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Small Craft Engineering: Structures

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SMALL CRAFT DESIGN

STRUCTURES

Peter A. Silvia

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I. INTRODUCTION

STATE OF THE ART

A look at the state of the art in small craft structural design today produces something of a mixed bag. There are a few examples of highly optimized structure in high speed craft, a lot of adequate but relatively heavy structures based on traditional scantlings, and a few inadequate designs resulting from lack of, or misapplication of, design principles. Standards for small craft structure exist for the traditional materials but are only occasionally applied. In some of the newer materials standards are inadequate or non-existent. A great deal of literature exists, even on ferro-cement, but much of it is misleading or not easily obtainable. There is no comprehensive text on small craft structures except for the chapter by Kenneth B. Spaulding, Jr. for the 1969 Small Craft Design course.

In the past, considerably more attention has been paid to the hydrodynamic and styling aspects of design. These are, after all, the principal interests of the small craft designer, who likes to consider himself something more of an artist than an engineer. A careful structural analysis is, at best, a 'drag'. Traditionally the builder has been the expert in materials and structure. The designer simply specified the material and a few basic scantlings and the builder constructed the boat as he always had. Materials selection has only recently begun to trouble the designer. Today a 'crazy' customer may even ask for a yacht design in concrete.

Our society is engulfed in a technological explosion from which boat design is not excepted. New materials and methods of fabrication are appearing daily. The small craft designer must be prepared to deal objectively with them. 'Objectively' is perhaps a key word. Far from being a science, small craft design is a mix of tradition, economics, expediency, prejudice, and not a little witchcraft. We must step back a few paces, view our problem in its proper perspective, and construct as scientific an approach as possible to its solution.

SCOPE AND APPROACH

This chapter will attempt to outline the entire structural design process from basic principles through preliminary and final design including materials comparison and selection, design criteria, structural design, structural details, and a discussion of characteristics and fabrication techniques for Ferro-Cement (F-C), Steel, and Wood. Aluminum and Fiberglass Reinforced Plastics (FRP) will be covered in separate chapters of the Small Craft Design course.

Design strength criteria will be established without reference to a specific material. This is a logical approach since the criteria simply reflect the loads to which the craft will be subjected, these being the same for craft of all materials. The basic analytical approach is independent of hull material. A detailed structural design will be outlined for a simple V-bottom box form.

The structural design process outlined in this chapter represents a hypothetical design started from scratch. In practice, particularly in the preliminary stages, the designer will short circuit some of these procedures based on experience or comparison to other designs. Conversely in the case of an expensive, high performance, weight critical craft it becomes cost effective to carry the structural analysis much further, approaching aircraft design procedures.

Attention is directed to the bibliography attached to this chapter containing some 250 entries. Reference to the bibliography throughout this chapter is by number in parentheses, i.e. (C-3). The designer will be well advised to assemble and maintain a comprehensive and current personal file.

COMMON SENSE

Before commencing on the mechanical process of analyzing a structure it seems appropriate to emphasize the important element of common sense. In making the initial structural layout every effort should be made to integrate the basic arrangement of the craft with the structural arrangement. Wherever possible joiner work should serve as structure and vice-versa. Even the basic styling elements can be integrated with the structure. For example knuckles and fairings molded into FRP craft are often stiffeners for hull or cabin as well as styling devices. Structure should be continuous. Hard spots and discontinuities always spell trouble. Redundancy of structure should be avoided. With a little experience the eye can follow the stresses through a structure just the way a skilled designer visualizes the water flow around his faired lines. At times a more sound structural design may result from a cultivated instinct for the subject than from reams of calculations.

II. CRITERIA

GENERAL DISCUSSION

Design criteria would ultimately include all the guidelines observed by the designer in developing a quantification of the forces to which man and nature subject a craft throughout its service life. Some actual forces: waves, impacts, groundings, and the like, are dynamic and of such varying amplitudes that they defy representation in terms of simple static design loads. Thus many of the design loads listed here are somewhat empirical in nature. They reflect successful designs or tradition or 'best guess' estimates of equivalent static loads. They should be used as guidelines rather than rigid rules. Obviously they will vary with the application. For example, designing a houseboat and a pilot boat to the same criteria would be nonsensical. Hopefully future research and test programs will enable us both to develop criteria more representative of actual loads and to better predict dynamic response of the structure.

It should be noted here that many aspects of plank-on-frame wooden construction lie outside the logic of an engineering approach. Uncertainties in fastener effeciency, low joint strength except in laminated members, and unique requirements such as that planking be thick enough to properly take caulking all combine to make historically derived scantling tables the most satisfactory guide to this type structure (M-20, W-13, 29, 35, 46).

DYNAMIC/STATIC LOADS

With a few exceptions small craft design loads are all dynamic. The duration of the load varies from milliseconds to seconds depending on the load. Procedures do exist, and are used extensively in aircraft design, for the design of structures under dynamic load. A 'dynamic load factor' is calculated for a given structural configuration and material. The product of the dynamic load factor and the dynamic load gives the equivalent static load. (The equivalent static load produces the same strain in the structure as the dynamic load.) For several reasons this approach is rarely used in small craft design: complexity and expense of calculation, lack of structural test information required to determine dynamic load factors, and ignorance of the actual magnitude and duration of the dynamic loads.

In general, for design of small craft, a maximum expected load is estimated (hydrostatic, deck load, etc.) and the structure designed as if that load were static. Where a certain "g" loading (acceleration) is expected the load is simply multiplied by the number of "g"s and a static design conducted. Sometimes this "g" factor is misleadingly termed a factor of safety.

It is important to remember in consideration of this dynamic/static problem that calculation of local scantlings using a static equivalent of the expected dynamic load is only part of the solution. The dynamic response of the structure must sometimes also be determined, a process which may necessitate full scale structural testing. A case in point is the design of Navy small craft to resist mine explosions. The exact nature of the pressure waves from a given mine are known but effective methods of structural analysis are still lacking. Or, more commonly, the hull shell over propellers may require special consideration, particularly in vibration-sensitive materials.

FACTORS OF SAFETY

The factor of safety is something of an ignorance factor. The more that is known about loadings and structural response the lower the factor of safety can be. Factors of safety have been used or misused in small craft design in every conceivable manner. They may account for "g" loads, for extreme or unexpected loads, for poor quality control in fabrication, for variations in basic material weld strengths, or for design errors. Many tables or design data sheets have built-in safety factors. Scantling rules imposed by regulatory agencies specify factors of safety which may appear arbitrary. Under these conditions generalizations are dangerous and the best advice is to consider each use of a factor of safety on a case basis. Always determine what factor of safety is being used and why it is being used.

Also worthy of mention here is the question of ultimate versus yield strength. Metals have clearly defined yield strengths.

Fiberglass, wood and ferro-cement exhibit certain yield characteristics but do not have discernible yield points. Note should be taken of whether factors of safety apply to ultimate or yield strengths.

Recommended factors of safety to be used with the design criteria presented in this chapter are presented later in this section.

DURABILITY

Strength criteria have been defined as a quantification of the forces on a craft 'throughout its service life'. In fact, the criteria developed in this section consider only single load applications. The time dimension will be considered under III. DESIGN PROCEDURE and the materials section. Allowances for corrosion, fatigue, and creep must be considered in final selection of design stresses.

STRENGTH vs DEFLECTION

Deflection limits will be listed later in this section. In many cases they may be the governing criteria. Their selection is somewhat arbitrary and should really be considered on a case basis. Where joint fatigue strength, local interferences and overall structural rigidity are not compromised, deflection limits may well be relaxed.

OTHER STRENGTH RELATED CONSIDERATIONS

No local impact criteria will be listed but the problems cannot be ignored and will be further discussed in the materials section. A material may meet all other structural requirements but be vulnerable to puncture type failures.

Vibration will be discussed later in this section where an approximate method of determining natural frequencies is presented.

SCANTLING RULES

The design criteria developed in this chapter DO NOT reflect the requirements of any scantling rules such as those of the classification societies. Where design to those rules is required, then they must take precedence over the criteria presented herein.

STRENGTH CRITERIA

HULL BOTTOM (Planing Craft)

The problem of the slamming loads developed in the bottom panels of planing craft will be considered first, as purely displacement craft pose a relatively simpler case. Several references are cited: Heller-Jasper (M-12) and DuCane (M-8), both Transactions of the Royal Institution of Naval Architects (1960 and 1956 respectively), Danahy (M-5) (SNAME, May, 1967), and the Gibbs & Cox FRP manual (F-35).

The Heller-Jasper paper and a predecessor paper by Mr. Jasper alone (M-14) have been the authoritative references since 1949. These works develop a complete design procedure from experimental data taken from full scale rough water tests of the 75 ft. YP 110 (ex PT-8). Dynamic structural response is considered. The DuCane paper presents actual test data from a 68 ft. high speed launch. The Gibbs & Cox manual and the Danahy paper present shortcut design procedures. (The Danahy paper is stated to be applicable only to craft with design speeds over 30 knots.) The Heller-Jasper design procedure is somewhat complex and depends upon experimental determination of craft accelerations.

The Danahy and Gibbs & Cox procedures are much simplified. For example: given a 40 ft. waterline length craft with a design speed of 30 knots

From Danahy: Design Pressure (sta. 2 1/2 to 5) = $Kv^2/100$
$K = 2$ Design pressure = 18 psi.

From Gibbs & Cox (Nomograph on page 2-16):
Design pressure = 19.5 psi.

The reader is also referred to the chapter contributed by Mr. Savitsky for the latest thinking in the prediction of slamming pressures.

Danahy suggests that plating, longitudinals, and transverses be designed for the static pressure (p = 18) with a safety factor of 1.5 on yield or 2.0 on ultimate, whichever gives the lowest stress level. He provides a graph for reduction of pressure forward of station 2 1/2 and aft of station 5. Gibbs & Cox provides graphs for reduction factors based on Jasper's work (M-14) for design of plating, transverses, and longitudinals, to be applied to the design pressure from the nomograph (p = 19.5). The local hydrostatic pressure is added. A safety factor of 1.5 to the ultimate wet strength of the fiberglass is suggested.

