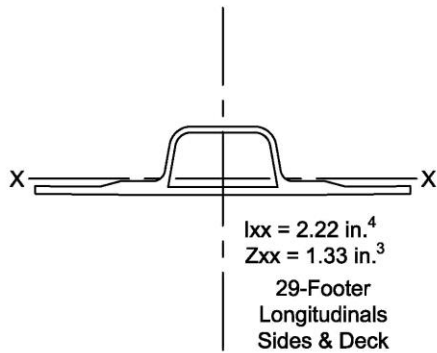
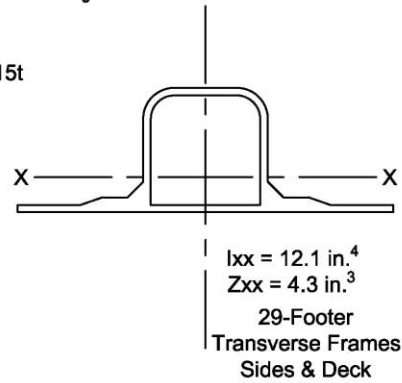
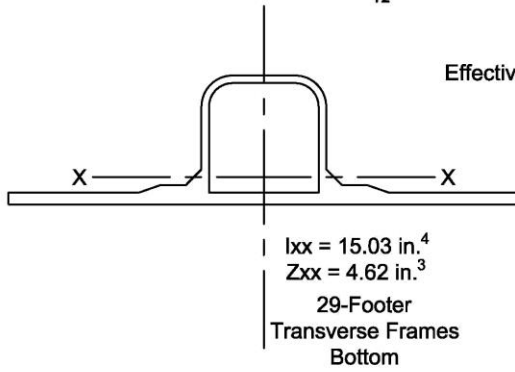


29 Foot Aluminum  
Section Properties of  
Principle Members



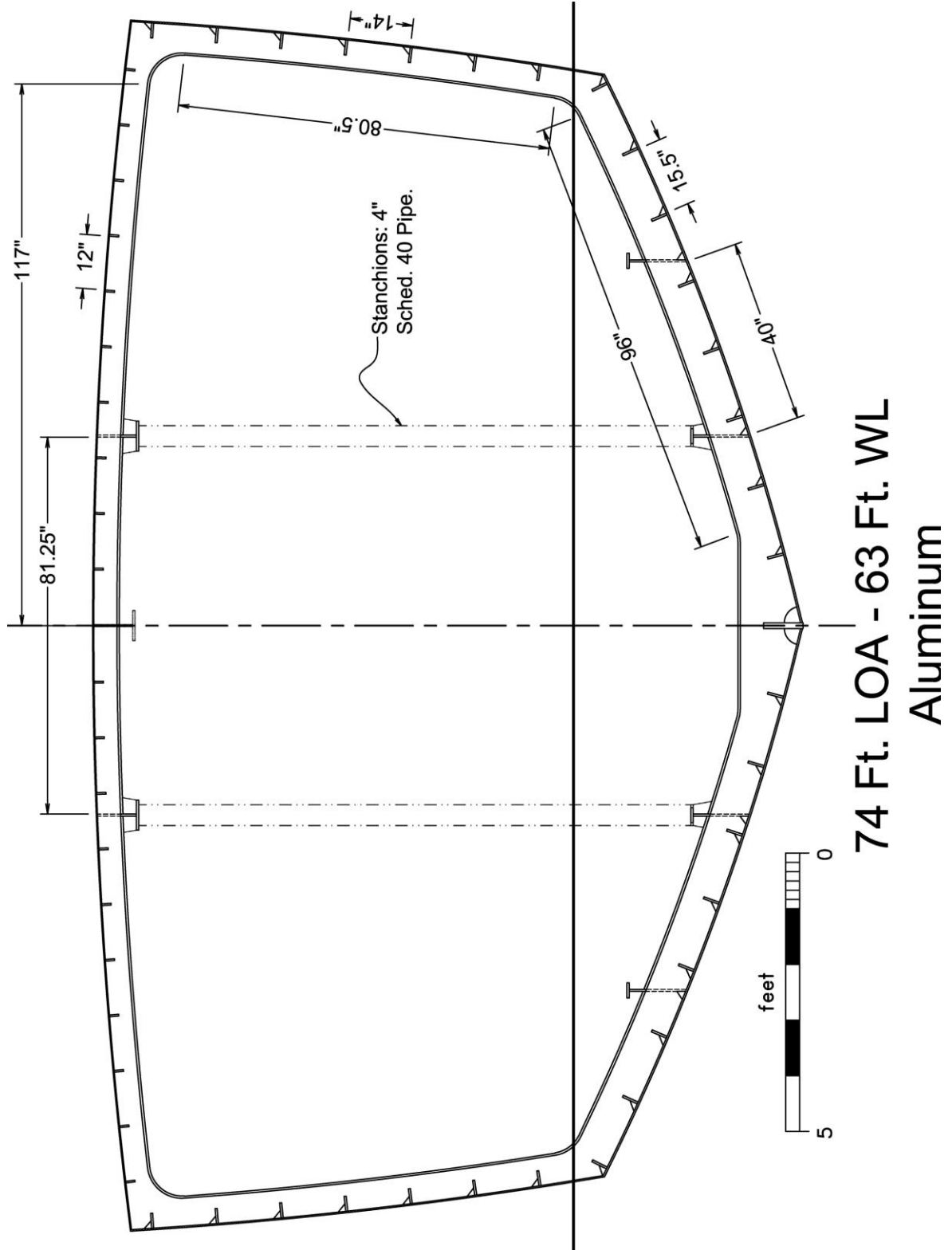


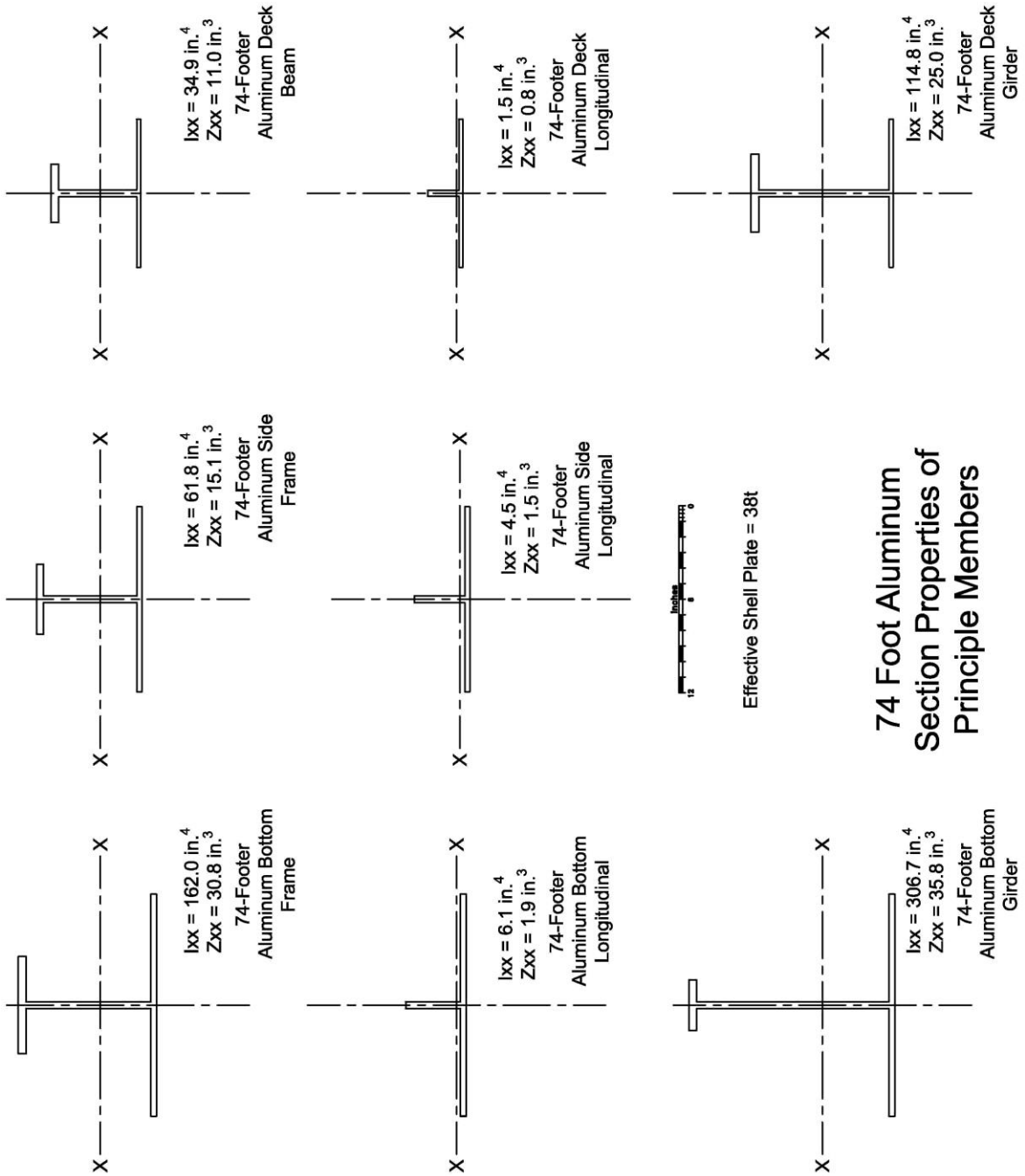
Effective Shell Plate = 15t



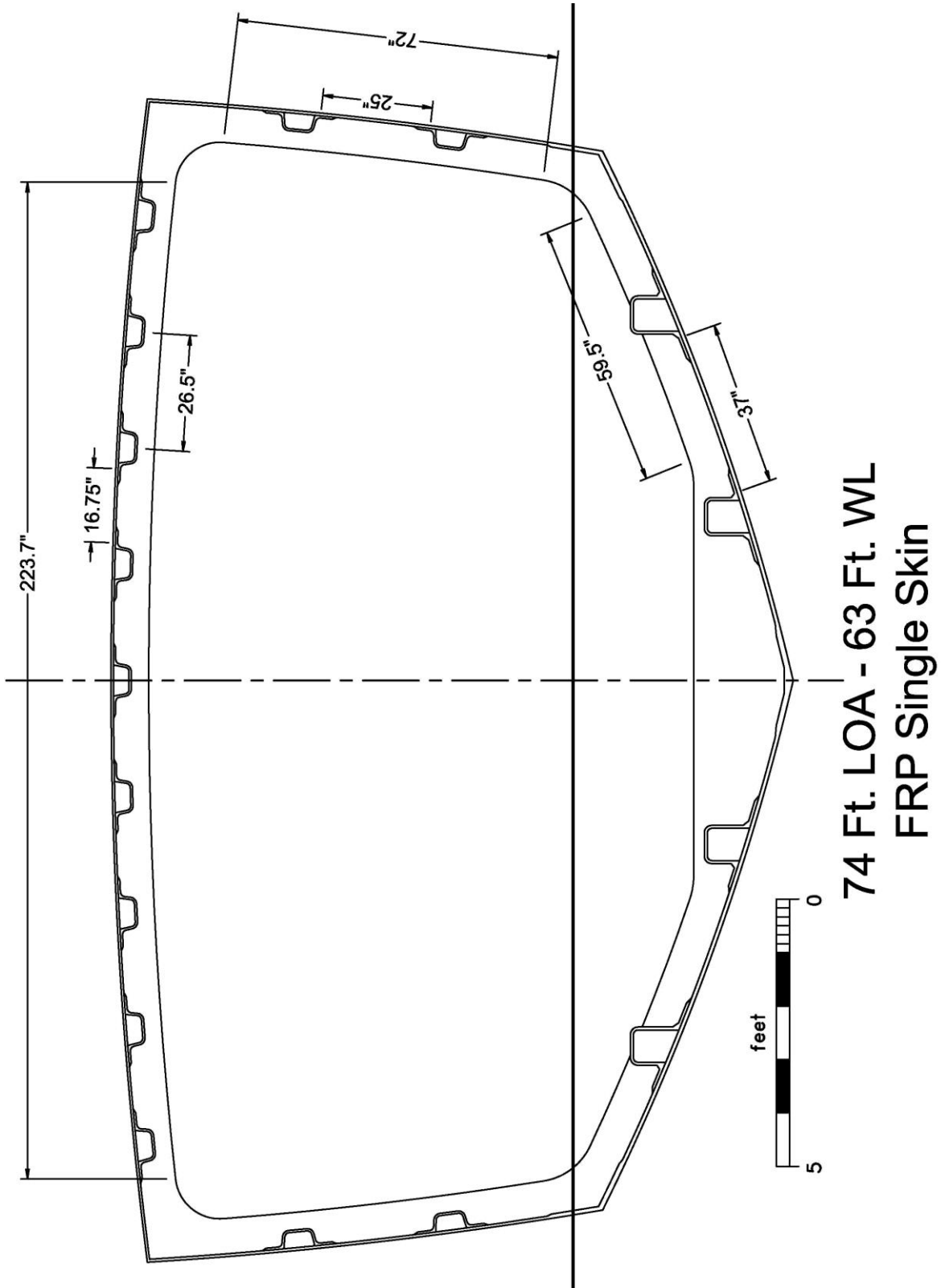
**29 Foot FRP Single Skin  
Section Properties of  
Principle Members**