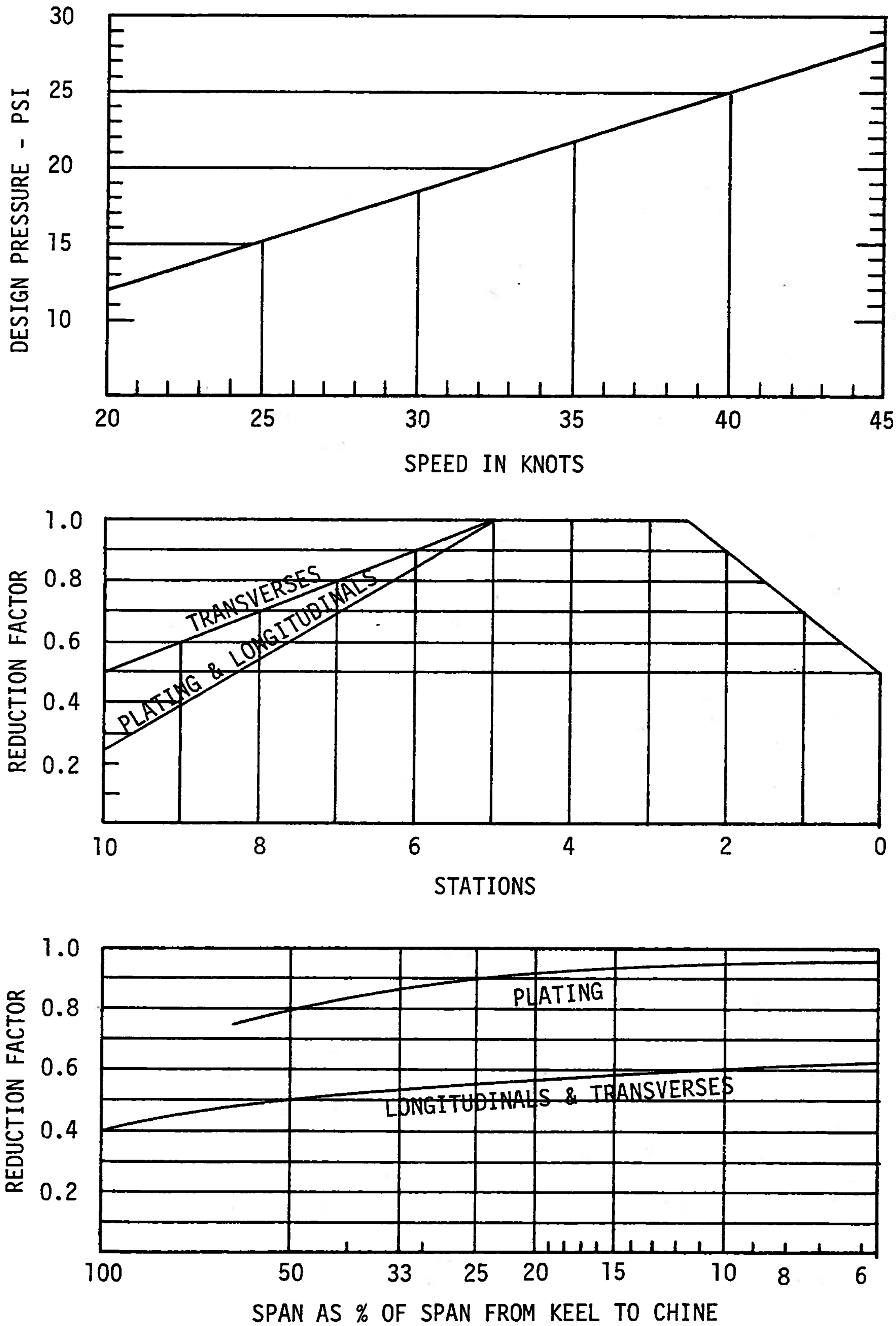


FIGURE I - PLANING BOTTOM DESIGN CRITERIA

There is a good deal of controversy in the area of the reduction factors--the percentages of the maximum design pressure that should be assumed to be acting respectively on the plating, longitudinal stringers and transverse frames. Because maximum slamming pressures are very localized, large plating panels or stiffeners supporting large areas of plating can be designed to some lower average pressure. The larger the area influencing the member, the lower the average load will be. Mr. Kenneth B. Spaulding, Jr., who first presented this small craft structures chapter in 1969, and his associates at Navy concluded after reviewing the original YP 110 test data and data from other tests that the reduction factors in references (M-12) and (M-14) were improperly applied. And in fact a careful reading of (M-12) leaves some doubt as to whether the recommended application of its reduction factors is consistent with the reasoning presented in their development.

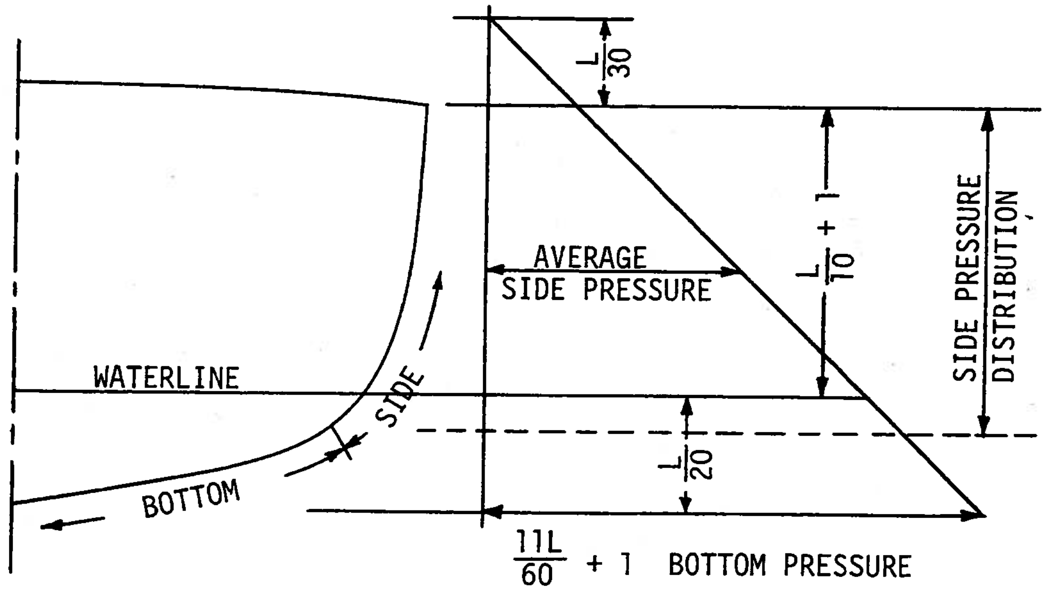
It is this writer's contention that the Heller-Jasper reduction factors are applied to the wrong members. If the Transverse factor were applied to plating and longitudinals and if the Longitudinal factor were applied to transverses, this would be more consistent with the logic of the paper. The net result would be similar to that of Mr. Spaulding's approach. However, it must be admitted that 22 years' use of the Heller-Jasper approach has not produced a mass of structural calamities. The conclusion here might be that both approaches are overly conservative in one way or another. Several designers, including this writer, concerned with high speed craft have come to exactly this conclusion.

Until money and time is found to conduct an exhaustive strain gage investigation of structural response to slamming loads, approximations will continue to be used. The criteria and reduction factors of Figure 1 are presented for guidance. They are an amalgam of Mr. Spaulding's work, this writer's interpretation of the Heller-Jasper information and experience, and factors and guidelines from several other sources. It is considered that this simplification may ultimately be as accurate as the more sophisticated approaches because of the degree of uncertainty in determining the various parameters in the more complex approaches.

HULL BOTTOM (Displacement Craft)

For non-planing craft a hydrostatic head is generally assumed. Recommended heads range from six inches (F-35) to eight feet (F-72) above the deck at side with a usual safety factor of four.

Figure 2 presents curves of recommended pressures. They are based on the following reasoning: The freeboard and draft of an average craft can be approximated by (L/10 + 1) and L/20



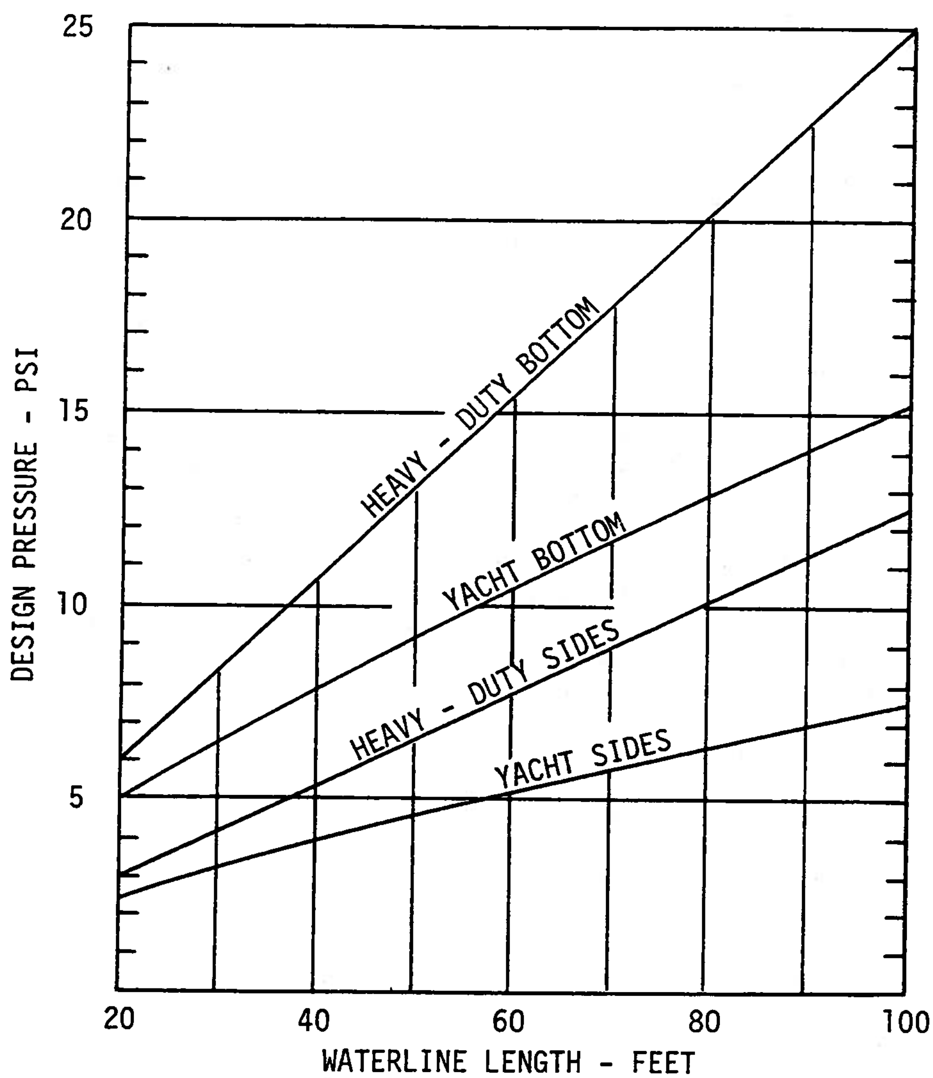


FIGURE 2 - DISPLACEMENT HULL LOADING

respectively. For workboats and ocean-going craft, an additional head of L/30 is recommended. This results in a total assumed head on the bottom of (11L/60 + 1) feet. Values so derived for various lengths were then reduced to psi and multiplied by 2.86 to yield an overall safety factor of four when used with the general safety factors recommended later in this section. The yacht curve assumes more sheltered conditions.

In spite of a lack of historical precedent, this writer believes that the interior structure of a displacement craft should be designed under a lower load than the shell in a similar manner to that of a planing craft. The commonly accepted safety factor of four is largely intended to ensure that the inevitable bumps and knocks which the craft will encounter will not cause excessive damage. These impacts are limited in area in the same way that slamming impacts have been determined to be in planing craft. Therefore, by the same logic that produced reduction factors for planing craft structure, framing in displacement craft should also be designed to something less than full shell pressure. A factor of 0.75 is suggested for consideration.

HULL SIDES (Planing and Displacement Craft)

Most references specify the same hydrostatic head assumption for the sides as for a displacement bottom. This is the equivalent of using approximately one-half the assumed bottom pressure as shown in Figure 2. Minimum side thickness should be no less than 3/4 bottom thickness. Side thickness for the forward 25 percent of length of workboats and ocean-going craft should approach full bottom thickness. Full bottom thickness should be carried above the turn of the bilge and the waterline for round bilged craft for protection against floating debris.

WEATHER DECKS

Reference (F-72) recommends 250 psf on exposed decks or a concentrated load of 100 pounds per inch midway between frames, whichever is more severe. Reference (M-5) recommends 600 psf for weather decks forward of amidships, 300 psf aft. Reference (F-35) suggests a water head of two feet for pleasure boats, increased for workboats, or a man-weight placed at mid-span. All the foregoing recommend a safety factor of 4.

It is the opinion of this writer that these combinations of loads and safety factors are overly conservative. For most craft, a load of 3 psi with the safety factors prescribed later in this section is recommended for the stiffeners supporting the deck. Workboats in very severe service might be designed to 4.5 psi. The plating itself should be designed using an approximation of a man's weight similar to assuming a 100 pound load centered between the supports on a one-inch strip of plating.

Cargo decks will have their own governing criteria such as expected cargo density and wheel footprint loads. Note the comments on "real loads" in the discussion on safety factors later in this section.

INTERIOR DECKS

Reference (F-72) recommends 100 psf in living and control spaces. Reference (F-35) recommends 40 psf for pleasure craft and 60 psf for workboats, doubled where "g" loads are expected. Both references use a safety factor of four.

1.5 psi is recommended for craft exceeding 20 knots design speed, 1.1 psi for displacement craft. A one inch wide strip of deck plating should be capable of supporting 75 pounds concentrated at the center of the span.

BULKHEADS

For watertight bulkheads a hydrostatic head to one foot above the uppermost continuous deck should be applied.

SUPERSTRUCTURE

Reference (F-72) recommends a head of water of four feet at the main deck tapering to 30 psf wind load, or 30 pounds per inch at mid span for house front and sides, and 100 psf for exterior decks, all at a safety factor of four. Reference (M-5) suggests 750 psf for front, 300 psf for sides, and 150 psf for the superstructure top.

For the house top, sides and rear, 1.5 psi is recommended. In addition, a one inch strip of house top plating should be capable of supporting 75 pounds concentrated at the center of the span. Front loading should be 3.5 psi. Yachts may be designed to 2/3 these values.

HULL GIRDER

Hull girder loading in waves as applied in ship design is not normally a small craft design criterion. The stresses resulting from wave loadings in craft under 100 feet in length do not approach design working stresses. The exception would be a craft with exceptionally low midship section modulus resulting, for example, from lack of continuous longitudinal members and/or large cut-outs or discontinuities in decks or sides. There are, however, several loading conditions which stress the craft as a girder to a degree far more severe than any wave loading. They are:

1. Hoisting or blocking condition - The craft is supported at two hoisting or blocking points.

2. Hull slamming - Accelerations above 10 g's have been measured on small craft driven at high speeds in a seaway. These forces are reflected in a girder loading on the craft. A similar condition occurs when a craft grounds at high speed.

3. Underwater explosions - This is an extreme design condition only encountered in military craft but it is interesting to note that in addition to extreme local loads, the entire craft is subjected to a "whipping" action which may fail the craft as a girder.

4. Hull racking - No quantitative criteria are offered for this loading but a common sense approach is dictated. Racking is resisted by bulkheads and decks. A craft lacking this structure or its equivalent box type stiffening may develop hull racking though it meets all other design requirements.

Discounting the case of underwater explosion, it is suggested that a craft which is expected to be hoisted or blocked at two points, or slammed at high speeds be calculated for resistance to a bending moment equivalent to twice the craft weight acting at its center of gravity with the craft assumed supported at two appropriate points near the bow and stern. In the slamming case, the bending moment stress should be superposed on the stresses calculated according to the hull bottom and deck criteria. More rigorous methods for approximating bending due to slamming are presented in references (A-31) and (M-12). These methods depend upon knowing the accelerations of the craft in a seaway.

MISCELLANEOUS LOADS

Gunwale load - Reference (F-35), the Gibbs & Cox manual, suggests that, particularly for smaller craft, gunwale strength be checked by simulating the boat on its side resting on a single point midway in the longest span between gunwale supports. Obviously, as craft size increases, this becomes an unreasonable criterion. Reference (A-31), "Aluminum Boats" by Kaiser, recommends a load equal to one third the craft weight. This seems reasonable for boats larger than 20 feet.

Docking and Grounding loads - These are essentially keel loads although bilge blocks might be considered in the same manner if their location is known. It is recommended that the craft be considered at two times the full load displacement resting on a number of keel blocks equal to (1 + L/20).

FACTORS OF SAFETY

The suggested factor of safety for application to all the foregoing strength criteria based on assumed loading is 1.1 to yield strength or 1.4 to ultimate strength, whichever gives the lower stress level. This is based on two conditions:

1. That the assumed loads are truly the MAXIMUM expected loads, including "g" loadings.

2. That the design stresses assumed for each material are truly the MINIMUM strength which may be expected. For example, the design stresses should already have been reduced for fatigue, creep, welding, etc. before the above recommended safety factors are applied.

Given the above two conditions, higher factors of safety cannot be justified. If higher loads are expected, then the assumed load should be increased. If further reductions in material properties are expected, the design stresses should be reduced.

Real loads such as are imposed by rigging, machinery foundations, or well defined cargo should be protected with safety factors of 4 against ultimate or 3 against yield. Critical loads such as are imposed by hoisting fittings may require even higher factors.

DEFLECTION LIMITS

In certain cases, particularly with low modulus FRP, deflection rather than stress is expected to control the design. References (F-35) and (F-72) suggest a limit of 1/200 of the span for plating or plating/stiffener combinations. This is a somewhat arbitrary limit, and under extreme dynamic loads deflections would be expected to exceed this value. It may be primarily a psychological factor as the owner may be dismayed to see his deck or hull flexing half an inch even if the structure is not jeopardized. Structural considerations should be:

1. Do deflections exceed clearances between the structure and equipment or other structural members?

2. Will extreme deflections tend to induce joint failure or fatigue at the edges of the deflecting panel?

3. Do extreme panel deflections jeopardize stiffness or buckling stability of the entire structure?

VIBRATION

Destructive vibrations may be set up in a structural part because its natural frequency coincides with a frequency produced by the engine or propeller or some other piece of machinery. Engine firing frequency (RPM x number of cylinders/60 for two-stroke cycle engines) or propeller blade rate (Shaft RPM x number of propeller blades/60) are the most common exciting frequencies transmitted to boat structure. Engine vibrations can be alleviated through use of resilient mounts and foundations rigid enough that their natural frequency will be above that of the engine.

However, blade rate vibration working on the shell panels in the vicinity of the propeller can be very destructive. Reference (A-31) suggests checking the natural frequency of this structure with the formula: $F = 3.55/\sqrt{D}$ where F is the approximate natural frequency and D is the deflection in inches of the structure under the influence of the ordinary (NOT maximum expected) hydrostatic or planing pressure. The structure should be adjusted so that F is well clear of the planned operating range of the engine. For a planing boat, the local pressure used in the calculation of the deflection for vibration purposes can be taken as twice the at-rest hydrostatic head. In fatigue sensitive materials it is not necessary for the natural frequency of the structure to be near the normal operating range in order for failures to occur. As much propeller tip clearance as possible and extensive "egg-crating" and/or locally thicker shell plating is strongly recommended for such materials.

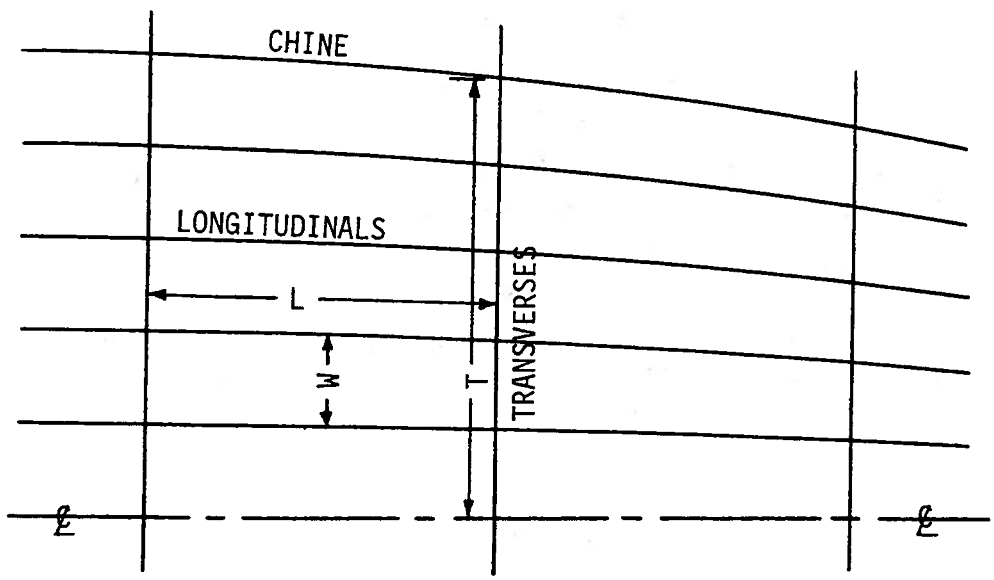
III. DESIGN PROCEDURE

Structural design is an iterative process. For example, in design of the bottom structure assumption of the plating thickness will fix the stiffener spacing. With fixed stiffener spacing, assumption of a transverse spacing fixes the section modulus of the longitudinals and so forth. We have several interdependent variables. To optimize the structure (that is to obtain the lightest structure which will carry the design load) we must run through a series of parametric studies fixing one or more variables at a time until the optimum combination "falls out". On a computer this is a rapid process but, of course, the average designer could not justify this expense. In practice two or three trys with each combination of variables will show a trend and lead to an essentially optimized structure. The point here is that it is not generally acceptable to simply run once through the structure and use these results. Though an adequate structure would result, it would not likely be efficient. Common sense must, however, prevail.

In a small working yard, the designer often has to optimize his structure around the plates and shapes that happen to be at hand. In most cases optimization should not be pursued to the point where varieties of plate thicknesses and numbers of shape sizes gets out of hand, or the slight increase in theoretical efficiency will be outweighed by construction costs. In the example to follow the process is not iterated. A single pass through the structure is made as if an existing design were being checked. This will illustrate the basic method of calculation.

STRUCTURAL DESIGN

HULL BOTTOM



W = WIDTH OF THE PLATING PANEL
L = LENGTH OF THE LONGITUDINAL
T = TOTAL SPAN OF TRANSVERSES

FIGURE 3 - TYPICAL BOTTOM IMPACT AREA FROM A 30 KNOT PLANING BOAT - BETWEEN FRAMES 2 1/2 AND 5

Plating

Effective Pressure - For the example shown in Figure 3 the design pressure from the upper graph of Figure 1 equals 18.5 PSI. In the impact area between stations 2 1/2 and 5 the reduction factor for location in the boat from the middle graph of Figure 1 is 1.0. Since there are four longitudinals between chine and keel, the width (W) of each plating panel is 20% of the total span from chine to keel. Therefore, from the lower graph of Figure 1 the span reduction factor is 0.92. The average pressure on the plating panel is therefore:

$$P = 18.5 \times 1.0 \times 0.92 = 17 \text{ PSI}$$

Beam Analogy - Assume a one inch wide strip of plating in simple beam loading with a uniform load of P lbs per inch. The maximum moment and maximum stress occur at the longitudinal supports. This maximum moment equals $PW^2/12$. Since stress equals Moment/Section Modulus and Section Modulus of a rectangle equals $bt^2/6$ and in this case $b = 1"$:

$$(\text{plating thickness})^2 = t^2 = \frac{6M}{S} = \frac{PW^2}{2S} \qquad (1)$$

Before thickness can be determined, an allowable stress must be chosen. If the example boat were built of 5086 aluminum alloy, H116 or H117 temper, then the ultimate stress could be 40 KSI and the yield stress could be 28 KSI if the impact load were applied only once. However, a planing bottom will be subjected to thousands of significant impacts during its life time. From Figure 4, the "book" ultimate stresses should be reduced to about one half for aluminum and steel or one third for fiberglass in order to account for fatigue. (For FRP, flexural ultimate would be the "book" strength used for plating calculations.)

Working from the "book" stress of 40 KSI and using the factor of safety of 1.4 against ultimate the allowable stress for 5086-H116 or H117 becomes:

$$S = 40{,}000 \times 0.5/1.4 = 14{,}300 \text{ PSI}$$

Using this number the thickness formula (1) can be reduced for this case as follows:

$$t^2 = \frac{17\ W^2}{2 \times 14{,}300}$$

or:

$$t = W/41$$

By assigning a value to either variable the other can be determined. If, for example in Figure 3, t equals 0.25 inch plate,