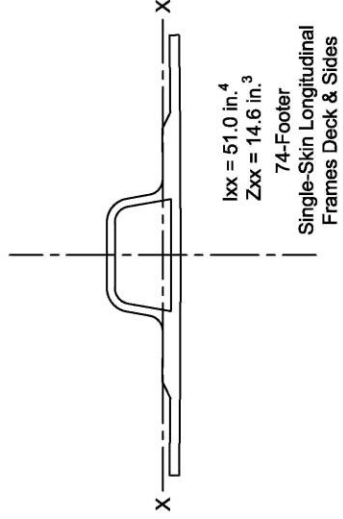
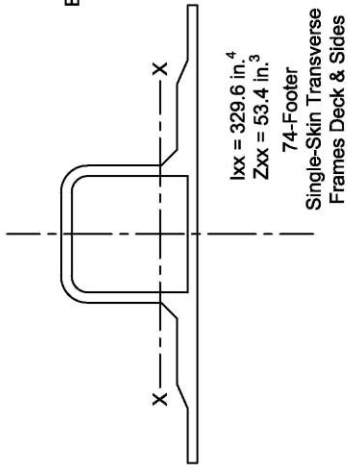
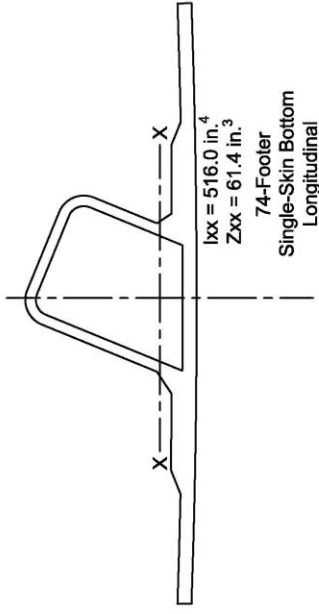
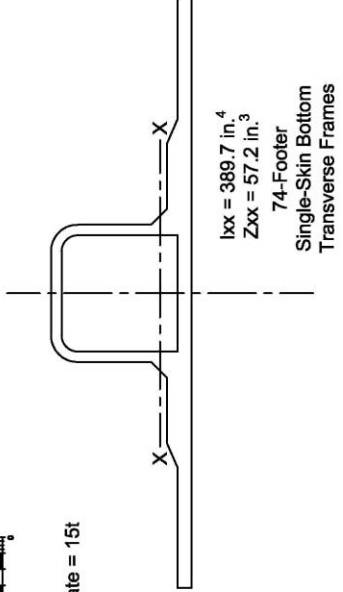
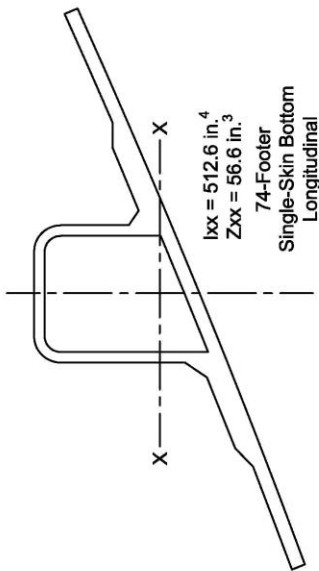