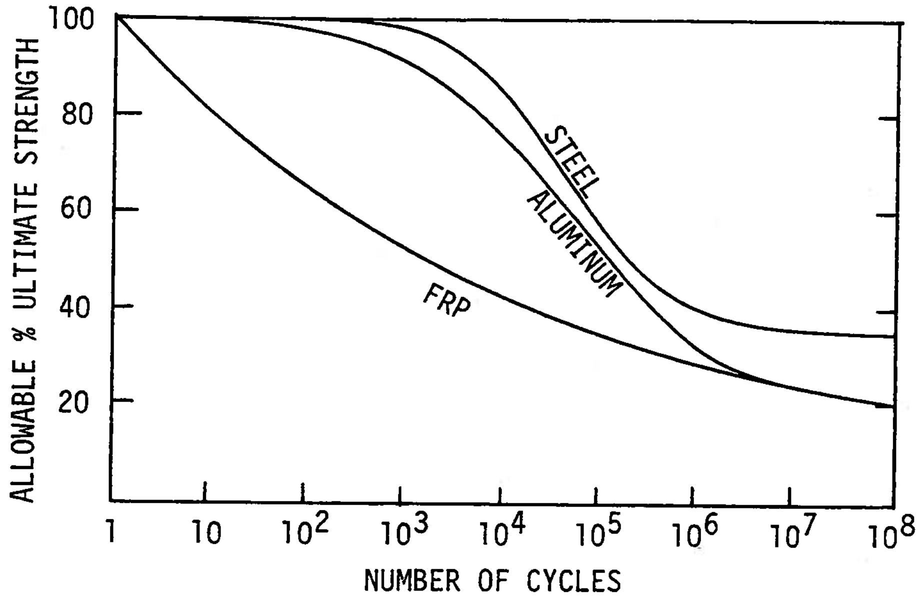


FIGURE 4 - TYPICAL FATIGUE CURVES

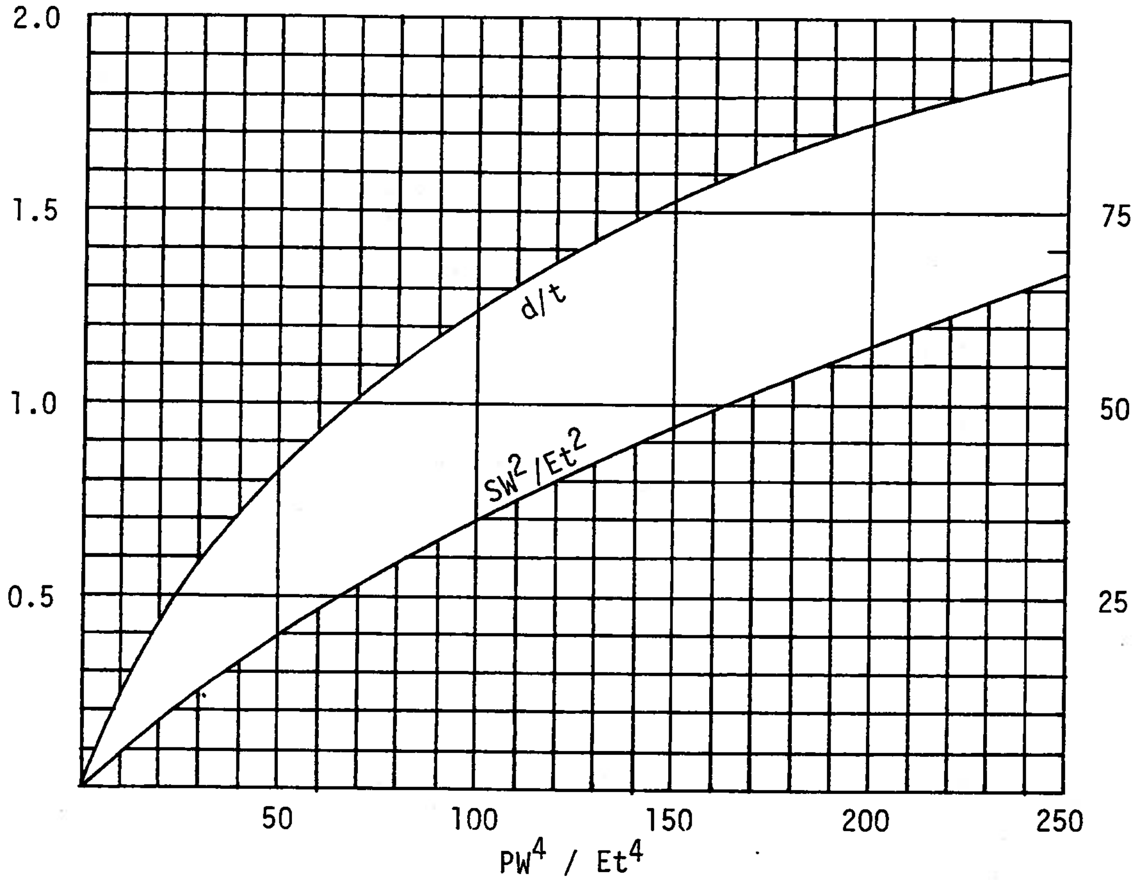
then W is 10.25 inches. In yacht service where the craft will not see many hours of rough water each year, the span might be allowed to increase toward 11 inches. In very severe service, shading toward 10 inches might be appropriate.

Deflections must also be considered. For a rectangular beam of unit width:

$$\text{plating deflection} = d = \frac{PW^4}{32\ Et^3} \qquad (2)$$

With W = 10.25 and t = 0.25 and E = 10.3 x 10^6, deflection is 0.036 inches. This is less than W/200 and is therefore satisfactory.

<u>Membrane Stress</u> - When plating spans are very large, the deflection may exceed one-half the plate thickness. In such a case, appreciable membrane loading begins to develop and the simple beam formula is no longer accurate. (It will produce an overly conservative design.) In membrane loading, tensile stresses predominate over compressive. The extreme example is the case of a cable suspended entirely in tension from fixed end points. In practice, allowing high deflections with resultant membrane stresses actually allows the plating to carry a greater load for a given allowable stress level. The deflections associated with membrane loading generally exceed



P = AVERAGE PRESSURE
W = WIDTH OF PLATING PANEL BETWEEN LONGITUDINALS
t = PLATING THICKNESS
E = FLEXURAL MODULUS OF ELASTICITY
d = DEFLECTION AT MID-SPAN
S = MAXIMUM STRESS

CALCULATE PW^4/Et^4 AND SOLVE FOR S AND d

FROM ROARK - "FORMULAS FOR STRESS AND STRAIN" (M-17)

FIGURE 5 - PLATING MEMBRANE STRESS

deflection limits of 1/200 or 1/100 of span but as mentioned in the discussion of deflection limits, this may be acceptable.

For the procedure for calculating membrane stresses see Figure 5. This figure is developed from a table on page 246 of (M-17), Roark's "Formulas for Stress and Strain", and represents the case of a rectangular plate held and fixed at the edges and under a uniform load. The span between longitudinals (W) is assumed to be less than 2/3 the span between the transverses (L).

Longitudinals

Effective Pressure - A stringer located between stations 2 1/2 and 5 will have a reduction factor of 1.0 from the middle graph of Figure 1. A stringer carries the load from a strip of plating W inches wide. In the example problem of Figure 3, W is 20 percent of the span between keel and chine. Therefore, from the lower graph of Figure 1, the span reduction factor for these longitudinals is 0.56. The design pressure remains 18.5 PSI. Thus the average pressure is:

$$P = 18.5 \times 1.0 \times 0.56 = 10.36 \text{ PSI}$$

Each inch of length of the longitudinal carries a load (p) equal to PW or, in this case: $p = 10.36 \times 10.25 = 106$ pounds per inch.

Beam Calculation - The plating/stiffener combination may be considered as a simple beam with a uniform load. To determine the number of thicknesses of plating acting with the stiffener, Heller-Jasper (M-12) suggests the formula: effective plating width = $2t\sqrt{E/\text{yield strength}}$. For 5086 aluminum this works out to 38t. Use the lesser of this value or W.

There is some question as to what end fixity should be assumed. If the effective load were continuous beyond each support, full fixity would be logical. This assumption is recommended in the case of displacement hulls. This is not the case for slamming, however, as the adjacent longitudinal spans will carry lesser loads since the maximum slamming loads are limited in area. Following are the common formulas for uniformly loaded beams:

Case	M_{max}	d_{max}
Full Fixity - Both Ends	$\frac{pL^2}{12}$	$\frac{pL^4}{384EI}$
One End Fixed, One End Simply Supported	$\frac{pL^2}{8}$	$\frac{(2.1)pL^4}{384\ EI}$

Both Ends Simply Supported	$\frac{pL^2}{8}$	$\frac{5pL^4}{384EI}$

It can be shown that in the simplified case shown in Figure 6 the maximum bending moment at center or ends does not approach $pL^2/12$ until p_2 is nearly 3/4 the magnitude of p_1.

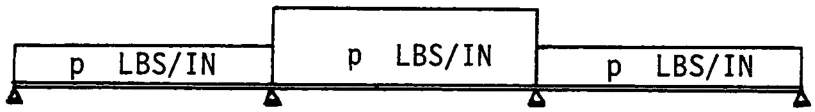


FIGURE 6 - SIMPLIFIED STRINGER LOADING DIAGRAM

It is therefore suggested that the stiffener/plating beam be checked at ends and center for

$$M_{max} = \frac{pL^2}{12} \qquad (3)$$

It is necessary to check for both tension and compression at both ends and center when the material used does not have equal tensile and compressive allowable stresses since the loads are reversed from center to ends (tension to compression).

For deflection

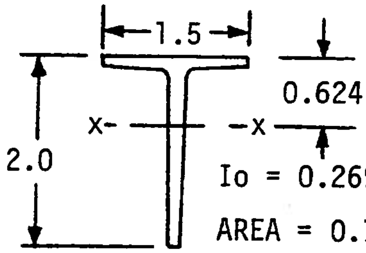
$$d_{max} = \frac{3pL^4}{384EI} \qquad (4)$$

is suggested as a worst case where $p_2 = 0$.

Example - Assume the longitudinal stringers in Figure 3 are as illustrated in Figure 7. In that figure, Io is the moment of inertia of each component about its own neutral axis (x-x). The width of plate acting with the tee is 38t or 9.5 inches for 0.25 inch thick plate. When dealing with shapes whose characteristics are tabulated in the aluminum or steel handbooks, it is most convenient to take the trial neutral axis at the neutral axis of the stringer.

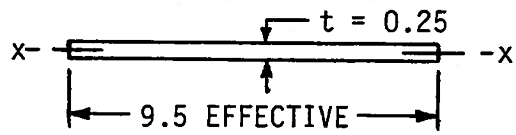
Recalling that S = M/Z and using the 14,300 PSI previously chosen as the allowable stress, M = 14,300 x 0.863 = 12,340 inch pounds. From equation (3), $12,340 = 106L^2/12$. Thus L = 37.4 inches.

This problem can be worked in the other direction with an assumed L and solving by trial and error for the plating/stiffener combination that provides the required Z. Obviously a designer is wise to file every plating/stiffener calculation that he does.



Io = 0.269 IN^4

AREA = 0.73 IN^2



Io = 0.012 IN^4

AREA = 2.37 IN^2

AREA	DIST OF LOCAL NEUTRAL AXIS TO ASSUMED AXIS	ADn	ADn^2	Io
0.73	0.0	0.0	0.0	0.269
2.37	-1.501	-3.56	5.34	0.012
3.10		-3.56	5.34	0.281
			+0.28	
			5.62	
			-4.09 (ALWAYS NEG)	
			1.53 = I	

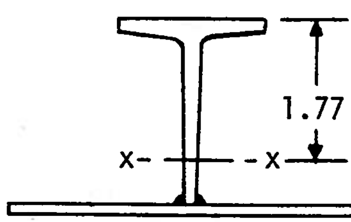
-3.56/3.10 = -1.148

CORRECTION TO ACTUAL AXIS:
3.56 x 1.148 = 4.09

DISTANCE FROM ASSUMED NEUTRAL AXIS TO ACTUAL NEUTRAL AXIS =
-1.148 (NEGATIVE INDICATES BELOW ASSUMED AXIS)

DISTANCE FROM TOP OF T TO NEUTRAL AXIS =
0.624 + 1.148 = 1.772 Z_{top} = 1.53/1.772 = 0.863 IN^3

DISTANCE FROM BOTTOM OF PLATE TO NEUTRAL AXIS =
2.00 + 0.25 - 1.77 = 0.48 Z_b = 1.53/0.48 = 3.19 IN^3



I = 1.53 IN^4

Z_t = 0.863 IN^3

Z_b = 3.19 IN^3

FIGURE 7 - TYPICAL PLATING/STIFFENER CALCULATION

From equation (4), deflection for this example is $(3 \times 106 \times 37.4^4)/(384 \times 10.3 \times 10^6 \times 1.53) = 0.103$ inches which is less than L/200.

Transverses

Effective Pressure - In the Figure 3 example, the transverse is supported only at the keel and chine. Therefore its span reduction factor from the lower graph of Figure 1 is 0.40. The design pressure and location reduction factor remain 18.5 PSI and 1.0 respectively. Therefore the average pressure on the transverse is

$$P = 18.5 \times 1.0 \times 0.4 = 7.4 \text{ PSI}$$

The transverse carries the load from a strip of plating L inches wide. In the Figure 3 example, L is 37.4 inches. Therefore, the transverse supports a load (p) equal to PL or, in this case: $p = 7.4 \times 37.4 = 277$ pounds per inch of length.