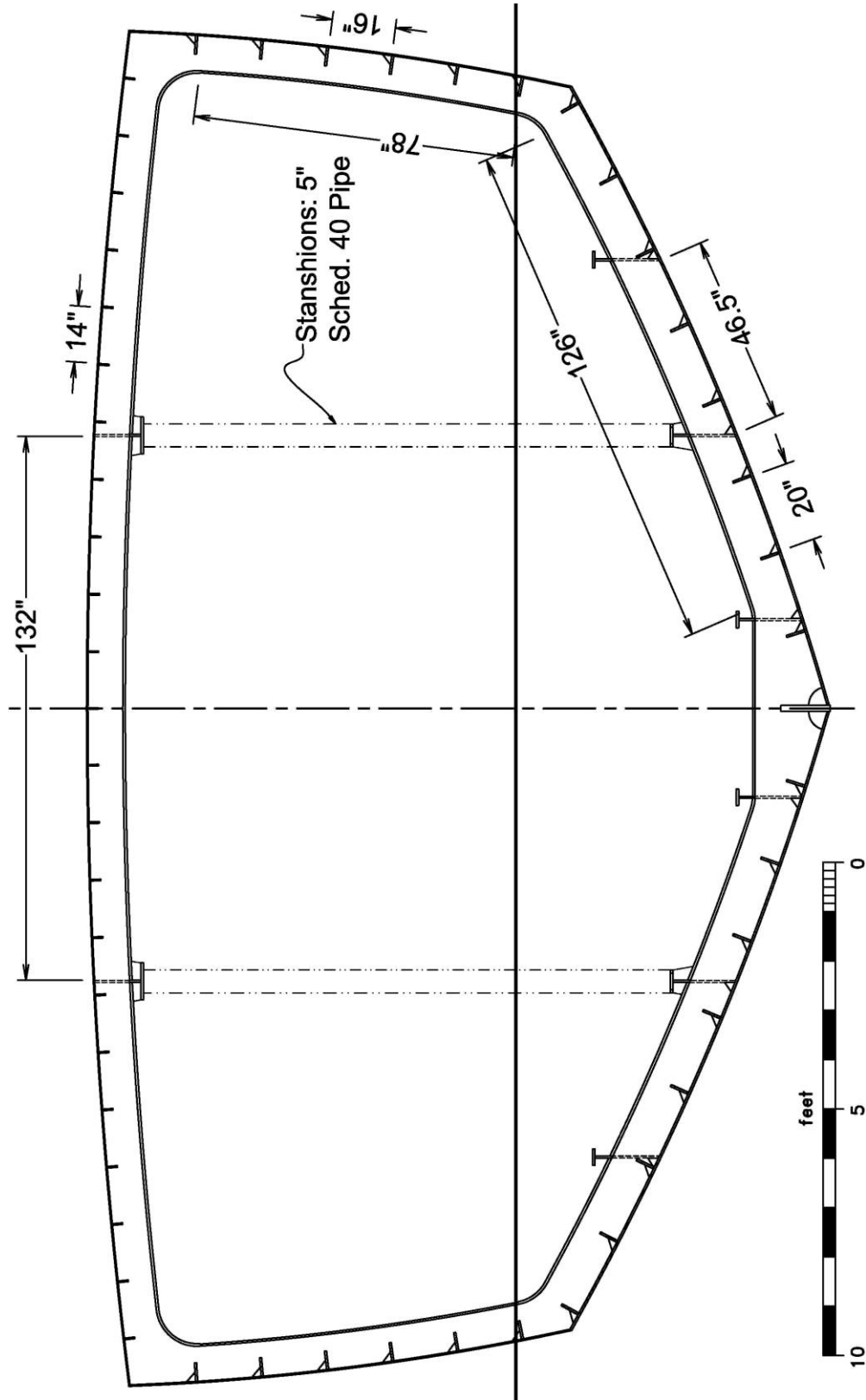


**74 Foot Aluminum Section Properties of Principle Members**

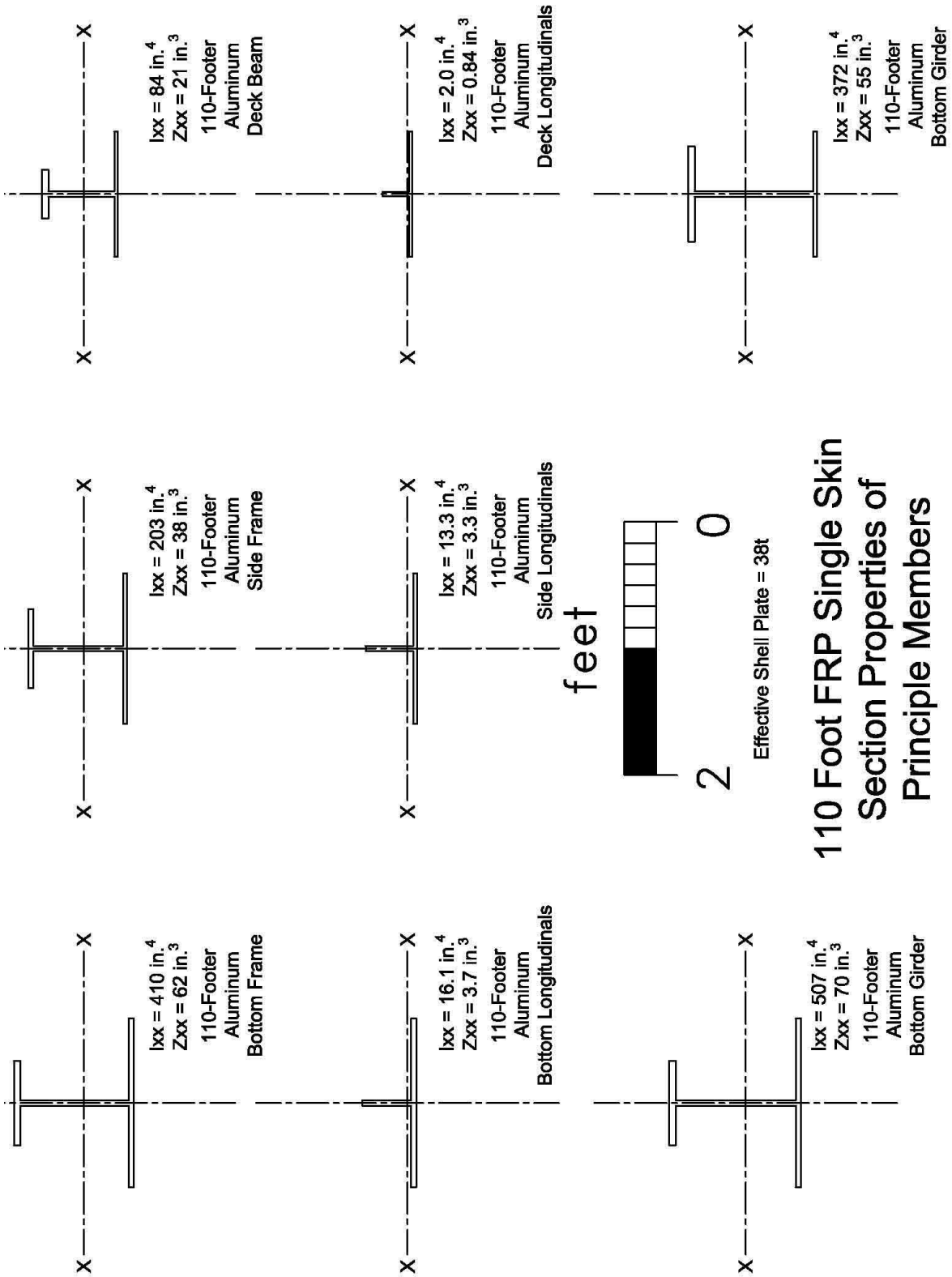




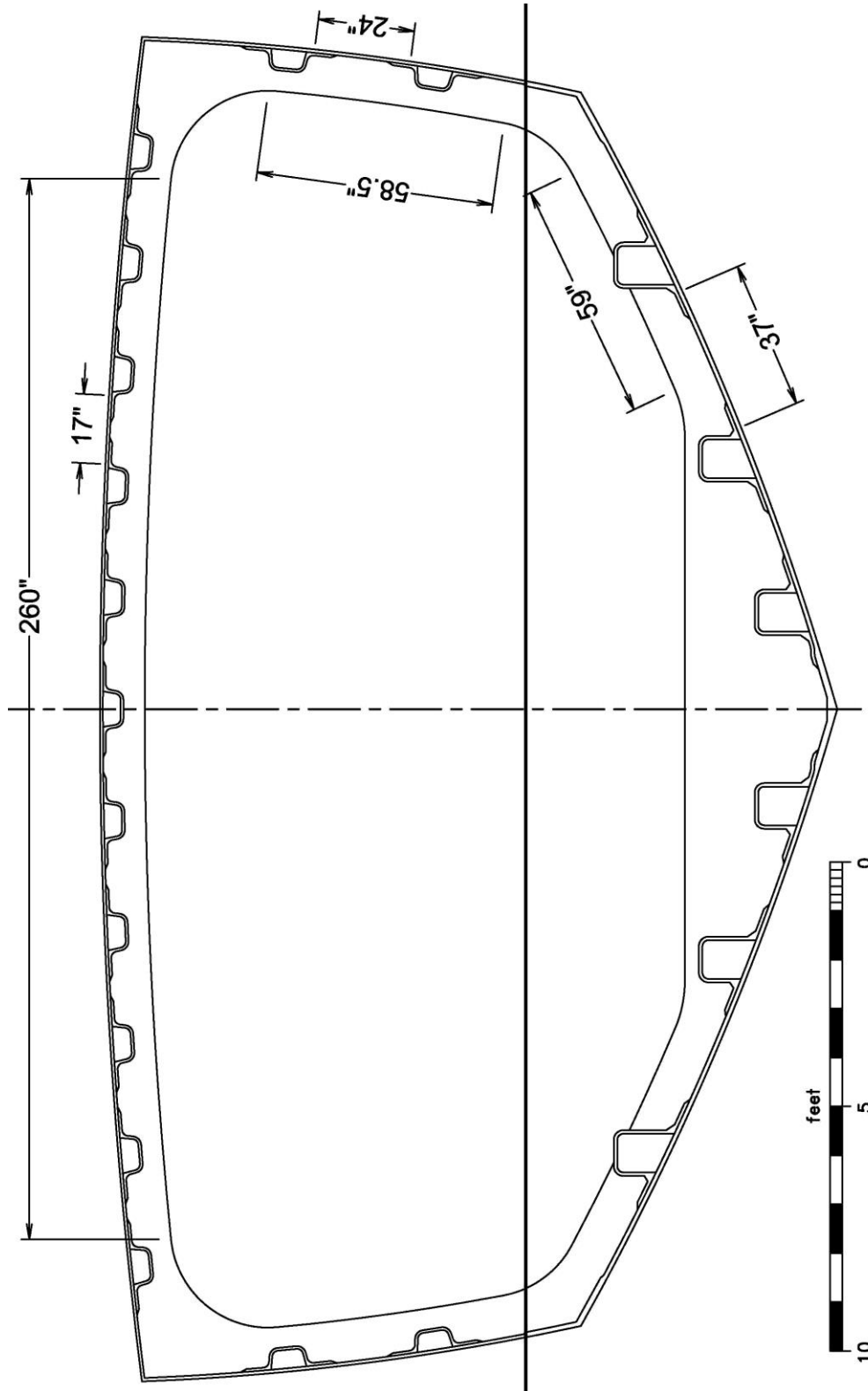
74 Foot FRP Single Skin  
Section Properties of  
Principle Members



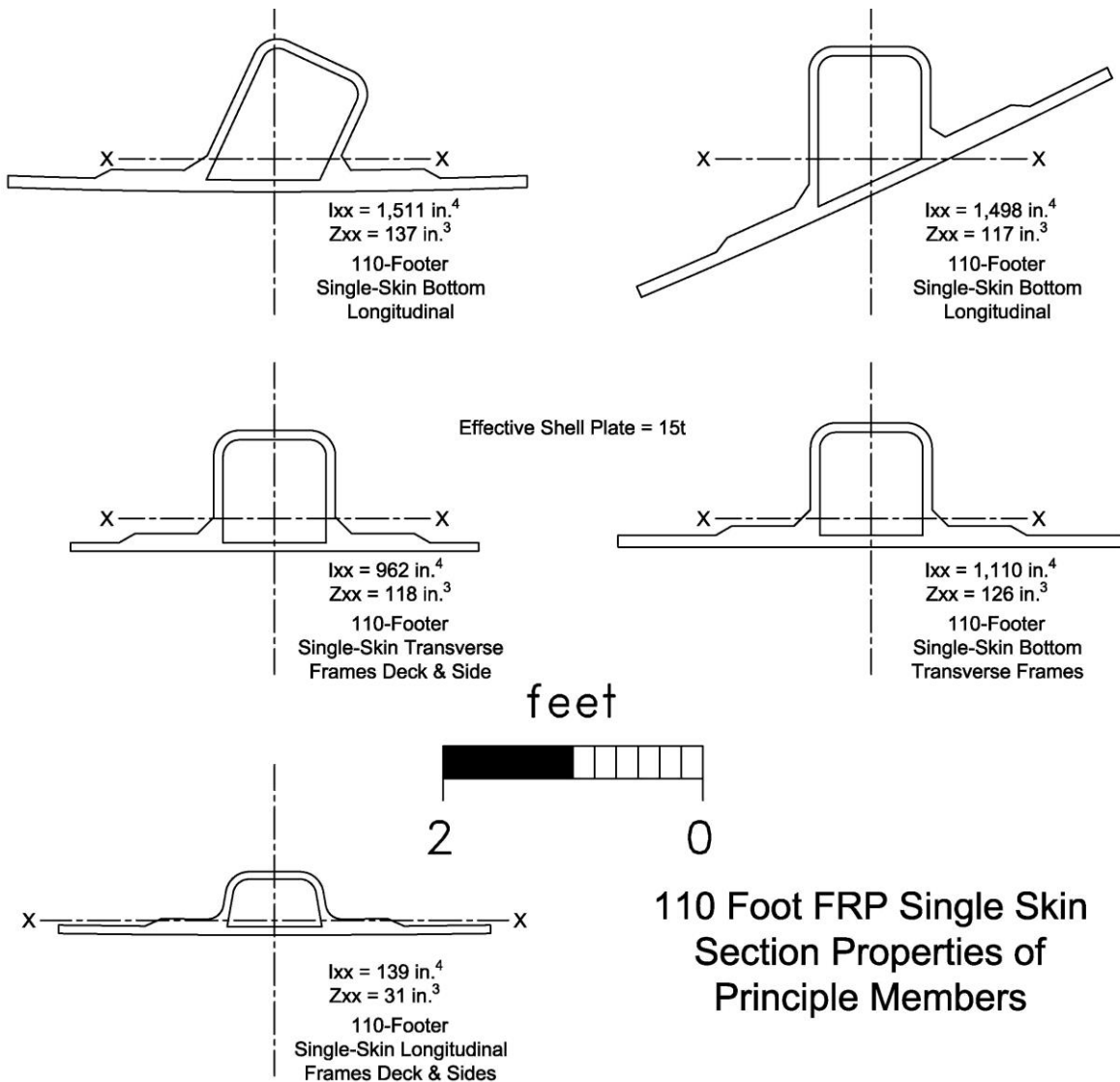
110 Ft. LOA - 94.3 Ft. WL  
Aluminum



## 110 Foot FRP Single Skin Section Properties of Principle Members



**110 Ft. LOA - 94.3 Ft. WL**  
**FRP Single Skin**



**Suitable Loads for Reviewing the Sn Scantlings**

Simple inspection shows that all six of these boats’ scantlings are sensible, but we can check their structures against some reasonable loads. One approach to get generally employed loads is to use ABS loads and then work through from these loads using standard engineering calculations. I believe that ABS loads are often too high and I know other designers who think so as well.

As we discussed earlier, really knowing the loads on a boat is not possible. For boats of the size and type covered by the Sn scantling method, I’ve found one of the best methods of determining loads was published in the SNAME paper by Hendrickson and Spencer, “A Synthesis of Aluminum Crewboat Structural Designs, October 15, 1980.”

As we’ve seen, the loads are based on acceleration, and the acceleration numbers from ABS are often remarkably high. Working through ABS loads for *High Speed Craft* for the 74-footer, gave an Ncg (acceleration at the center of gravity) of 26! Now, I don’t know about you, but I don’t think I’d be coming back home after experiencing repeated 26 gs—even for short durations. The fact is, when accelerations get too high, the crew slows the boat; they can’t take any more.



Hendrickson & Spencer found that:

*. . . assuming an exponential distribution for accelerations, for these crewboats, an acceleration of 3.0 g corresponds to the highest acceleration in at least 100,000 waves. . . . [T]he authors conclude that 3.0 g at the CG is much too severe a criteria for crewboat design.*

As explained in the Hendrickson & Spencer paper, these are workboats, which operate at low planing speed in rough waters in the Gulf and in the Atlantic. Boats meeting these acceleration and loading criteria will certainly be suited to both yacht and commercial work.

Another factor is that the crewboats used for reference by Hendrickson & Spencer aren't experiencing any structural problems:

*Operational experience with aluminum crewboats has been excellent, and neither failure by ultimate tensile stress nor failure by fatigue has been demonstrated as a principal mode of failure.*

Although I have the highest regard for the work many engineers are doing to evaluate accelerations and loads on boats, I've often found that working back from real-world data gives better results than working forward from first principles. Hendrickson & Spencer's resulting peak-impact pressure is thus based on real boats in real-world conditions. Hendrickson & Spencer peak-impact pressure is:

$$P_i = 16.0 + 0.078WL + 0.0487\Delta$$

Where:

P<sub>i</sub> = Peak impact pressure, psi

WL = Waterline length, ft.

Δ = Displacement, tons

Finally, the Hendrickson & Spencer paper forms the basis for USCG NVIC 11-80, "Structural Plan Review Guidelines for Aluminum Small Passenger Vessels." Accordingly, boats built to the Hendrickson & Spencer loads have been accepted by the Coast Guard and have been used successfully for over thirty years.

### **Understanding Hull Bottom Pressure**

The peak impact pressure (P<sub>i</sub>) occurs only in small areas for short durations and moves around on the surface. It isn't necessary (and would be heavy and wasteful) to design a hull to withstand full P<sub>i</sub> over the entire surface; such loads don't occur. In fact, the larger the area being supported by internal structure, the smaller the percentage of P<sub>i</sub> the structure should be designed to support as a whole. This means that the design loads for the components of a boat with widely spaced internal framing will be less than the loads on the components of the same boat with more closely spaced framing.

This all makes sense and is the standard, accepted approach. Because it's standard, it's the method we'll use here. Though I believe the logic behind this approach is generally sound, it does lead to some anomalies as we'll see in a bit.

A "reference area" (A<sub>r</sub>) is determined for each design. This is considered to be roughly the 30 percent of the hull bottom that is in the high-impact zone on the hull—from about station 1 aft to about station 4. A<sub>r</sub> can most directly be taken as:

$$Ar = 0.3 \times WL \times b \times 144$$

Where:

Ar = Reference area, sq.in.

WL = Waterline length, ft.

b = Chine beam, ft. (but may be taken as waterline beam, BWL)

Most references choose instead to base the reference area (Ar) on fairbody draft and displacement. This relationship yields about the same area in square inches as the direct calculation above for boats of normal form, as follows:

$$Ar = 25 \times \Delta/d \times 144$$

Where:

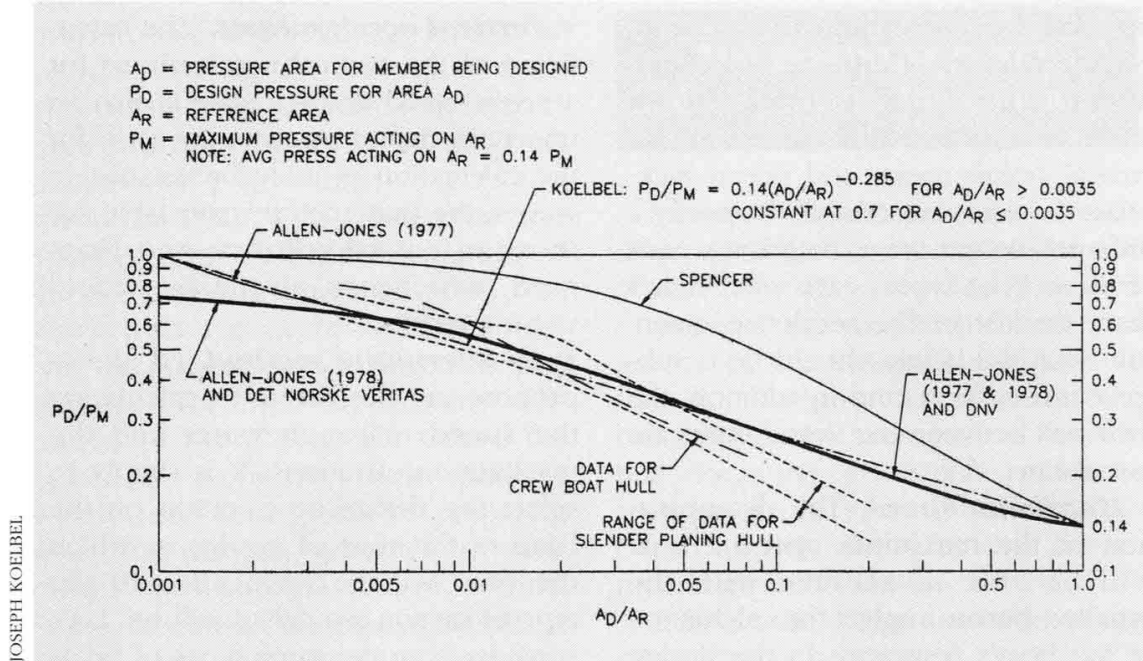
Ar = Reference area, sq.in.