Beam Calculation - The transverse frame is calculated as a simple beam with uniform load. Since the actual condition is one of partial end fixity it is suggested that the moment and deflection formulas used be the same as those for the calculation of the longitudinals (Formulas 3 and 4). As in the longitudinal calculation, the transverse should be checked at ends and center for both compressive and tensile strengths if the material used has different allowable stresses for compression and tension.

Section Modulus - In calculating the section modulus of the transverse, if it is structurally connected to the hull shell continuously (Figure 8A) then, as with the longitudinals $2t\sqrt{E/\text{yield strength}}$ width of plate may be considered as acting with the frame. If the transverse is of the "floating" type, i.e. crossing the tops of the longitudinals (figure 8B), no contribution of the shell to the section modulus should be considered. For notched systems, i.e. connecting to the shell only intermittently between longitudinals (Figure 9), the shell might be allowed but the part of the transverse web below the tops of the longitudinals cannot be included in the combined section modulus. For these systems, shear connection between the shell and frame may be a problem.

Structural Connections - A check should be made at this point of the load transfer between longitudinals and web frames of bulkheads. Bearing strengths and/or shear strengths through the connection must be adequate to carry the entire load in the longitudinal. A typical failure from overloading this connection is the buckling of a bulkhead over a longitudinal where the bulkhead stiffeners were not aligned with the longitudinals.

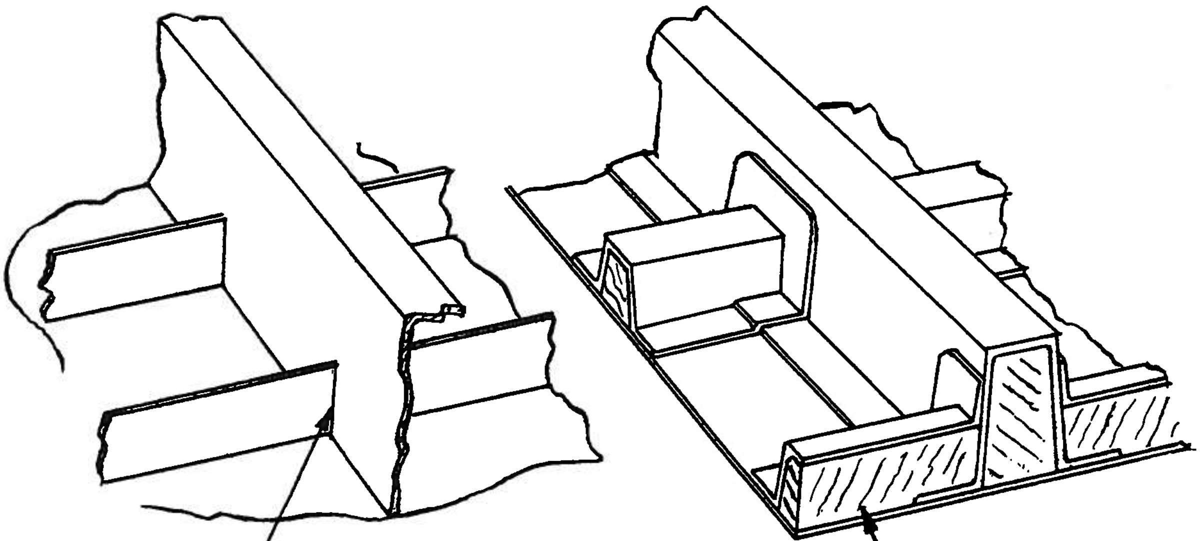


FIGURE 8A - TRANSVERSES AGAINST SHELL

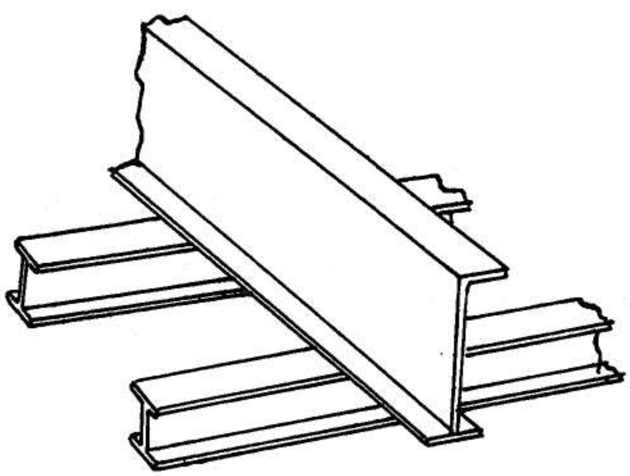


FIGURE 8B -"FLOATING" FRAME

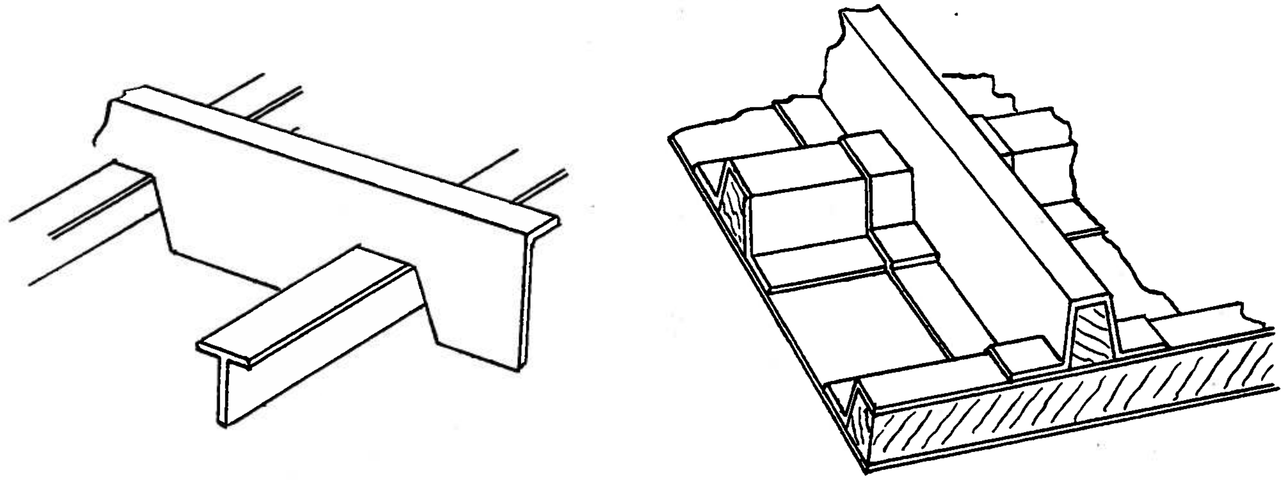


FIGURE 9 - TYPICAL NOTCHED FRAME

Displacement Bottom

The methods of determining plating and stiffener sizes for a displacement craft are the same as those for a planing craft except that the design pressures are taken from Figure 2 rather than from Figure 1, and reduction factors are not generally used.

A transverse frame will be calculated as an example, more to illustrate the method of handling the relatively complicated notched frame than to present any new basic calculation methods.

Consider a fiberglass frame which is penetrated by continuous longitudinal stringers as illustrated in Figure 9: If this frame is in a 60 ft. yacht, then its design pressure from Figure 2 is 10.5 PSI. In accordance with this writer's preference, an 0.75 reduction factor for interior stiffeners will reduce the average pressure P to 7.9 PSI. Let L = 48 inches and T = 75 inches (see Figure 3 for locations of L and T):

$$p = PL = 7.9 \times 48 = 379 \text{ pounds per inch}$$

$$M = 379 \times 75^2/12 = 178{,}000 \text{ inch pounds}$$

Taking the material to be average quality all woven roving laminate (at 0.04 inches thickness per ply of 24 ounce woven roving) then ultimate compressive stress is 26,000 PSI and ultimate tensile stress is 30,000 PSI. The compressive stress will govern. Compressive modulus is 2.0×10^6. With the safety factor of 1.4 against ultimate, the allowable compressive stress is 26,000/1.4 = 18,600 PSI. Therefore, the minimum section modulus which will satisfy stress requirements is:

$$Z_{min} = 178{,}000/18{,}600 = 9.55 \text{ in}^3$$

Figure 10 illustrates the calculation method. Since the modulus of elasticity of fiberglass is very low, the effective width of shell calculated according to the formula previously presented will be very narrow. It is recommended that the width of shell spanned by the toes of the bonding angles (12 inches in the Figure 10 example) be assumed effective.

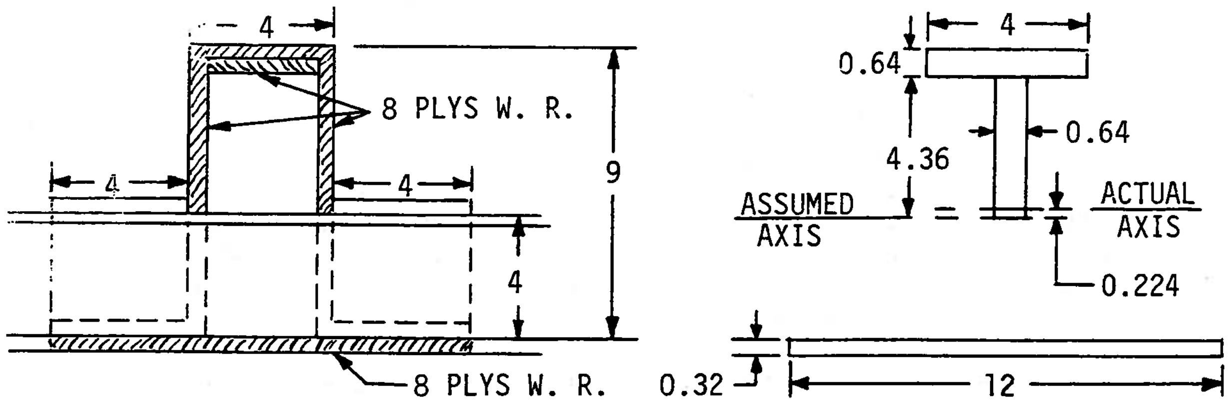
The section modulus of the example frame is considerably above the minimum necessary to carry the compressive load. However, note that the deflection of this frame is 0.336 inches--only slightly less than T/200 which for this example is 0.375 inches. This is a clear demonstration of why deflection must be carefully provided for in designs for materials having a low modulus of elasticity.

HULL SIDES

For hull sides a loading equivalent to one half that on the bottom of a displacement craft of equal length is suggested in the design criteria. All four formulas previously given apply. Care should be taken to ensure that topside plating is not reduced below a thickness which will effectively resist normal impacts and puncture loads.

RING FRAMES

Stresses have now been calculated in the transverse frame across the bottom and up the sides. In a similar manner, stresses will be determined in the frame across the deck. Bending moments developed at the sheer, chine and keel have not been accounted for. On a larger vessel, a ring frame calculation would be appropriate. The ring frame is isolated, all design loads applied, and the resultant moment diagram developed. On smaller craft this is generally not necessary. It is a complex and tedious calculation. In practice the design loads are never all applied at the same time. In effect, only partial fixity has been assumed at these corners. Since these connections will not be calculated, it is particularly important that careful attention be paid in the detail design to adequate strength. The chine connection is most critical, as the sheer connection in some cases may provide no fixity at all as in the case of a boat with an open cockpit and narrow side decks.



A	Dn	ADn	ADn^2	Io
2.56	4.68	11.98	56.1	0.088
2.79	2.18	6.08	13.3	4.42
3.84	-4.16	-16.00	66.6	0.033
9.19		+2.06	136.0	4.541
			4.5	
			140.5	
			- 0.5	
			140.0 = I	

2.06/9.19 = 0.224

2.06 x 0.224 = → (0.5)

DISTANCE FROM ASSUMED NEUTRAL AXIS TO ACTUAL NEUTRAL AXIS = 0.224 (POSITIVE INDICATES ABOVE ASSUMED AXIS)

DISTANCE FROM TOP OF TRANSVERSE TO NEUTRAL AXIS = 5.000 - 0.224 = 4.776 $\quad Z_{top} = 140.0/4.776 = 29.31 \text{ IN}^3$

DISTANCE FROM BOTTOM OF SHELL TO NEUTRAL AXIS = 4.000 + 0.224 + 0.320 = 4.544 $\quad Z_b = 140.0/4.544 = 30.81$

$$\text{DEFLECTION} = \frac{3 \times 379 \times 75^4}{384 \times 2.0 \times 10^6 \times 140.0} = 0.336$$

FIGURE 10 - TYPICAL NOTCHED FRAME CALCULATION

DECKS

Decks are calculated using the same four formulas already presented, using the design loads of Section II. Since decks in small craft are generally cut away over large areas for hatches, living spaces and what not, particular care must be given to maintaining structural continuity by providing headers and doublers around openings. Even in an open boat considerable rigidity can be contributed to the hull by the box girder formed between the bottom and walking flat. If this is intended the joint between the flat and hull sides must be a full structural connection.