$\Delta$  = Displacement, tons

d = Fairbody draft (hull draft), ft.

Since Hendrickson & Spencer use this formula for Ar (as does ABS), I'll use it here.

The relationship between peak impact pressure (Pi) and the area for design (Ad) was formalized by different researchers (Alan-Jones, Spencer and others) and has been adopted by class associations such as ABS and DNV. Joe Koelbel (in his excellent article in *ProBoat* No. 67, Oct/Nov 2000) presents a summary graph of the relationship between area for design (Ad)/reference area (Ar), and the percentage of peak impact pressure (Pi), which he terms maximum pressure (Pm) that should be used on that area.



From, *Professional Boatbuilder*, No. 67, Oct/Nov 2000

Koelbel also derived his own version of this curve, which can be reduced to a convenient formula:

$$Pd/Pm = 0.14(Ad/Ar)^{-0.285}$$

Pd/Pm not to be greater than 0.7 or less than 0.14

Pd = the design pressure, psi

Pm = Pi = Peak impact pressure or maximum pressure

Note: “Pd/Pm” is termed “Fd” in ABS

What we’ll do here is take a look at the Sn scantlings using both ABS loads and the more reasonable Hendrickson & Spencer loads. For ABS, we’ll use the ABS chart 8.1 for Fd based on Ad/Ar. For the Hendrickson & Spencer loads, we’ll use the Koelbel formula for Pd/Pm based on Ad/Ar.

### Basic Design Formulas

Almost all the structural members in our example boats are examined using simple beam analysis. In our case, all these beams are considered fixed at both ends, with the exception of the bottom frames, which are considered to be pin joined at the chine end and fixed at the inboard end—at the keel. A good review of these formulas and their application can be found in Robert J. Scott’s *Fiberglass Boat Design and Construction*, 2nd Edition, Society of Naval Architects and Marine Engineers, 1996.

Bending moment (M), in.lb. =

$WL^2/12$ , both ends fixed

$WL^2/8$ , one end fixed and one end pin-joined

Stress =  $M/Z$

Bending deflection, in, =

$WL^4/384 EI$ , both ends fixed

$WL^4/185 EI$ , one end fixed and one end pin-joined

Where:

W = load per inch on the member, lb.

L = length of the member, in.

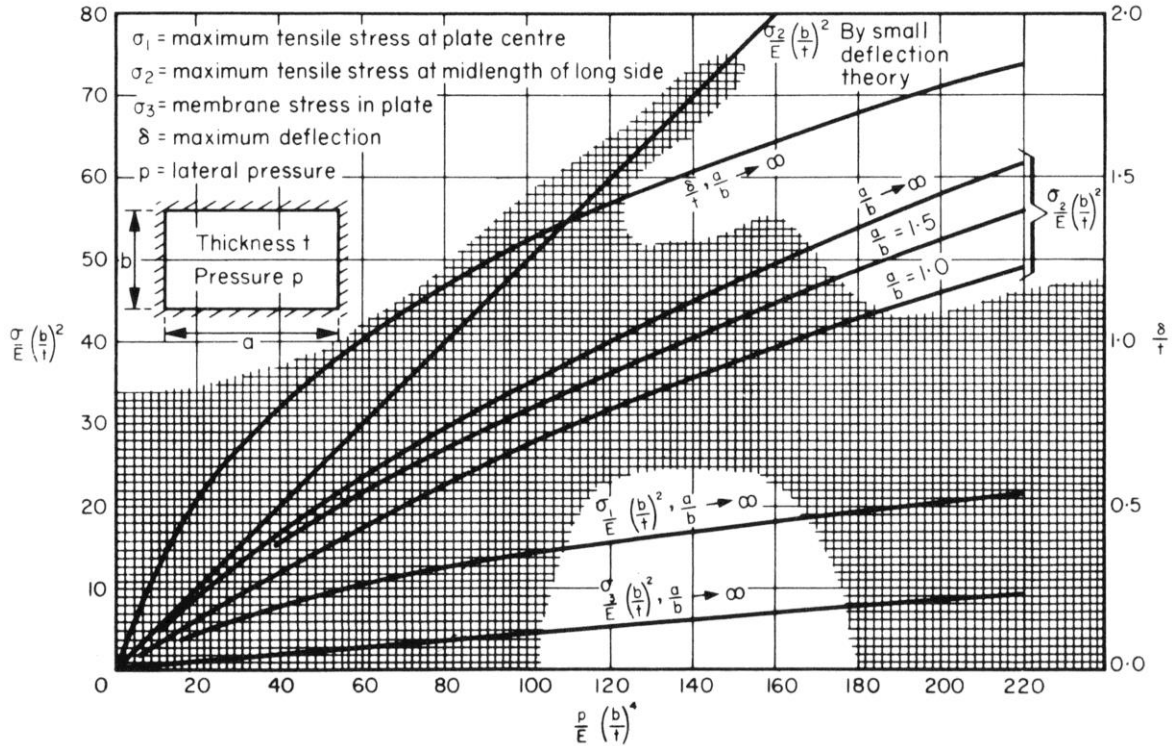
E = modulus of elasticity, psi

I = moment of inertia of the member, in.<sup>4</sup>

Z = section modulus of the member, in.<sup>3</sup>

### Shell Panels Under Membrane Stress

The shell plate is usually analyzed as a beam with two fixed ends using the 1-inch strip analogy—analyzing the load on a strip “beam” 1-inch wide. This works well at small deflections, but larger panels, with deflections greater than half the thickness, are also experiencing membrane stresses. As a result, they can be considerably thinner than simple beam analysis indicates. Scott discusses this and applies it in *Fiberglass Boat Design*, but the complete formulation can be found in *Basic Ship Theory*, Volume 1, 3rd edition, by K. J. Rawson and E. C. Tupper, or in *Formulas for Stress and Strain*, 4th Edition, by Raymond J. Roark (only in the 4th edition).



From, *Basic Ship Theory*, Volume 1, 3rd edition, by K. J. Rawson and E. C. Tupper

Using the above chart, you can calculate the stress and deflection of a shell plate undergoing membrane stress under lateral loading. In order to eliminate the need to look up the value from the chart, I've reduced the curves for stress  $a/b$  approaching infinity and for deflection to the following formulas so they can be entered into a spreadsheet.

For deflection:

$$A = \frac{P}{E} \left( \frac{b}{t} \right)^4 \quad B = \frac{d}{t}$$

Where:

$P$  = load, psi

$b$  = minimum panel span, in.

$t$  = thickness, in.

$E$  = modulus of elasticity, psi

$\delta$  = deflection, in.

For maximum membrane stress:

$$A = \frac{P}{E} \left( \frac{b}{t} \right)^4 \quad C = \frac{S}{E} \left( \frac{b}{t} \right)^4$$

$$C = 1.912 + 0.383A - \left( \frac{A^2}{1,922} \right)$$

Where:

$P$  = load, psi

$b$  = minimum panel span, in.

t = thickness, in.

E = modulus of elasticity, psi

$\sigma$  = stress, psi

### **Mechanical Properties, Allowable Stresses and Deflections**

Mechanical properties for fiberglass composites vary; however, for our review we'll use standard alternating 24 oz. roving and 15 oz. mat laminate in polyester resin at about 35% glass content by weight. Scott gives the following typical mechanical properties.

U<sub>t</sub> (ultimate tensile strength) = 29,000 psi

E<sub>t</sub> (tensile modulus) = 1,900,000 psi

U<sub>f</sub> (ultimate flexural strength) = 42,000 psi

E<sub>f</sub> (flexural modulus) = 1,900,000 psi

U<sub>c</sub> (ultimate compressive strength) = 26,000 psi

E<sub>c</sub> (compressive modulus) = 2,200,000 psi

Note: Flexural strength and modulus apply to shell panels

Safety factors and allowable deflection:

Bottom impact (dynamic) loads: SF 1.5, deflection 50:1

Side and deck static loads: SF 3, deflection 100:1

As-welded mechanical properties for 5083 aluminum, from *Engineering Data for Aluminum Structures*, The Aluminum Association, are:

U<sub>t</sub> (ultimate tensile strength) = 40,000 psi

Y (yield strength) = 24,000 psi

E (modulus) = 10,100,000 psi

Safety factors and allowable deflection:

Bottom impact (dynamic) loads: SF 1.5, deflection 75:1

Side and deck static loads: SF 3, deflection 1:150

### **Structural Review**

We have six example boats, three each in aluminum and in fiberglass single skin. Each has been reviewed to ABS loads and Hendrickson & Spencer loads. Including the design load spreadsheet pages and the structural review pages, this totals almost fifty sheets of calculations. We don't have the space to review all of this here, but we can look at a representative samples and see how things work out.

We can start with the 29-footer in FRP single skin to ABS loads.

<b>ABS MOTOR PLEASURE YACHTS 2000 - DESIGN PRESSURES</b>							
<b>29-Foot Hard-Chine Planing Hull</b>			<b>FRP SINGLE SKIN</b>		9/6/10		
Yellow Cells Are Values To Enter			Blue Cells Are Final Output				
Δ	Disp.	10,035	lb.	V	Speed	30.10	knots
Lw	WL	25.20	ft.	τ	Runing Trim	6.00	deg.
B	BOA	9.40	ft.	β	Deadrise	19.00	deg.
d	Fairbody Draft	1.72	ft.	s	Longitudinals	21.50	in.
D	Molded Depth	5.50	ft.	l	Transverses	58.00	in.
Fv1	Load Factor	1.00		Fv2	Load Factor	1.00	
N	Svc. Factor	2.50	g - Use 2.5 g for all by extreme patrol & race boats				
h	Hull Side Height	3.77	ft. - Use freeboard midships for max value				
sT	Trans'vs Length	24.80	in.	lT	Trans'vs Space	58.00	in.
<b>Plate &amp; Longitudinals</b>							
n		5.145		Fd min		0.19	
Ad max		924.5	in. <sup>2</sup>	Fd enter		0.48	Chart 8.1
Ad calc		1,247.0	in. <sup>2</sup>	Fd		0.48	
Ad		924.5	in. <sup>2</sup>	Pb		0.27	psi
Ar		9,393.2		Pi		6.81	psi
Ad/Ar		0.098		Pd		4.18	psi
Ps		1.713	psi				
<b>Transverse Bottom Frames</b>							
Ad min T		1,110.1	in. <sup>2</sup>	Fd T		0.42	Chart 8.1
Ad calc T		1,438.4	in. <sup>2</sup>	Fd min		0.19	
Ad T		1,110.1	in. <sup>2</sup>	Fd enter		0.42	
Ad/Ar		0.118		Pi T		5.17	psi
Pb T		0.24	psi				
<b>Design Loads</b>							
BOTTOM PLATE & LONG.		6.81	psi	max of Pb, Pi, Pd			
BOTTOM FRAMES		5.17	psi	max of Pb T, Pi T, Pd			
HULL SIDE		1.71	psi				
MAIN WEATHER DECK		0.88	psi				
SUPERSTRUCTURE DECKS		0.77	psi				
INTERIOR DECKS		0.50	psi				

The design pressures on the hull bottom are based on the design area supported by the engine/bed girder longitudinals and the transverse frames. The relatively large panel yields smaller design loads under the Ad/Ar relationship we discussed earlier.

The resulting *Sn Boat Strength* structure checks out as follows under ABS:

<b>STRUCTURAL REVIEW - FIBERGLASS SINGLE SKIN</b>			
<b>29-Foot Hard-Chine Planing Hull</b>		<b>BOTTOM</b>	9/6/10
Yellow Cells are Values To Enter		Blue Cells Are Final Output	
Blue Cells With Green Text Indicate, PASS		Blue Cells With Red Text, FAIL	
<b>Max Deflection</b>	<b>50 :1</b>	<b>Minimum SF</b>	<b>1.5</b>
<b>Mechanical Properties - 24/15 Roving/Mat in Polyester</b>			
Uts	29,000	psi	Tensile Strength - Ultimate
Et	1,900,000	psi	Tensile Modulus
Utf	42,000	psi	Flexural Strength - Ultimate
Ef	1,900,000	psi	Flexural Modulus
Utc	26,000	psi	Compressive Strength - Ultimate
Ec	2,200,000	psi	Compressive Modulus
<b>Load and Dimensions - Shell Plate &amp; Longitudinals</b>			
P	6.81	psi	Design Load
s	21.50	in.	Longitudinal Spacing
l	58.00	in.	Transverse Spacing
t	0.378	in.	Shell Plate Thickness
<b>Shell Plate by Membrane Analysis</b>			
MF	37.5		Membrane Factor = $p/E*(s/t)^4$
bt	15.5		$(b/t)^2 * S/E = 1.912 + 0.383 * MF - MF^2/1922$
S	9,131	psi	Stress = $bt * E * t^2/s^2$
SF	4.6		Safety Factor
d/t	0.73		Thickness to Deflection Ratio*
d	0.28	in.	Deflection
s/d	78	:1	Length to Deflection Ratio
$d/t = 0.057 + MF/45.6 + (-MF^2/8550) + MF^3/4,008,000$			
<b>Longitudinals</b>			
Z	5.06	in.3	Section Modulus
I	20.1	in.4	Moment of Inertia
Pl	6.81	psi	Longitudinal Frame Pressure
Ll	146.42	lb./in.	Load on Longitudinals
M	41,045	in.lb.	Moment on Longitudinals
S	8,112	psi	Stress
SF	3.2		Safety Factor
d	0.098	in.	Deflection
l/d	594	:1	Length to Deflection Ratio
<b>Load and Dimensions - Transverse Bottom Frames</b>			
P	5.17	psi	Design Load
s	58.00	in.	Transverse Spacing
IT	24.80	in.	Transverse Length - Bottom Frame Length
<b>Transverses - Bottom Frames</b>			
Z	5.06	in.3	Section Modulus
I	20.1	in.4	Moment of Inertia
Lt	299.9	lb./in.	Load on Transverse Frames
M	23,053	in.lb.	Moment on Frames
S	4,556	psi	Stress
SF	5.7		Safety Factor
d	0.014	in.	Deflection
IT/d	1,789	:1	Length to Deflection Ratio

In all cases, the structure easily meets ABS loads. The same applies to the side and deck, each of which has its own calculation sheet. Generally, the fiberglass structure from the Sn rule will meet or exceed ABS for boats under 45 feet, even though this wasn't a goal of the Sn rule process.

We can now take a look at the same 29-foot boat in aluminum. ABS pressures are:

<b>ABS MOTOR PLEASURE YACHTS 2000 - DESIGN PRESSURES</b>						
<b>29-Foot Hard-Chine Planing Hull</b>			<b>Aluminum</b>		9/12/10	
Yellow Cells Are Values To Enter			Blue Cells Are Final Output			
Δ	Disp.	10,035	lb.	V	Speed	30.10 knots
Lw	WL	25.20	ft.	τ	Runing Trim	6.00 deg.
B	BOA	9.40	ft.	β	Deadrise	19.00 deg.
d	Fairbody Draft	1.72	ft.	s	Longitudinals	11.38 in.
D	Molded Depth	5.50	ft.	l	Transverses	29.00 in.
Fv1	Load Factor	1.00		Fv2	Load Factor	1.00
N	Svc. Factor	2.50	g - Use 2.5 g for all by extreme patrol & race boats			
h	Hull Side Height	3.77	ft. - Use freeboard midships for max value			
sT	Trans'vs Length	42.75	in.	lT	Trans'vs Space	29.00 in.
<b>Plate &amp; Longitudinals</b>						
Note: Effective Pannel For Bottom is Bounded by Girders and 1 Frame Bay						
n		5.145		Fd min		0.19
Ad max		1,682.0	in. <sup>2</sup>	Fd enter		0.55 Chart 8.1
Ad calc		674.3	in. <sup>2</sup>	Fd		0.55
Ad		674.3	in. <sup>2</sup>	Pb		0.31 psi
Ar		9,393.2		Pi		7.80 psi
Ad/Ar		0.072		Pd		4.18 psi
Ps		1.721	psi			
<b>Transverse Bottom Frames</b>						
Ad min T		277.5	in. <sup>2</sup>	Fd T		0.55 Chart 8.1
Ad calc T		674.3	in. <sup>2</sup>	Fd min		0.19 in. <sup>2</sup>
Ad T		674.3	in. <sup>2</sup>	Fd enter		0.55 in. <sup>2</sup>
Ad/Ar		0.072		Pi T		6.76 psi
Pb T		0.31	psi			
<b>Hull Bottom Girders</b>						
Ad min G		6,938.3	in. <sup>2</sup>	l G		145 in.
AD calc G		3,371.3	in. <sup>2</sup>	s G		23.25 in.
Ad G		6,938.3	in. <sup>2</sup>	Fd G		0.18 Chart 8.1
Ad/Ar		0.74		Fd Min.		0.19 in. <sup>2</sup>
Pb G		0.11	psi	Fd enter		0.19 in. <sup>2</sup>
				Pi G		2.70 psi
<b>Design Loads</b>						
BOTTOM PLATE & LONG.		7.80	psi	max of Pb, Pi, Pd		
BOTTOM FRAMES		6.76	psi	max of Pb T, Pi T, Pd		
BOTTOM GIRDERS		2.70	psi			
HULL SIDE		1.72	psi			
MAIN WEATHER DECK		0.88	psi			
SUPERSTRUCTURE DECKS		0.77	psi			
INTERIOR DECKS		0.50	psi			

See how the pressures are different due to the different internal framing, which changes the Ad/Ar ratio. In this case, the reference bottom panel is based on the area supported by the engine/bed girders and the transverse frames. For this boat, I've omitted the smaller longitudinals, which keeps the design pressures lower, but isn't according to form. We'll discuss this in a moment.

The Sn bottom structure to ABS loads then checks to:



STRUCTURAL REVIEW - ALUMINUM		
29-Foot Hard-Chine Planing Hull		BOTTOM 9/12/10
Yellow Cells are Values To Enter		Blue Cells Are Final Output
Blue Cells With Green Text Indicate, PASS		Blue Cells With Red Text, FAIL
Max Deflection	75 :1	Minimum SF 1.5
<b>Mechanical Properties - 24/15 Roving/Mat in Polyester</b>		
Uts	40,000 psi	Tensile Strength - Ultimate
E	10,100,000 psi	Tensile Modulus
<b>Load and Dimensions - Shell Plate &amp; Longitudinals</b>		
P	7.80 psi	Design Load
s	23.25 in.	Longitudinal Spacing
l	29.00 in.	Transverse Spacing
t	0.250 in.	Shell Plate Thickness
<b>Shell Plate By Beam Analysis - 1" Strip</b>		
Z	0.010 in.3	
I	0.0013 in.4	
M	351.366 in.lb.	
S	33,731 psi	
d	0.4513 in.	
SF	1.2	
s/d	52 :1	
<b>Shell Plate by Membrane Analysis</b>		
MF	57.8	Membrane Factor =p/E*(s/t)^4
bt	22.3	(b/t)^2 x S/E =1.912+0.383 x MF - MF^2/1922
S	26,043 psi	Stress =bt x E x t^2/s^2
SF	1.5	Safety Factor
d/t	0.98	Thickness to Deflection Ratio*
d	0.25 in.	Deflection
s/d	95 :1	Length to Deflection Ratio
d/t = 0.057+MF/45.6+(-MF^2/8550)+MF^3/4,008,000		
<b>Shell Plate Stress, Safety Factor &amp; Deflection</b>		
S	26,043 psi	
d	0.2454 in.	
s/d	95 :1	
SF	1.5	
<b>Longitudinals - NOT REQUIRED FOR PLATE STRENGTH OR STIFFNESS</b>		
Z	0.19 in.3	Section Modulus
I	0.26 in.4	Moment of Inertia
Pl	7.80 psi	Longitudinal Frame Pressure
Ll	181.35 lb./in.	Load on Longitudinals
M	12,710 in.lb.	Moment on Longitudinals
S	66,893 psi	Stress
SF	0.6	Safety Factor
d	0.127 in.	Deflection
l/d	228 :1	Length to Deflection Ratio
<b>Load and Dimensions - Transverse Bottom Frames</b>		
P	6.76 psi	Design Load
s	29.00 in.	Transverse Spacing
IT	42.75 in.	Transverse Length - Bottom Frame Length
<b>Transverses - Bottom Frames</b>		
Z	2.6 in.3	Section Modulus
I	6.3 in.4	Moment of Inertia
Lt	196.0 lb./in.	Load on Transverse Frames
M	44,784 in.lb.	Moment on Frames
S	17,225 psi	Stress
SF	2.3	Safety Factor
d	0.056 in.	Deflection
IT/d	769 :1	Length to Deflection Ratio
<b>Load and Dimensions - Bottom Girders</b>		
P	3.26 psi	Design Load
s	23.25 in.	Girder Spacing
IG	145.00 in.	Girder Length
<b>Bottom Girders</b>		
Z	6.5 in.3	Section Modulus
I	31.7 in.4	Moment of Inertia
Lg	75.8 lb./in.	Load on Bottom Girders
M	55,541 in.lb.	Moment on Bottom Girders
S	8,545 psi	Stress
SF	4.7	Safety Factor
d	0.27 in.	Deflection
IT/d	532 :1	Length to Deflection Ratio

This brings us to one of the anomalies in using a design load based on the Ad/Ar ratio to get Pd/Pm (or Fd). You can see that I've neglected the small longitudinals in the design pressures and so the bottom plate is being analyzed as being supported only by the transverse frames and engine beds. It passes. Using ABS loads, we supposedly don't need these longitudinals. If we add them, though, you can see they are supposed to fail. It makes no sense. In fact, if we add the longitudinals, then the bottom design loads for the longitudinals and the shell panel become higher (under the Ad/Ar relationship) and both the shell **and** the longitudinals will supposedly fail. So adding the longitudinals makes the structure, which was strong enough without them, weaker? This is not realistic.

I'm not condemning the Ad/Ar approach. It seems one of the better methods we have, but you should be aware of its peculiarities and limitations. Indeed, something completely different is going on in the bottom panels. The Gerr 34-Foot Sportfish is a good example. This is a 32-knot fiberglass boat. It was designed all cored almost exactly to the Sn rule (years before the rule was fully formalized). The boat is almost the same size as our 29-foot example boat, just a bit longer. The builder fabricated the bottom solid glass (single skin). He used the engine/bed girder longitudinals I specified (almost exactly per the Sn rule), and the solid bottom thickness was about 0.39 inches, very close to the 0.378 in the example 29-footer. I also specified a number of full and partial bulkheads—transverse framing. The builder left most of these transverse out. In the full 32-foot length, there were only two full bulkheads no other transverses!



Gerr 34 Sportfish

I wasn't happy about this at the time, but about two dozen of these boats were built. I personally have driven hull number 2 dead up wind in force 6 conditions on Long Island Sound at a full 32 knots. (The boat handled excellently.) I can tell you that these huge bottom panels were stiff as granite. This was close to twenty years ago, and last I heard the boat is going strong.

With huge panels like this, the boat's structure would not pass ABS and many other rules, but the thing is bulletproof. In fact, the comment from everyone involved with these boats is that they were overbuilt and overdesigned.

We need to keep this in mind. My practical experience has been that the scantlings from many sources are very conservative indeed.

Let's return to our aluminum 29-footer, which easily passes ABS loads for side and deck as well.

According to the Hendrickson & Spencer loads for the bottom, the boat’s bottom structure is way overbuilt.