BULKHEADS

For watertight bulkheads, a hydrostatic head to one foot above the uppermost continuous deck should be applied. The pressure is averaged across the height of the bulkhead and applied as a uniform load in the design of the plating and stiffeners. If no deformation is desired at the bottom of the bulkhead, then the plating and stiffeners should be designed for a graduated load (see the appropriate case in reference M-17).

Where the bulkheads are not watertight it must be kept in mind that they must still function as web frames to support the longitudinals and that they are the principal members resistant to racking loads on the hull. Full strength (bearing and shear) connections to all longitudinals must be provided. Structural continuity should be insured around all bulkhead openings.

SUPERSTRUCTURE

Area pressure or point loads, as appropriate, should be applied and stresses determined as with the hull and deck. Particular attention should be paid to the connection between transverses on the side and top of the deck house in order to resist racking loads. Modern small craft cabin sides may be predominately glass windows. Where this is the case careful design of the window columns is required.

BEAM LOADING

This is discussed at length in Section II. The midship section modulus may be calculated as illustrated on page 183 of reference M-21, "Principles of Naval Architecture". Shapes of complex members can be approximated by rectangles of similar area. Both tensile and compressive stresses should be checked. Only continuous longitudinal members should be included in the midship section modulus calculation.

MISCELLANEOUS LOADS

Gunwale Load - The gunwale, particularly on workboats, is the area most subject to repeated damage. On yachts, in the interest of appearance, economy, and weight reduction the gunwale design is often completely inadequate to resist anything more than a moderate impact. Yachts are protected throughout their life with all manner of elaborate padding and mooring devices to prevent serious damage. The workboat, on the other hand, is continuously slammed against pier and piling and is expected to take it with minimal damage.

In either case the designer's goal should be to provide maximum strength and protection within the limits of cost, weight, and appearance. The design criteria should be applied through formulas (3) and (4). The importance of adequate support from the deck is clear. Deck buckling is a common failure. In an open boat, or one with narrow side decks, survival of the gunwale may be primarily due to flexibility of the entire side structure. In this case hard spots must be avoided.

There is some controversy as to the best material for rub strips, the "sacrifice" material which makes the contact in gunwale impacts. Workboats and tugs traditionally use rubber fenders or old tires. These have good durability but it must be kept in mind that the underlying structure must be stronger with a rubber guard as the load is transferred directly through the guard and not spread out. Oak scuffing timbers, while not as resilient as rubber, contribute to the strength of the gunwale by spreading the load fore and aft.

Docking and Grounding Loads - Section II suggests two times the craft weight loaded onto the keel blocks. The load should be followed in the calculations from the keel into the frames and particularly the bulkheads.

IV. MATERIALS

The selection of a hull material for a particular design seldom involves an objective analysis. Both customer and designer are biased in one manner or another. The customer has had good, or bad experience with a particular material or has been persuaded by a friend that "There's only one way to go". The designer's bias may stem from familiarity with certain materials and an apprehension toward designing with the others. Sales representatives for each material invariably oversell their product. The builder enters the picture with a capability of working in only one or two materials. There are only a handful of yards in the U. S. capable of building in all four of the older materials, even excluding ferro-cement. All this is not to say that the wrong decisions are consistently made, but rather that the right decisions are often made for the wrong reasons.

It is common practice to justify the choice of a material by presenting a table of properties for the competing materials or, to carry it a step further, to include a weighted scoring system. A similar artifice will be used in this section, but it is very easy to grossly misrepresent the case by this technique. The material is taken out of the context of the actual design and the conclusion rests entirely on which data is presented. The materials suppliers are particularly suspect in this respect. Ultimately, a truly objective analysis consists of a feasibility study for each material under consideration. When costs and weights are developed, even if preliminary, there is concrete information on which to base a decision. Feasibility studies are essentially "trade-off" studies. Where gains are made in one area a sacrifice is made in another. Reference (M-10) is an excellent example: A trawler preliminary design including weights and costs is completed for all five common materials. The true value of a good comparative table is to provide directly comparable data for feasibility studies.

Various forms of composite construction are often practical, but for clarity this discussion will, in general, be restricted to constructions of a single material.

SELECTION FACTORS

In order to relate material and structural factors most closely to the end product, let us start from the requirements of the customer and work backwards. The factors affecting the selection of a craft by the customer may be listed as follows:

- Operating Characteristics
- Habitability
- Appearance
- Safety
- Acquisition Cost
- Ownership Cost
- Psychological Factors

Each of the above will be considered with respect to their relationship to materials selection.

OPERATING CHARACTERISTICS

The following characteristics are critical to overall craft performance:

- Speed
- Payload
- Maneuverability
- Endurance
- Draft
- Running Trim
- Rolling & Pitching Motions
- Seaworthiness

Careful consideration of these characteristics reveals that materials and structural configuration can affect hull form, weight, and, to some degree, location of the center of gravity, all of which in turn directly affect each of the operating characteristics.

HABITABILITY

The following characteristics are all critical to habitability:

Characteristic	Material Influence
Internal Volume	Space Occupied by Structure
Arrangement & Visibility	Versatility of Material
Noise & Vibration	Inherent Damping Qualities
Temperature Control	Thermal Conductivity
Motions	Weight, C. G. & Hull Form

Space Occupied by Structure - It is quite obviously desirable in any craft to provide the maximum useable volume, i.e. to design the structure to occupy the minimum possible volume. Smoothness of space boundaries is also desirable for appearance, cleaning, etc. In the fish holds of trawlers or cargo spaces of workboats these factors are highly critical. At one end of the scale we have FRP sandwich and ferro-cement with a nearly complete absence of framing. Single skin FRP comes next with relatively simple structural shapes and reduced framing, then plywood, steel, aluminum, and finally conventionally framed planked wood construction as the worst offender.

Versatility of Material - It is often said that,"Form should follow function". In small craft construction, form often follows material characteristics. Steel, aluminum and plywood hulls usually have developed surfaces. Planked wood follows available material limitations and fabrication techniques. Ferro-cement and FRP appear to offer nearly unlimited forming possibilities.

Inherent Damping Qualities - Wood is excellent in this respect, particularly planked construction. As glued plywood construction approaches the properties of a homogeneous structure, sound damping and insulation is decreased. FRP sandwich structure is somewhat better than single skin FRP. It would seem that ferro-cement would be somewhat better than sandwich FRP due to its greater mass. Aluminum and steel are the worst. Careful provision must be made to isolate sound and vibration sources. Insulation should be provided and panels stiffened to reduce vibration. Wave slap alone may be a considerable annoyance with some metal boats.

Thermal Conductivity - This affects condensation and effectiveness of heating, air conditioning and refrigeration. "K" factors for the various materials are listed in the table of properties later in this section.

APPEARANCE

Appearance is of critical concern only with pleasure craft or craft for hire. It must be conceded that the surfaces of any of the five construction materials can be faired and finished to yacht standards. This may, however, be at prohibitive expense. FRP, undoubtedly, presents a superior finish when fabricated in a female mold. The finish is, however, no better than that of the mold surface which requires many hours of careful hand polishing and fairing. "Telegraphing" of the reinforcement pattern through the gel coat may also occur if proper gel coat and surfacing reinforcement are not employed.

Wood fabrication techniques may also produce an excellent finish though considerable sanding and occasional glazing is required. FRP non-mold surfaces require extensive glazing and fairing. Ferro-cement surfaces, since they are hand finished, will inevitably require extensive fairing and smoothing.

Both steel and aluminum present major problems because of plate distortion. Aluminum distortion is worse than steel of equal thickness, but thicker plating is used with aluminum construction which helps reduce distortion.

SAFETY

This is an area of major concern. Insurance companies and regulatory agencies are notably restrictive, particularly where paying passengers are carried. Damage resistance, durability, fire resistance, flotation, seaworthiness, and stability are all of importance. Many of these characteristics are dependent on the basic design regardless of material, and others have been or will be mentioned in other paragraphs. Only fire resistance and flotation will be discussed here.

Fire Resistance - Fire resistance is a serious problem in small craft. Steel and ferro-cement are essentially fireproof though paints applied to them may burn. Aluminum distorts and melts at a relatively low temperature. Wood and FRP as basic materials are similar in fire resistance. Fire retardant resins are available. All Navy and large Coast Guard FRP craft and some yachts (notably Uniflite) are constructed of fire retardant resins. Fire retardant resins have a slightly higher specific gravity than ordinary resins, and cost roughly twice as much.

Use of fire retardant resins produces a laminate which is "self-extinguishing", not fire "proof". These laminates will burn much as a non-fire retardant laminate when an external flame source is applied but when the heat source is removed the fire retardant laminate will extinguish itself while the other will continue to burn. It is noteworthy that FRP fires produce a particularly thick, oily smoke. Fire retardant coatings are available but as they are expensive and in some cases difficult to apply, they are seldom used.

Flotation - It is desirable to provide some means of positive flotation for a damaged and flooded craft. It is common practice to provide watertight compartmentation in larger decked over craft. This is basically a matter of careful design: calculating floodable lengths and locating bulkheads to provide a one or two compartment standard of floodability. This is inconvenient from an arrangement standpoint as watertight doors (usually open in an emergency) must be provided and bulkheads often must be placed at locations least advantageous to the arrangement. The smaller the craft the more difficult it is to provide even a one compartment standard. In addition the nature of small craft environmental hazards makes it likely that more than one compartment would be flooded.

An answer to this dilemma is the provision of flotation foam sufficient to support the swamped craft and its complement of personnel. Other provisions than foam, such as air tanks, inflatable bags, or even ping-pong balls have been used but with limited success. The volume of foam required depends on the "wet weight" of the entire craft. This, in turn, depends largely on the density of the hull material. Material densities (see Table B) range from 490 for steel to 37 for wood. Obviously, a steel craft will require considerably more flotation volume than wood. In fact, wooden structure may even provide sufficient flotation volume to eliminate the requirement for foam. The same can also be true of sandwich FRP construction.

Foam location, as well as volume, is critical. Since it is desirable that the flooded craft float upright with reserve buoyancy and stability the foam must be installed high and outboard in the hull with sufficient foam forward and aft to give longitudinal stability. In calculating the foam volume and location required, a wet weight and wet center of gravity are developed from the weight estimate. The foam volume to provide the necessary buoyancy plus reserve is determined. The center of the submerged foam volume is located above the wet center of gravity.

Finding space for foam is a steel or aluminum (or FRP) craft can be a real problem and depends upon the space occupied by the structure. It should also be mentioned that "foam in place" foam may be used only with FRP and possibly ferro-cement without some serious concern for corrosion or decay of structure around the foam. Flotation foams currently used are 2.5 to 3 pounds per cubic foot density polyurethanes or styrofoam. Compressive strength of these foams is not adequate to provide structural support of adjacent panels. Numerous problems have developed where panel loads or vibrations have gradually pulverized flotation foam backing the panel. Foams with a density of less than two pounds per cubic foot are extremely liable to water soakage.

ACQUISITION COST - The following factors influence the purchase price of a craft:

- Materials Cost
- Special Equipment or Facilities Required
- Labor Cost (Rate and Hours)
- Number of Craft Built

Reference is made to Table A for the following discussion of acquisition cost.

Materials Cost - The costs listed in Table A include waste, i.e. these are dollars per pound of completed craft structure. These figures by themselves are not very significant in relation to the final craft costs except perhaps to the amateur builder.