We can now take a look at the 74-footer using ABS. Design pressures are:

<b>ABS MOTOR PLEASURE YACHTS 2000 - DESIGN PRESSURES</b>						
<b>74-Foot Hard-Chine Planing Hull</b>			<b>Aluminum</b>		9/14/10	
Yellow Cells Are Values To Enter			Blue Cells Are Final Output			
Δ	Disp.	128,822	lb.	V	Speed	27.70 knots
Lw	WL	63.00	ft.	τ	Runing Trim	5.50 deg.
B	BOA	21.75	ft.	β	Deadrise	20.00 deg.
d	Fairbody Draft	4.12	ft.	s	Longitudinals	15.50 in.
D	Molded Depth	12.07	ft.	l	Transverses	44.00 in.
Fv1	Load Factor	1.00		Fv2	Load Factor	1.00
N	Svc. Factor	2.50	g - Use 2.5 g for all by extreme patrol & race boats			
h	Hull Side Height	7.95	ft. - Use freeboard midships for max value			
sT	Trans'vs Length	40.00	in.	IT	Trans'vs Space	44.00 in.
<b>Plate &amp; Longitudinals</b>						
Note: Effective Pannel For Bottom is Bounded by Girders and 1 Frame Bay						
n	1.706			Fd min	0.19	
Ad max	3,872.0	in. <sup>2</sup>		Fd enter	0.72	Chart 8.1
Ad calc	1,760.0	in. <sup>2</sup>		Fd	0.72	
Ad	1,760.0	in. <sup>2</sup>		Pb	2.74	psi
Ar	50,340.6			Pi	24.47	psi
Ad/Ar	0.035			Pd	7.07	psi
Ps	4.045	psi				
<b>Transverse Bottom Frames</b>						
Ad min T	638.9	in. <sup>2</sup>		Fd T	0.72	Chart 8.1
Ad calc T	1,760.0	in. <sup>2</sup>		Fd min	0.19	in. <sup>2</sup>
Ad T	1,760.0	in. <sup>2</sup>		Fd enter	0.72	in. <sup>2</sup>
Ad/Ar	0.035			Pi T	21.21	psi
Pb T	2.74	psi				
<b>Hull Bottom Girders</b>						
Ad min G	10,222.1	in. <sup>2</sup>		l G	176.0	in.
AD calc G	7,040.0	in. <sup>2</sup>		s G	40.0	in.
Ad G	10,222.1	in. <sup>2</sup>		Fd G	0.34	Chart 8.1
Ad/Ar	0.20			Fd Min.	0.19	in. <sup>2</sup>
Pb G	1.29	psi		Fd enter	0.34	in. <sup>2</sup>
				Pi G	11.56	psi
<b>Design Loads</b>						
BOTTOM PLATE & LONG.	24.47	psi	max of Pb, Pi, Pd			
BOTTOM FRAMES	21.21	psi	max of Pb T, Pi T, Pd			
BOTTOM GIRDERS	11.56	psi				
HULL SIDE	4.05	psi				
MAIN WEATHER DECK	1.21	psi				
SUPERSTRUCTURE DECKS	0.94	psi				
INTERIOR DECKS	0.50	psi				

The Sn bottom structure checks out as follows:

STRUCTURAL REVIEW - ALUMINUM			
74-Foot Hard-Chine Planing Hull		BOTTOM	9/14/10
Yellow Cells are Values To Enter		Blue Cells Are Final Output	
Blue Cells With Green Text Indicate, PASS		Blue Cells With Red Text, FAIL	
Max Deflection	75 :1	Minimum SF	1.5
<b>Mechanical Properties - 24/15 Roving/Mat in Polyester</b>			
Uts	40,000 psi	Tensile Strength - Ultimate	
E	10,100,000 psi	Tensile Modulus	
<b>Load and Dimensions - Shell Plate &amp; Longitudinals</b>			
P	24.47 psi	Design Load	
s	15.50 in.	Longitudinal Spacing	
l	44.00 in.	Transverse Spacing	
t	0.375 in.	Shell Plate Thickness	
<b>Shell Plate By Beam Analysis - 1" Strip</b>			
Z	0.023 in.3		
I	0.0044 in.4		
M	489.910 in.lb.		
S	20,903 psi		
d	0.08 in.		
SF	1.9		
s/d	187 :1		
<b>Shell Plate by Membrane Analysis</b>			
MF	7.1	Membrane Factor = $p/E*(s/t)^4$	
bt	4.6	$(b/t)^2 * S/E = 1.912 + 0.383 * MF - MF^2/1922$	
S	27,161 psi	Stress = $bt * E * t^2/s^2$	
SF	1.5	Safety Factor	
d/t	0.21	Thickness to Deflection Ratio*	
d	0.08 in.	Deflection	
s/d	200 :1	Length to Deflection Ratio	
$d/t = 0.057 + MF/45.6 + (-MF^2/8550) + MF^3/4,008,000$			
<b>Shell Plate Stress, Safety Factor &amp; Deflection</b>			
S	20,903 psi		
d	0.0774 in		
s/d	200 :1		
SF	1.9		
<b>Longitudinals</b>			
Z	1.9 in.3	Section Modulus	
I	6.1 in.4	Moment of Inertia	
Pl	24.47 psi	Longitudinal Frame Pressure	
Ll	379.29 lb./in.	Load on Longitudinals	
M	61,191 in.lb.	Moment on Longitudinals	
S	32,206 psi	Stress	
SF	1.2	Safety Factor	
d	0.060 in.	Deflection	
l/d	732 :1	Length to Deflection Ratio	
<b>Load and Dimensions - Transverse Bottom Frames</b>			
P	21.20 psi	Design Load	
s	44.00 in.	Transverse Spacing	
lT	40.00 in.	Transverse Length - Bottom Frame Length	
<b>Transverses - Bottom Frames</b>			
Z	30.8 in.3	Section Modulus	
I	162.0 in.4	Moment of Inertia	
Lt	932.8 lb./in.	Load on Transverse Frames	
M	186,560 in.lb.	Moment on Frames	
S	6,057 psi	Stress	
SF	6.6	Safety Factor	
d	0.008 in.	Deflection	
lT/d	5,070 :1	Length to Deflection Ratio	
<b>Load and Dimensions - Bottom Girders</b>			
P	11.56 psi	Design Load	
s	40.00 in.	Girder Spacing	
lG	176.00 in.	Girder Length	
<b>Bottom Girders</b>			
Z	35.8 in.3	Section Modulus	
I	306.7 in.4	Moment of Inertia	
Lg	462.4 lb./in.	Load on Bottom Girders	
M	791,695 in.lb.	Moment on Bottom Girders	
S	22,114 psi	Stress	
SF	1.8	Safety Factor	
d	0.37 in.	Deflection	
lT/d	472 :1	Length to Deflection Ratio	

You can see that everything passes with ease, except for the bottom longitudinals, with a SF of 1.2. In planing and semi-planing boats ABS loads really want to see the bottom longitudinals as Ls or Ts. In fact, changing the longitudinals from the Sn rule's flat bars to Ls with the same flange width and thickness as the web (the flat bar) usually makes all these structures from the Sn rule meet

ABS design loads in planing boats. Remember, however, that real-world experience indicates this approach is considerably too conservative as well see in a more detailed analysis shortly.

For the Sn rule, in boats of this size and type, the Hendrickson & Spencer loads are much more realistic. In fact, this boat would be typical of the size, form and speed of a smaller crewboat, the exact type of boat the Hendrickson & Spencer loads were derived from. The Hendrickson & Spencer loads for our aluminum 74-footer are:

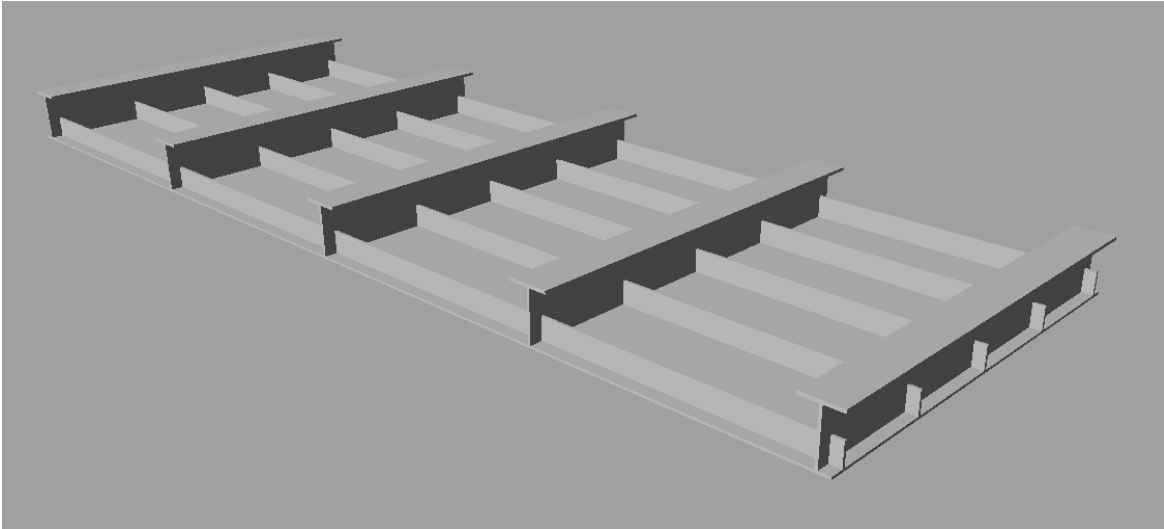
<b>HENDRICKSON-SPENSER - DESIGN PRESSURES</b>						
<b>74-Foot Hard-Chine Planing Hull</b>			<b>Aluminum</b>		9/16/10	
Yellow Cells Are Values To Enter			Blue Cells Are Final Output			
Δ	Disp.	128,882	lb.	Δt	Disp.	57.54 tons
Lw	WL	63.00	ft.	d	Fairbody Draft	4.12 ft.
Ar	Reference Area	50274.7	in.^2	Pi	Peak Impact	23.72 psi
<b>Bottom Plate &amp; Longitudinals</b>						
s	Spacing	15.5	in.	Fd max	Max Pd/Pi	0.70
l	Length	44.0	in.	Fd min	Min Pd/Pi	0.14
Ad	Area Design	682.0	in.^2	Fd calc	Calculated Fd	0.48
Ad/Ar	Ratio	0.01		Fd calc2	Calculated Fd2	0.48
Pd	Design Pressure	11.31	psi	Fd	Pd/Pi	0.48
<b>Bottom Frames</b>						
s	Spacing	44.0	in.	Fd max	Max Pd/Pi	0.70
l	Length	40.0	in.	Fd min	Min Pd/Pi	0.14
Ad	Area Design	1760.0	in.^2	Fd calc	Calculated Fd	0.36
Ad/Ar	Ratio	0.04		Fd calc2	Calculated Fd2	0.36
Pd	Design Pressure	8.63	psi	Fd	Pd/Pi	0.36
<b>Bottom Girders</b>						
s	Spacing	40.0	in.	Fd max	Max Pd/Pi	0.70
l	Length	176.0	in.	Fd min	Min Pd/Pi	0.14
Ad	Area Design	7040.0	in.^2	Fd calc	Calculated Fd	0.25
Ad/Ar	Ratio	0.1		Fd calc2	Calculated Fd2	0.25
Pd	Design Pressure	5.81	psi	Fd	Pd/Pi	0.25
<b>Hull Side (ABS)</b>						
B	BOA	21.75	ft.	τ	Running Trim	5.50 deg.
h	Hull Side Height	7.95	ft.	β	Deadrise	20.00 deg.
V	Speed	27.70	knots	n		1.71 g
s	Spacing	14.0	in.	Fd max	Max Pd/Pi	0.70
l	Length	44.0	in.	Fd min	Min Pd/Pi	0.14
Ad	Area Design	616.0	in.^2	Fd calc	Calculated Fd	0.49
Ad/Ar	Ratio	0.0		Fd calc2	Calculated Fd2	0.49
Pb	Ref. Pressure	1.87	psi	Fd	Pd/Pi	0.49
Ps	Design Pressure	3.87	psi			
<b>Design Pressures</b>						
BOTTOM PLATE & LONG.		11.31	psi			
BOTTOM FRAMES		8.63	psi			
BOTTOM GIRDERS		5.81	psi			
HULL SIDE		3.87	psi	ABS		
MAIN WEATHER DECK		1.04	psi	150 lb./sq.ft.		
SUPERSTRUCTURE DECKS		0.88	psi	125 lb./sq.ft.		
INTERIOR DECKS		0.70	psi	100 lb./sq.ft.		

The Sn bottom structure for the 74-footer then checks out as:

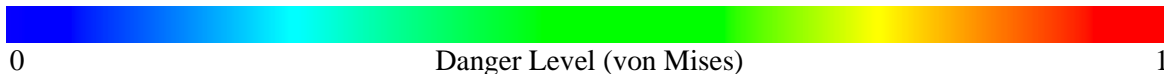
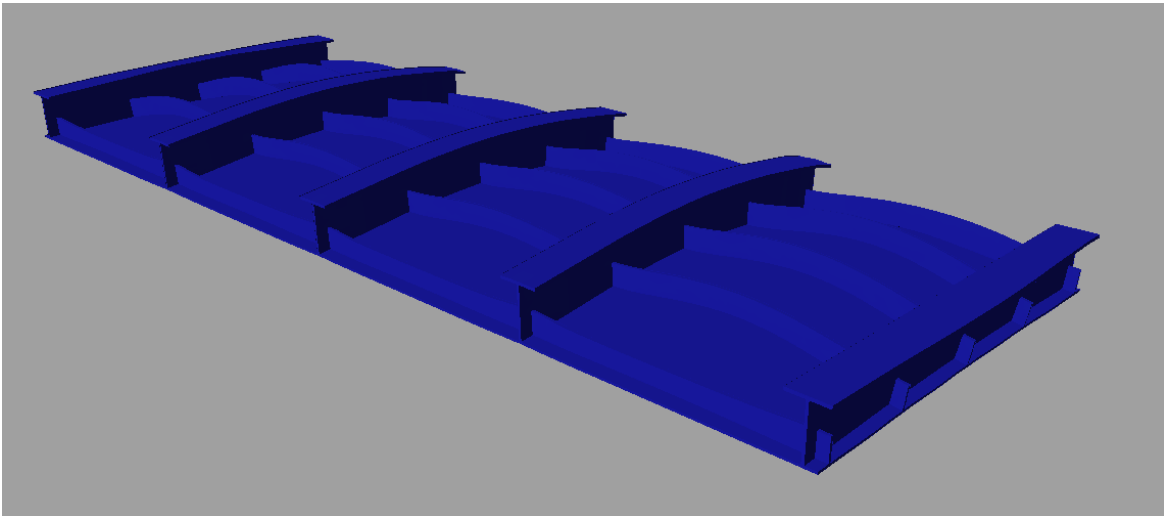
HS - STRUCTURAL REVIEW - ALUMINUM			
74-Foot Hard-Chine Planing Hull		<b>BOTTOM</b>	9/14/10
Yellow Cells are Values To Enter		Blue Cells Are Final Output	
Blue Cells With Green Text Indicate, PASS		Blue Cells With Red Text, FAIL	
<b>Max Deflection</b>	<b>75</b>	<b>:1</b>	<b>Minimum SF</b> <b>1.5</b>
<b>Mechanical Properties - 24/15 Roving/Mat in Polyester</b>			
Uts	40,000	psi	Tensile Strength - Ultimate
E	10,100,000	psi	Tensile Modulus
<b>Load and Dimensions - Shell Plate &amp; Longitudinals</b>			
P	11.31	psi	Design Load
s	15.50	in.	Longitudinal Spacing
l	44.00	in.	Transverse Spacing
t	0.375	in.	Shell Plate Thickness
<b>Shell Plate By Beam Analysis - 1" Strip</b>			
Z	0.023	in.3	
I	0.0044	in.4	
M	226.436	in.lb.	
S	<b>9,661</b>	psi	
d	<b>0.04</b>	in.	
SF	<b>4.1</b>		
s/d	<b>405</b>	<b>:1</b>	
<b>Shell Plate by Membrane Analysis</b>			
MF	3.3		Membrane Factor = $p/E*(s/t)^4$
bt	3.2		$(b/t)^2 * S/E = 1.912 + 0.383 * MF - MF^2/1922$
S	<b>18,671</b>	psi	Stress = $bt * E * t^2/s^2$
SF	<b>2.1</b>		Safety Factor
d/t	0.13		Thickness to Deflection Ratio*
d	<b>0.05</b>	in.	Deflection
s/d	<b>324</b>	<b>:1</b>	Length to Deflection Ratio
$d/t = 0.057 + MF/45.6 + (-MF^2/8550) + MF^3/4,008,000$			
<b>Shell Plate Stress, Safety Factor &amp; Deflection</b>			
S	<b>9,661</b>	psi	
d	<b>0.0383</b>	in	
s/d	<b>405</b>	<b>:1</b>	
SF	<b>4.1</b>		
<b>Longitudinals</b>			
Z	1.9	in.3	Section Modulus
I	6.1	in.4	Moment of Inertia
Pl	11.31	psi	Longitudinal Frame Pressure
Ll	175.31	lb./in.	Load on Longitudinals
M	28,283	in.lb.	Moment on Longitudinals
S	<b>14,886</b>	psi	Stress
SF	<b>2.7</b>		Safety Factor
d	<b>0.028</b>	in.	Deflection
l/d	<b>1,584</b>	<b>:1</b>	Length to Deflection Ratio
<b>Load and Dimensions - Transverse Bottom Frames</b>			
P	8.63	psi	Design Load
s	44.00	in.	Transverse Spacing
lT	40.00	in.	Transverse Length - Bottom Frame Length
<b>Transverses - Bottom Frames</b>			
Z	30.8	in.3	Section Modulus
I	162.0	in.4	Moment of Inertia
Lt	379.7	lb./in.	Load on Transverse Frames
M	75,944	in.lb.	Moment on Frames
S	<b>2,466</b>	psi	Stress
SF	<b>16.2</b>		Safety Factor
d	<b>0.003</b>	in.	Deflection
lT/d	<b>12,456</b>	<b>:1</b>	Length to Deflection Ratio
<b>Load and Dimensions - Bottom Girders</b>			
P	5.81	psi	Design Load
s	40.00	in.	Girder Spacing
lG	176.00	in.	Girder Length
<b>Bottom Girders</b>			
Z	35.8	in.3	Section Modulus
I	306.7	in.4	Moment of Inertia
Lg	232.4	lb./in.	Load on Bottom Girders
M	791,695	in.lb.	Moment on Bottom Girders
S	<b>22,114</b>	psi	Stress
SF	<b>1.8</b>		Safety Factor
d	<b>0.19</b>	in.	Deflection
lT/d	<b>939</b>	<b>:1</b>	Length to Deflection Ratio

You can see that this structure supports these loads by a wide margin. The same applies to the side and deck structure review sheets. In fact, the 74-footer—a largish boat in the middle of the Sn rule size range—passes deck and sides for ABS and for Hendrickson & Spenser in aluminum and FRP. The only value that’s just in the red, is that the ABS loads say the side frames have a SF of 2.9, which is just under the desired SF of 3, but—with very low deflections—acceptable.

We can return to the ABS bottom structure and do a more detailed investigation of the longitudinals that are apparently too weak per ABS loads on our example 74-footer. To get a more detailed insight, we can use a finite-element analysis (FEA) of the structure. In fact, Jay Jeffries of Ceros3D LLC ran an FEA on the sample bottom panels for the 74-footer. The bottom panel structure for this boat is modeled is as shown:



The von Mises stresses are extremely low at just 339 psi. Maximum deflection is just 0.0014 inches. The von Mises danger levels are depicted below:



You can see that the entire structure is dark blue, zero danger level relative to the von Mises stress. The von Mises stress is the average of the three stresses (in the x, y, z directions). The von Mises danger level is the von Mises stress divided by the yield stress of the material. This extremely low danger level is confirming that the entire bottom structure (including the longitudinals) are undergoing exceptionally low stress at ABS design loads. Thus the entire structure from the Sn rule, including the longitudinals in question, is conservative even for the higher ABS loads.

Turning now to the 110-footer in aluminum, this is exactly the size, speed and form of many crew boats, so Hendrickson & Spencer is clearly applicable. Design pressures are:

<b>HENDRICKSON-SPENSER - DESIGN PRESSURES</b>							
<b>110-Foot Hard-Chine Planing Hull Aluminum</b>							
					9/16/10		
Yellow Cells Are Values To Enter			Blue Cells Are Final Output				
Δ	Disp.	375,670	lb.	Δt	Disp.	167.71	tons
Lw	WL	94.30	ft.	d	Fairbody Draft	6.37	ft.
Ar	Reference Area	94781.1	in.^2	Pi	Peak Impact	31.52	psi
<b>Bottom Plate &amp; Longitudinals</b>							
s	Spacing	20	in.	Fd max	Max Pd/Pi	0.70	
l	Length	53.0	in.	Fd min	Min Pd/Pi	0.14	
Ad	Area Design	1060.0	in.^2	Fd calc	Calculated Fd	0.50	
Ad/Ar	Ratio	0.01		Fd calc2	Calculated Fd2	0.50	
Pd	Design Pressure	15.88	psi	Fd	Pd/Pi	0.50	
<b>Bottom Frames</b>							
s	Spacing	53.0	in.	Fd max	Max Pd/Pi	0.70	
l	Length	46.5	in.	Fd min	Min Pd/Pi	0.14	
Ad	Area Design	2464.5	in.^2	Fd calc	Calculated Fd	0.40	
Ad/Ar	Ratio	0.03		Fd calc2	Calculated Fd2	0.40	
Pd	Design Pressure	12.49	psi	Fd	Pd/Pi	0.40	
<b>Bottom Girders</b>							
s	Spacing	46.5	in.	Fd max	Max Pd/Pi	0.70	
l	Length	212.0	in.	Fd min	Min Pd/Pi	0.14	
Ad	Area Design	9858.0	in.^2	Fd calc	Calculated Fd	0.27	
Ad/Ar	Ratio	0.1		Fd calc2	Calculated Fd2	0.27	
Pd	Design Pressure	8.41	psi	Fd	Pd/Pi	0.27	
<b>Hull Side (ABS)</b>							
B	BOA	27.50	ft.	τ	Running Trim	5.00	deg.
h	Hull Side Height	7.85	ft.	β	Deadrise	23.00	deg.
V	Speed	21.40	knots	n		0.52	g
s	Spacing	16.0	in.	Fd max	Max Pd/Pi	0.70	
l	Length	53.0	in.	Fd min	Min Pd/Pi	0.14	
Ad	Area Design	848.0	in.^2	Fd calc	Calculated Fd	0.54	
Ad/Ar	Ratio	0.0		Fd calc2	Calculated Fd2	0.54	
Pb	Ref. Pressure	10.34	psi	Fd	Pd/Pi	0.54	
Ps	Design Pressure	5.52	psi				
<b>Design Pressures</b>							
BOTTOM PLATE & LONG.		15.88	psi				
BOTTOM FRAMES		12.49	psi				
BOTTOM GIRDERS		8.41	psi				
HULL SIDE		5.52	psi	ABS			
MAIN WEATHER DECK		1.04	psi	150 lb./sq.ft.			
SUPERSTRUCTURE DECKS		0.88	psi	125 lb./sq.ft.			
INTERIOR DECKS		0.70	psi	100 lb./sq.ft.			

The Sn bottom structure checks out as:



HS - STRUCTURAL REVIEW - ALUMINUM			
110-Foot Hard-Chine Planing Hull		BOTTOM	9/15/10
Yellow Cells are Values To Enter		Blue Cells Are Final Output	
Blue Cells With Green Text Indicate, PASS		Blue Cells With Red Text, FAIL	
Max Deflection	75 :1	Minimum SF	1.5
<b>Mechanical Properties - 24/15 Roving/Mat in Polyester</b>			
Uts	40,000 psi	Tensile Strength - Ultimate	
E	10,100,000 psi	Tensile Modulus	
<b>Load and Dimensions - Shell Plate &amp; Longitudinals</b>			
P	15.88 psi	Design Load	
s	20.00 in.	Longitudinal Spacing	
l	53.00 in.	Transverse Spacing	
t	0.500 in.	Shell Plate Thickness	
<b>Shell Plate By Beam Analysis - 1" Strip</b>			
Z	0.042 in.3	Section Modulus	
I	0.0104 in.4	Moment of Inertia	
M	529.333 in.lb.	Moment on Longitudinals	
S	12,704 psi	Stress	
d	0.06 in.	Deflection	
SF	3.1	Safety Factor	
s/d	318 :1	Length to Deflection Ratio	
<b>Shell Plate by Membrane Analysis</b>			
MF	4.0	Membrane Factor = $p/E*(s/t)^4$	
bt	3.4	$(b/t)^2 * S/E = 1.912 + 0.383 * MF - MF^2/1922$	
S	21,748 psi	Stress = $bt * E * t^2/s^2$	
SF	1.8	Safety Factor	
d/t	0.14	Thickness to Deflection Ratio*	
d	0.07 in.	Deflection	
s/d	279 :1	Length to Deflection Ratio	
$d/t = 0.057 + MF/45.6 + (-MF^2/8550) + MF^3/4,008,000$			
<b>Shell Plate Stress, Safety Factor &amp; Deflection</b>			
S	12,704 psi	Stress	
d	0.0629 in.	Deflection	
s/d	318 :1	Length to Deflection Ratio	
SF	3.1	Safety Factor	
<b>Longitudinals</b>			
Z	3.7 in.3	Section Modulus	
I	16.1 in.4	Moment of Inertia	
Pl	15.88 psi	Longitudinal Frame Pressure	
Ll	317.60 lb./in.	Load on Longitudinals	
M	74,345 in.lb.	Moment on Longitudinals	
S	20,093 psi	Stress	
SF	2.0	Safety Factor	
d	0.040 in.	Deflection	
l/d	1,321 :1	Length to Deflection Ratio	
<b>Load and Dimensions - Transverse Bottom Frames</b>			
P	12.49 psi	Design Load	
s	53.00 in.	Transverse Spacing	
lT	46.50 in.	Transverse Length - Bottom Frame Length	
<b>Transverses - Bottom Frames</b>			
Z	62 in.3	Section Modulus	
I	410.0 in.4	Moment of Inertia	
Lt	662.0 lb./in.	Load on Transverse Frames	
M	178,918 in.lb.	Moment on Frames	
S	2,886 psi	Stress	
SF	13.9	Safety Factor	
d	0.004 in.	Deflection	
lT/d	11,510 :1	Length to Deflection Ratio	
<b>Load and Dimensions - Bottom Girders</b>			
P	8.41 psi	Design Load	
s	46.50 in.	Girder Spacing	
lG	212.00 in.	Girder Length	
<b>Bottom Girders</b>			
Z	70 in.3	Section Modulus	
I	507.0 in.4	Moment of Inertia	
Lg	391.1 lb./in.	Load on Bottom Girders	
M	1,898,884 in.lb.	Moment on Bottom Girders	
S	27,127 psi	Stress	
SF	1.47	Safety Factor	
d	0.40 in.	Deflection	
lT/d	528 :1	Length to Deflection Ratio	

Once again, the Sn rule scantlings work across the board. The only borderline value is the SF for the bottom girders. At 1.47 it's so close to 1.5 as to be acceptable.