Availability of Materials - Material availability is a consideration that the designer cannot overlook. The cost figures in Table A assume readily available materials. If the designer selects a non-standard structural shape in steel or aluminum or specifies a proprietary FRP material such as "Unicore", the price per pound goes up along with the delivery time of the materials which may increase yard costs. The point here is that the designer must ultimately check cost and availability of any materials he is not certain are standard and correct the cost figures accordingly.

Equipment and Facilities - Special equipment or yard facilities required will inevitably increase craft cost. An attempt was made to account for this factor by varying the overhead rates

			5086 ALUMINUM	FERRO-CEMENT	MAT/W. R. COMPOSITE	ALL WOVEN ROVING	STEEL	MAHOGANY PLYWOOD	SOLID MAHOGANY	SOLID DOUGLAS FIR
1	MATERIAL COST	$/#	.70	.08	.50	.60	.10		.18	
2	PRODUCTIVITY	HR/#	.16	.06	.08	.08	.08		.07	
3	WAGES, ETC	$/HR	3.25	3.00	3.00	3.00	3.00		3.50	
4	LABOR COST (2) x (3)	$/#	.52	.18	.24	.24	.24		.25	
5	DIRECT COST (1) + (4)	$/#	1.22	.26	.74	.84	.34		.43	
6	OVERHEAD	%	90	80	100	100	80		80	
7	O'HEAD COST (5) x (6)	$/#	1.10	.21	.74	.84	.27		.34	
8	TOTAL COST (5) + (7)	$/#	2.32	.47	1.48	1.68	.61		.77	
9	MATERIAL COST INDEX		100	20	64	72	26		33	
10	STRUCTURAL WEIGHT INDEX		49	104	55	52	100		105	
11	STRUCTURAL COST INDEX		100	42	72	76	53		71	

TABLE A - BOATBUILDING MATERIALS COST COMPARISON in Table A. Wood and steel construction traditionally can be a "backyard" operation. Of course this is not always the case but a steel or wood builder with a low overhead rate can generally be located. Ferro-cement falls into the same category as steel or wood. Aluminum overhead was increased to 90% as some what higher and less available skills are required and equipment is more specialized. A sheltered work area is most desirable for aluminum construction. FRP, though labor rates are not excessive, requires a sheltered, temperature controlled working space, hence 100% overhead.

Labor Cost - Labor cost may be separated into two factors: production rate (row 2) and wage rate (row 3). Labor rates will vary greatly with locality. The figures in Table A should be modified accordingly. The hours per pound figures of row 2 are a composite of several sources. The steel figures should be the most reliable, those for ferro-cement the least.

Total Acquisition Cost - The total material cost on a per-pound basis (row 8) is reduced in row 9 to an index based on 100. Row 10 is taken from Table B and is the weight index for "equally sound" structure. Multiplying rows 9 and 10 and again reducing the results to a 100 index produced row 11, the relative cost of completed structures in the various materials.

Number of Craft Built - Table A cost figures are for three or four craft of the same type built under the same contract. A reduction in costs of 10 to 15 percent might be expected for 20 hulls. Note that mold costs are not included for FRP. The cost of construction of a female mold varies depending on the method of mold construction. The chapter of Fiberglass by Mr. Robert Scott addresses the question of amortization of mold costs.

OWNERSHIP COST - The following factors affect ownership cost of a craft:

Expected Life
Resale or Scrap Value
Maintenance
Repair

Expected Life - The expected life of a craft depends on its use, its durability, and the maintenance it receives. In theory any craft could be made to last forever. In practice there is a point of diminishing returns where it is cheaper to replace the craft than to continue to meet increasing maintenance costs. Navy and Coast Guard craft are expected to last 15 to 20 years though in combat service they are expendable. Wooden fishing craft in Japan reportedly have a life expectancy of only five years. A commercial operation might amortize a craft in 5, 10

15 or 20 years depending on the service and the financial considerations.

Though there are certainly many older craft in existence, this writer would guess at an average life of small pleasure craft of 20 to 25 years. Both wood and steel craft are subject to decomposition with inadequate maintenance as a result of which their average life expectancy is definitely limited. Craft constructed of the newer materials, ferro-cement, fiberglass and aluminum, are expected to have, on the average, higher life expectancy, though they have not been with us long enough to provide any statistical evidence.

Scrap Value - Aluminum has an appreciable scrap value. Larger steel craft also would have some scrap value. Hulls of abandoned ferro-cement, wood or FRP would seem to be something more of a liability than an asset.

Resale Value - Resale value depends on craft age and condition and also the popularity of the particular type of craft. In the present used pleasure craft market, for example, fiberglass is much favored over wood. The public has been thoroughly sold on the durability of FRP in comparison to wood and this in turn has depressed the re-sale value of all but the truly classic wooden yachts.

In the commercial market aluminum, then steel, and finally wood would seem to be the order of preference. There are very few FRP commercial craft in existence but they would be expected to have a resale value comparable to aluminum.

Maintenance Cost - In the area of maintenance both the amount of maintenance and the frequency of maintenance are of concern. This writer would list the materials from best to worst as fiberglass, ferro-cement, aluminum, steel and wood. Reliable statistics on craft maintenance costs are nearly non-existent.

Repairs - Ease of repair and cost and availability of repair materials, labor and facilities are of concern. Ferro-cement is claimed to be the easiest, cheapest and fastest of the materials to repair. FRP has proven itself to be easily and quickly repairable by unskilled labor with simple repair kits or readily available materials. Shelter and some degree of temperature control are required.

Steel and aluminum are readily repairable when welding facilities are available but aluminum facilities are not yet as plentiful as steel. Wood repair is relatively simple for plywood but increasingly expensive and time consuming for planked hulls.

Navy experience has shown that for a given impact, damage to a planked hull is far more extensive than damage to hulls of the other materials. This confirms the somewhat academic determination of relative damage resistance presented in Table C.

PSYCHOLOGICAL FACTORS

These are the non-objective publicity and opinion factors which strongly influence the customer even though they may in fact have little substance. Different customers are susceptible to different influences. One man will want only the "tried and true" traditional construction while the next may consider himself modern and progressive and want only the latest material or fabrication system. These attitudes are influenced by publicity, past experience, general philosophy, opinions of friends, etc.

PHYSICAL PROPERTIES

Table B is a summary of the engineering properties of the most common boatbuilding materials. These figures were assembled from a wide variety of sources. In the cases of fiberglass and ferro-cement where the basic material is created by the builder at the same time that the structure is fabricated, the data scatter is extreme. Prudence dictates using the lower values where a range is given. Extensive testing by the builder under shop conditions is strongly recommended in order to verify predictions.

Particular attention should be paid to the fact that aluminum and steel have distinct yield points beyond which they still bear loads effectively while taking a permanent set or distortion. Fiberglass and wood are not ductile and have no discernible yield points. In other words they strain elastically to failure and do not take a permanent set at some lower stress. Ferro-cement does have an apparent yield point. When a ferro-cement beam is tested in bending, at some point cracks develop and a permanent set is

PROPERTY	NOTES	5086 ALUMINUM [1]	FERRO-CEMENT [2]	MAT/W. R. COMPOSITE [3]	ALL WOVEN ROVING [3]	STEEL	MAHOGANY PLYWOOD [4]	SOLID MAHOGANY	SOLID DOUGLAS FIR
DENSITY	#/FT^3	166	150	94	103	490	37	34	34
FLEXURAL YIELD OR PROPORTIONAL LIMIT	KSI		2.0-4.5			30	3.5/5.5	8.8	8.0
FLEXURAL ULTIMATE	KSI	40	2.0-5.4	30	40	60	4.6/7.2	11.6	11.5
MODULUS OF ELASTICITY	x 10^6	10.3	1.3	1.3	2.0	30	0.4/0.9	1.3	1.7
TENSILE YIELD	KSI	28/18	0.5-1.1			30			
TENSILE ULTIMATE	KSI	40/38	0.7-1.7	15	30	60	5.0/6.6		
COMPRESSION	KSI	26	6.5-12.2	22	26	60	3.1/4.0	6.5	7.4
INTERLAMINAR SHEAR	KSI		0.1-1.2	1.2	1.3		1.1	0.9	0.8-1.2
PERPENDICULAR SHEAR	KSI	25		12	14	50			
BEARING	KSI	48		18	18				
ENDURANCE LIMIT	% OF ULT.	20		20	20	35	40	40	40
K FACTOR	BTU/IN/FT^2/^{o}F/HR	1400	69	3.6		312	1.5	1.5	1.5

1. Basic value / Within one inch of a weld.
2. The lower values are the more probable.
3. W. R. = 24 oz. per square yard Woven Roving. Verify properties by testing.
4. Perpendicular to face grain / Parallel to face grain

TABLE B - PHYSICAL PROPERTIES OF BOATBUILDING MATERIALS taken, the material continuing to bear a load to a point of extreme deflection increase which is considered to be the ultimate strength.

MATERIAL COMPARISONS

Table C represents an attempt to compare structures built of the various materials. For convenience in comparison, steel is used as the baseline. Each material is assumed to be in the form of a beam of rectangular cross section of unit width and of variable thickness. It is recognized that moment of inertia can be varied considerably by changing the sectional shape; however, the effect of this would generally favor the lighter materials and would therefore change the magnitude, but not the trends of the comparisons.

STRUCTURAL WEIGHT

As mentioned in Section II, the deflection of a structure is psychologically taken as an indication of its strength and, from an engineering point of view, deflection may lead to problems such as in shaft alignment or fatigue. It is therefore of interest to compare materials on a deflection basis: For a given configuration and load, the deflection of a rectangular beam is a function of thickness cubed multiplied by modulus of elasticity. On this basis, the required thickness of beams of the various materials to result in the same deflections as a steel beam were calculated.

In order to compare the materials on a basis of stress, the safety factors of Section II are applied to the values of Table B. It is interesting to note that these limits result in nearly the same allowable stress for fiberglass, steel and aluminum, i.e. 25 to 27 KSI. Stress in a rectangular beam is a function of the section modulus or thickness squared for unit width. On this basis the thicknesses required to keep beams of the various materials within their allowable stress limits were calculated.

With the exception of ferro-cement, all of the materials are deflection limited rather than stress limited compared to steel. That is, designing for equal deflection will result in greater relative thickness than would designing to equal safety vs bending stresses. Multiplying the relative thicknesses by material densities resulted in structural weights based primarily on equal deflection.

PROPERTY		5086 ALUMINUM	FERRO-CEMENT	MAT/W. R. COMPOSITE	ALL WOVEN ROVING	STEEL	MAHOGANY PLYWOOD	SOLID MAHOGANY	SOLID DOUGLAS FIR
THICKNESS FOR EQUAL DEFLECTION	$Tx = \left(\frac{Es}{Ex}\right)^{\frac{1}{3}}$	1.43	2.84	2.85	2.47	1.00	3.22	2.84	2.65
THICKNESS VS SAFE BENDING STRESS	$Tx = \left(\frac{Ss}{Sx}\right)^{\frac{1}{2}}$	1.04	4.38	1.04	0.98	1.00	2.33	1.84	1.92
WEIGHT FOR "EQUALLY SOUND" STRUCTURE	$\frac{100\ Tx\ Dx}{Ds}$	49	143/104 [1]	55	52	100	[2] 24	[2] 20/105 [3]	[2] 18/105 [3]
RELATIVE MINOR DAMAGE RESISTANCE	$Tx\ \frac{100\ Sx}{30\ E}$	362	200		3800	100	620	570	345
WORK TO FAILURE	$IN\text{-}\#/IN^3$	5720	See Text		3830	13,500	[2] 12	[2] 20	[2] 26/150 [3]

1. Lower number represents normal practice.
2. Low value represents highly sophisticated, delicate construction.
3. High value represents normal, heavy plank-and-frame construction.

TABLE C - COMPARISON OF SMALL CRAFT STRUCTURES

IMPACT STRENGTH

Boats suffer two basic levels of damage: cracks and dents, or holes and major buckling. The impact level (minor impact) at which a metal boat is dented, a fiberglass boat suffers crazing in the gel coat, and minor cracks and distortion develop in a wooden or ferro-cement boat is related to the yield strength or elastic limit and modulus of elasticity of the hull material.