We can look at the side and deck structure for the aluminum 110-footer:

HS - STRUCTURAL REVIEW - ALUMINUM			
110-Foot Hard-Chine Planing Hull		SIDE	9/15/10
Yellow Cells are Values To Enter		Blue Cells Are Final Output	
Blue Cells With Green Text Indicate, PASS		Blue Cells With Red Text, FAIL	
Max Deflection	150 :1	Minimum SF	3
<b>Mechanical Properties - 24/15 Roving/Mat in Polyester</b>			
Uts	40,000 psi	Tensile Strength - Ultimate	
E	10,100,000 psi	Tensile Modulus	
<b>Load and Dimensions - Shell Plate &amp; Longitudinals</b>			
P	5.52 psi	Design Load	
s	16.00 in.	Longitudinal Spacing	
l	53.00 in.	Transverse Spacing	
t	0.375 in.	Shell Plate Thickness	
<b>Shell Plate By Beam Analysis - 1" Strip</b>			
Z	0.023 in.3		
I	0.0044 in.4		
M	117.760 in.lb.		
S	5,024 psi		
d	0.0212 in.		
SF	8.0		
s/d	754 :1		
<b>Shell Plate by Membrane Analysis</b>			
MF	1.8	Membrane Factor = $p/E*(s/t)^4$	
bt	2.6	$(b/t)^2 * S/E$	
S	14,447 psi	Stress = $bt * E * t^2/s^2$	
SF	2.8	Safety Factor	
d/t	0.10	Thickness to Deflection Ratio*	
d	0.04 in.	Deflection	
s/d	443 :1	Length to Deflection Ratio	
$d/t = 0.057+MF/45.6+(-MF^2/8550)+MF^3/4,008,000$			
<b>Shell Plate Stress, Safety Factor &amp; Deflection</b>			
S	5,024 psi		
d	0.0212 in		
s/d	754 :1		
SF	8.0		
<b>Longitudinals</b>			
Z	3.3 in.3	Section Modulus	
I	13.3 in.4	Moment of Inertia	
Pl	5.52 psi	Longitudinal Frame Pressure	
Ll	88.32 lb./in.	Load on Longitudinals	
M	20,674 in.lb.	Moment on Longitudinals	
S	6,265 psi	Stress	
SF	6.4	Safety Factor	
d	0.014 in.	Deflection	
l/d	3,923 :1	Length to Deflection Ratio	
<b>Load and Dimensions - Transverse Side Frames</b>			
P	5.52 psi	Design Load	
s	53.00 in.	Transverse Spacing	
lT	80.50 in.	Transverse Length - Side Frame Length	
<b>Transverses - Side Frames</b>			
Z	38 in.3	Section Modulus	
I	203 in.4	Moment of Inertia	
Lt	292.6 lb./in.	Load on Transverse Frames	
M	236,983 in.lb.	Moment on Frames	
S	6,236 psi	Stress	
SF	6.4	Safety Factor	
d	0.032 in.	Deflection	
lT/d	2,485 :1	Length to Deflection Ratio	

HS - STRUCTURAL REVIEW - ALUMINUM			
110-Foot Hard-Chine Planing Hull		DECK	9/15/10
Yellow Cells are Values To Enter		Blue Cells Are Final Output	
Blue Cells With Green Text Indicate, PASS		Blue Cells With Red Text, FAIL	
Max Deflection	150	:1	Minimum SF 3
<b>Mechanical Properties - 24/15 Roving/Mat in Polyester</b>			
Uts	40,000	psi	Tensile Strength - Ultimate
E	10,100,000	psi	Tensile Modulus
<b>Load and Dimensions - Shell Plate &amp; Longitudinals</b>			
P	1.04	psi	Design Load
s	14.00	in.	Longitudinal Spacing
l	53.00	in.	Transverse Spacing
t	0.313	in.	Shell Plate Thickness
<b>Shell Plate By Beam Analysis - 1" Strip</b>			
Z	0.016	in.3	
I	0.0025	in.4	
M	16.987	in.lb.	
S	1,044	psi	
d	0.0041	in.	
SF	38.3		
s/d	3,456	:1	
<b>Shell Plate by Membrane Analysis</b>			
MF	0.4		Membrane Factor = $p/E*(s/t)^4$
bt	2.1		$(b/t)^2 * S/E = 1.912 + 0.383 * MF - MF^2/1922$
S	10,421	psi	Stress = $bt * E * t^2/s^2$
SF	3.8		Safety Factor
d/t	0.07		Thickness to Deflection Ratio*
d	0.02	in.	Deflection
s/d	678	:1	Length to Deflection Ratio
$d/t = 0.057 + MF/45.6 + (-MF^2/8550) + MF^3/4,008,000$			
<b>Shell Plate Stress, Safety Factor &amp; Deflection</b>			
S	1,044	psi	
d	0.0041	in.	
s/d	3456	:1	
SF	38.3		
<b>Longitudinals</b>			
Z	0.84	in.3	Section Modulus
I	2.00	in.4	Moment of Inertia
Pl	1.04	psi	Longitudinal Frame Pressure
Ll	14.56	lb./in.	Load on Longitudinals
M	3,408	in.lb.	Moment on Longitudinals
S	4,057	psi	Stress
SF	9.9		Safety Factor
d	0.015	in.	Deflection
l/d	3,578	:1	Length to Deflection Ratio
<b>Load and Dimensions - Transverse Deck Beams</b>			
P	1.04	psi	Design Load
s	53.00	in.	Transverse Spacing
lT	212.00	in.	Transverse Length - Deck Beam Length
<b>Transverses - Deck Beams</b>			
Z	21.0	in.3	Section Modulus
I	84.0	in.4	Moment of Inertia
Lt	55.1	lb./in.	Load on Transverse Frames
M	309,664	in.lb.	Moment on Frames
S	14,746	psi	Stress
SF	2.7		Safety Factor
d	0.709	in.	Deflection
lT/d	299	:1	Length to Deflection Ratio
<b>Load and Dimensions - Deck Girders</b>			
P	1.04	psi	Design Load
s	132.00	in.	Girder Spacing
lG	212.00	in.	Girder Length
<b>Deck Girders NONE</b>			
Z	55.0	in.3	Section Modulus
I	372.0	in.4	Moment of Inertia
Lg	137.3	lb./in.	Load on Deck Girders
M	1,393,264	in.lb.	Moment on Deck Girders
S	25,332	psi	Stress
SF	1.6		Safety Factor
d	0.19	in.	Deflection
lT/d	1,103	:1	Length to Deflection Ratio

Once again, this all works, with the exception of the deck structure. The same applies to the fiberglass version of our 110-footer.

### Deck Structure

The transverse deck beams are a bit weak (apparently). The deck girders—with the long distance between stanchions and bulkhead selected—are a bit weak too. But what is missing from the structure of our 110-footer, in fact from all our boats? Superstructure. We don't have space to review the superstructure (which works out about the same way), so all the example boats are drawn as flush decked, and that's across the middle of the widest part of the deck. The real spans, with superstructure, cockpits, hatches, and so on, will almost always be very substantially less. The deck structure in the Sn rule allows for this, though it's not shown in our examples.

For boats under about 85 feet (26 m), even on an all-flush-deck boat, the decks will be fine, but it might be worth mentioning that the Sn rule doesn't apply to the decks of boats over 85-feet, that are all flush decked. This is a rather rare configuration, but it could possibly be used at times.

### Displacement Boat Scantlings

We also don't have space do a detailed review of displacement hull structures under the Sn rule, but we reviewed the planing and semi-planing hulls because the loads on them are more severe. The Sn rule gives very rugged scantlings across the board for displacement boats. A good example is my 57-foot aluminum *Imagine* design, built by Kanter Yachts.



57-Foot *Imagine*

This is another boat that almost exactly follows the Sn rule scantlings but predates the formalized rule. I was cruising on *Imagine* during a severe storm in Lake Superior, in August 2000. Here's what her owner wrote me a few days after I got home about the experience we both had aboard:

I spoke to a long-time Bayfield charter captain who had his sailboat on Stockton Island [where we were too] that fateful evening and to the Park Service Ranger standing on shore watching the mayhem. The charter captain agrees with you that the best policy is once on the hook to just ride out the storm, although in this case, he pulled the hook and headed back to Red Cliff Marina because his guests were no longer enjoying themselves. He was anchored in the bay just west of us and did not experience the winds we did, but he did experience the swells. He claims he saw a genuine waterspout and that the cyclone was centered off the north end of Madeline Island. His estimate of the winds were 80-100 mph and that agrees with the doppler radar in Duluth that recorded wind speeds of 100 mph in the vicinity. He pulled the hook around 7:15 pm (about 30 minutes before we did) so he did not see us leave but he felt that if we headed to Madeline, that we sailed into the teeth of the storm.

The Park Ranger on Stockton had her hands full helping other boats anchored in the same bay we were. One family jumped from their sailboat (anchored in about 5 feet of water) and waded to shore to sit out the blow. Another boat asked for assistance when a woman

onboard was thrown off the settee and broke her arm. A third sailboat reported that their skipper had suffered a mild concussion when his head struck a doorway and the crew felt he was in no condition to sail the boat. A fourth sailboat broke free of its anchor and collided with another sailboat, crushing the bow pulpit, before the skipper could start his engine and redeploy the anchor. The park ranger saw us pull the hook and head south and was amazed to watch most of our boat disappear occasionally as we fell into a trough. Based on watching our boat, the Grand Banks decided NOT to sail south for protection and instead drove into the crowded dock area and begged the sailboats there to throw him a line so he could raft up with them. This tactic served him well. The ranger reported that the swells did not seem to grow much larger after we left, but they did continue for at least an hour and a half after we left.

Some fun eh?  
Tom

To say that *Imagine* experienced no problems, structural or otherwise, would be an understatement. *Imagine*'s structure is very strong.

### Wooden Boat Scantlings

A wide assortment and many variations of wooden boat construction are covered in *The Elements of Boat Strength* Sn rule. Again, we don't have space to review them in detail, but boats built to this rule have proven very tough as well. One example of these is my *Summer Kyle/Belle Marie* tunnel-drive design. The first *Summer Kyle* design, *Belle Marie*, has over 30,000 miles under her keel, about a third of that offshore. Her owner reports she is solid as a rock and always has been. I've cruised aboard *Belle*, too. If you include her sister ships of various sizes from 43 to 76 feet, this is something like a combined 100,000-plus miles without a hint of a single structural problem. Most of these boat are wood epoxy sheathed with glass, almost exactly to the Sn rule. One was built in FRP to about the Sn rule and the 76-footer in aluminum to the Sn rule.



*Summer Kyle/Belle Marie*, photo Starke Jette

*Belle Marie* even T-boned a day marker at speed: Her owner is an experienced boater and an excellent navigator, but he was single-handing one day and had what was then a new WAAS GPS installed. He wasn't used to the accuracy. With no boats in sight or on the radar, he dashed down to make a quick sandwich while on autopilot. The boat was going just a bit faster than he estimated, and right as he came up to the wheelhouse, *Belle* smashed into the day marker that was the next waypoint at a full 9 knots, just to one side of the stem! There was no damage to the hull of any sort! Only the rubrail was cracked. The boat carried on with no problems. This is a STRONG boat!

**Summarizing the Sn Scantling Rule**

The goal of *The Elements of Boat Strength* and the Sn scantling rule it embodies was to provide an easy-to-apply method of generating scantlings that produce strong, sensible boat structures. You can see from the our discussion that it delivers exactly this for the boats of the size and type it covers, and it does so based on sound underlying engineering principles. I've been using this general approach (gradually more and more formalized) for nearly twenty years, in one form or another. The solid and long-lasting real boats built to this rule over the years have only increased my confidence in the Sn rule's utility.