The area under its stress-strain curve up to the yield point or elastic limit will give an indication of the relative ability of a material to withstand minor damage. This area is approximately equal to 1/2 yield stress times elongation to the yield point. Since the modulus of elasticity equals stress divided by elongation ($E = S/e$), then stress times elongation is equal to stress squared divided by E. That is: $eS = s^2/E$. Ignoring the 1/2 term, dividing through by 30 (representing the modulus of steel), and multiplying by 100 gives a set of numbers indicative of relative resistance to minor impact damage on an equal thickness basis compared against steel with its arbitrary value of 100. Multiplying these numbers by the thicknesses determined during the weight comparison produced the values in Table C labeled "Relative Minor Damage Resistance" for structures designed on an equal deflection basis.

The numbers labeled "Work to Failure" were generated in a similar manner using an approximation of the entire area under the stress-strain curve to failure. The calculations involved are explained in reference (A-4), page 60. Experimental data on wood are published in reference (W-52). Unfortunately, data were not available for ferro-cement.

These relative impact strength numbers whould not be taken at face value. While it may be possible to verify them in laboratory scale panel testing, boats in the real world only generally conform to these predictions. The flexibility of a boat will allow part of an impact to be dissipated in deflection of the hull as a whole. In addition, this limberness may change the time response of the impacted area, further reducing the effect of the blow. Careful engineering may also minimize the poorer qualities of a material.

Aluminum and steel with their yield point and resultant ductility exhibit extreme resistance to large impacts, punctures, and cracks. Stress concentrations are less critical as plastic deformation redistributes the stresses. However, metals "dent" much before fiberglass would begin to fracture. Where appearance is critical this may not be acceptable, but for commercial craft and workboats it is a great advantage. Fiberglass or wood must be protected from heavy impact by protective guards. This writer has very limited knowledge of ferro-cement impact resistance but discussions at the 1968 fishing hull materials conference in Montreal would indicate that this material's resistance to puncture is highly suspect.

FATIGUE STRENGTH

Basically, fatigue strength is a consideration only in the bottom slamming areas of planing craft. The fatigue strength of a material is the level to which it may be stressed multiple times without failure. The typical fatigue curve, Figure 4 of Section III, shows a gradual reduction of allowable stress with increase in number of loading cycles, finally becoming roughly asymptotic to the endurance limit value at 10^8 cycles.

Steel and aluminum in the unwelded condition and steel in the weld area are not appreciably reduced in strength by load cycling. Aluminum welds may be reduced to an endurance limit as low as 2,000 PSI (A-40).

Reference (W-51) indicates that wood will be reduced to between 40% and 60% of static strength at 3×10^6 cycles. This writer has located no data on fatigue strength of ferro-cement.

CREEP CHARACTERISTICS

The reduction in load carrying ability of a material over long periods of time when loaded to high stress levels is referred to here. Since nearly everything in a small craft is designed for dynamic loads, continuous loads are at relatively low stress levels. An exception might be the support of a craft for long periods on inadequate keel blocks. When thermoplastic foam cores such as PVC are used in FRP sandwich structures the core must be designed for low continuous stress levels as creep occurs at relatively low temperatures. A temperature of 158° F. has been recorded on a dark colored deck exposed to full summer sunlight.

ABRASION RESISTANCE

Steel has excellent abrasion resistance. Reports on aluminum are somewhat contradictory though Navy tests for small craft applications indicate that aluminum is entirely satisfactory. Wood has relatively high abrasion resistance compared to FRP. Fiberglass has the poorest abrasion resistance of the boat building materials. It must be protected from continued abrasion by wood, steel, aluminum or other abrasion resistant material. Surface layers of Dynel fabric have proven very effective in Navy tests and service application. Ferro-cement abrasion resistance is reportedly superior to that of FRP or wood. Woods will vary greatly depending on the species.

FORMABILITY

Selection of aluminum, steel, or plywood as a hull material effectively limits the hull form to a developed surface. Notable exceptions would be aluminum sailing yachts where a premium is paid for double curvature of hull plating. It is not within the scope of this chapter to discuss the implications of restriction to a developed surface. Suffice it to say that there are numerous occasions when it is desireable to use other than a developed surface either for appearance or hydrodynamic considerations.

Fiberglass, ferro-cement and wood give the designer considerable freedom in his choice of hull form.

EVALUATIONS

Shape, type and arrangement of the structural system, expected durability, and the skill of the operator must all be considered when choosing a material. With those thoughts in mind, and tempering the numbers with practical experience, several important inferences can be drawn from the material comparisons presented above and in Tables B and C. Taking each category of material in turn:

ALUMINUM

Aluminum offers an interesting combination of properties. Its structures can weigh half as much as steel and up to ten percent less than fiberglass. In resistance to major impact it is only 40 percent as good as steel, but it is 50 percent better than fiberglass. Its best point compared to steel is its low weight, and its worst point compared to fiberglass is its lower resistance to minor impacts. It is, however, easier to effect major repairs and modifications in aluminum than in fiberglass.

As in fiberglass, joints in aluminum must be given careful consideration in view of the reduction of strength in way of welds.

The ductility of aluminum allows it to be more tolerant than fiberglass of hard spots and discontinuities. But deflections must be kept lower than in other materials in order to minimize stresses where repetitive loading may lead to fatigue. This is particularly important in plating panels over propellers where blade rate cycling will load the panels hundreds of millions of times during the course of the craft's lifetime.

Aluminum has two unique problems: One is its susceptibility to electrolytic corrosion in the presence of dissimilar metals; and the other is the critical importance of using proper alloys. Copper alloys such as in brass or bronze in contact with aluminum in a marine atmosphere will cause the aluminum to waste away. And mercury bearing paints or free mercury from such sources as broken thermometers and U-tube manometers aggressively attacks aluminum destroying its strength.

The best aluminum alloys to use in a marine environment are the weldable 5000 series and the 6000 series which is better suited for rivetted construction due to its low welded strength. Exceptional corrosion resistance has been demonstrated by 5086 aluminum, the most common boatbuilding alloy for larger craft. The highest strength aluminum alloys are in the 2000 and 7000 series which are generally used in aircraft construction. These alloys contain high percentages of copper and will set up severe internal electrolytic corrosion in the presence of sea water. Since all aluminum alloys are visually similar, great care must be exercised to avoid unsuitable alloys.

When drawing structural details, it is important to remember that the tip of an aluminum welder is approximately three-fourths of an inch in diameter and that it is connected to a stiff bundle of hoses. Clearances and access must be carefully considered when choosing sizes and arrangements.

Repairs are not difficult but workers experienced in handling the required sophisticated welding equipment are not yet universally available. Marine alloys, particularly in extruded shapes, may be difficult to obtain in some areas.

FERRO-CEMENT

Though boats were built of this material as early as the late 1800's, ferro-cement has only recently become popular. And unfortunately its popularity is not founded on a very substantial scientific base. A comprehensive study has been published by the Russians (C-10), and some of the more technically inclined and well financed builders may have done some in-house testing, but public data from United States' sources is very scarce. (At the time this is being written, (C-45) had not yet been presented.)

Except in compression, the material does not appear to be quite as strong as wood. Curved shapes arranged to depend more on compressive rather than flexural strength are the most logical for ferro-cement. Its applications have commonly been in heavy displacement craft of the type designed for plank-and-frame wooden construction, e.g. Tahiti ketches, trawler yachts, some types of fishing craft. Hull weights are comparable to those of steel or very heavy wooden boats. Speed must obviously be a secondary consideration if ferro-cement is to be the hull material.

Ferro-cement's advantages are that it is a chemically inert, rot-proof, fireproof, inexpensive material. It also seems to produce rugged hulls despite its low physical properties. This is apparently due to several factors:

a) The material is essentially isotropic and eliminates the plank edge connection problem faced in wooden construction.

b) A ferro-cement hull is essentially monolithic and eliminates the fastening and joint problems of wooden boats.

c) Most ferro-cement boats have comparatively weak plywood bulkheads and no frames and therefore very few hard spots. this allows deflections to be distributed over large areas of the boat and minimises local stresses.

d) The use of resilient coatings as a waterproof membrane helps to block the flow of water through minor impact cracks.

e) When ferro-cement does fail, the meshes of reinforcing wire serve to retain the crushed pieces of concrete thus limiting flooding.

Overall, its damage resistance seems to fall somewhere between fiberglass and aluminum.

Repairs seem to be very easy and are effected by pounding out the broken pieces of cement, pushing the mesh back into place with additional wire lacing as necessary, and then plastering the hole with new mortar. Some care is required to ensure a good bond between the new and old cement, but this does not appear to be a problem.

FIBERGLASS

Fiberglass reinforced plastic is almost too adaptable to be dealt with in generalities. Its structures can vary from monocoque sandwich systems with weight and stiffness competitive with plywood to single skin and frame systems offering unparallelled resistance to minor damage at half the weight of steel.

The ultra-light fiberglass constructions share the advantages and disadvantages of plywood except that they may have slightly lower resistance to minor damage and slightly higher resistance to major damage. In addition they are immune to rot.

The more common single skin and frame systems using woven reinforcements can provide outstanding performance in light to moderate service. For structures designed to equal deflections the material's low modulus of elasticity and high strength combine to give these structures a resistance to minor impact ten times better than aluminum and thirty times better than steel. On the other hand, its lack of ductility limits its resistance to major impact damage to two-thirds that of aluminum and one-fourth that of steel.

A recent Navy survey of the durability of their fiberglass boats (F-36) both verifies this disparity in the reaction of fiberglass to major and minor impacts and points the way to circumventing its lower ultimate strength. Panels that were free to flex and take advantage of the low modulus of elasticity were comparatively free of damage. However, areas such as the stem, transom corners, chines and gunwales which took the brunt of major impacts due to their rigid shape suffered heavy damage because they were not made sufficiently thick. It is apparent that these areas should be two to three times as thick as the basic flat-panel laminate.

Flex across bonded stringers is also bad as it leads to cracks in the shell and peeling in the bonds. For the bottoms of planing craft which are subject to frequent impacts slightly curved convex arcs are particularly dangerous if there is a possibility of encountering loads high enough to pop them inside out. Flat panels are acceptable as long as they are designed to reasonable deflection limits (span/100 or less). But concave arcs from stringer to stringer are the best since these panels go directly into tension under load and the angular flexing at the stringers is minimized. Convex curved shells that are thick enough to withstand their loads without stringers are also quite successful.

In boats large enough to require single skins over 3/8 inch thick, cored constructions may become attractive. These systems offer great panel stiffness with little or no framing. The depth of the core itself reduces the probability of damage extending completely through the shell.

In fiberglass construction, then, it is imperative to avoid hard spots and to heavily reinforce those that are unavoidable. Extra thickness must be built into prominent corners to take impact and chafe. And the shell must be reinforced or shaped so that it does not tend to hinge over bulkhead edges or stiff stringers. The net result of this reinforcement is a slight weight penalty over an aluminum structure.

Minor damage is easily repaired. But major damage, where a hole has to be spanned, is difficult since some sort of a temporary form must be arranged in order to define the surface to which the patch must conform. Repairs can be as strong or stronger than the original laminate. The most difficult part of the average fiberglass repair job is matching the gel coat color, a project which calls for no little artistry on some of the exotic metalflake finishes of the runabouts.

STEEL

Where brute strength is of primary importance steel is the material to use. Its resistance to major impact failure is two and one-half times that of its nearest rival, aluminum. Hard corners are tolerated by its extreme ductility. Welds in nearly any configuration are as strong as the base metal. A boat can be severely battered without losing its watertight integrity. It is the obvious choice for rough service craft such as tugs, lighters, barges, and floating cranes.

However, when speed, weight, appearance, and resistance to corrosion begin to become important, steel loses its advantage. A steel hull light enough for a planing boat, for example, will be so thin as to exaggerate its vulnerability to dents and will have no margin at all for the inevitable corrosion in sea water. Steel has the lowest resistance of all the common boatbuilding materials to minor impact damage. It also has the most severe corrosion problem. And its high density leads to hull weights double those obtainable in fiberglass and aluminum.

The U. S. Coast Guard's forty foot steel utility boats provide good examples of the kinds of trouble one can expect from excessively light steel hulls. Built of eleven gage (3 mm) steel sheet with a minimum panel span of sixteen inches in the planing impact area, these 20-knot boats soon developed a "hungry horse" look from denting the side and botton plating between frames. By the time the boats were eight years old, half of them had required new bottoms due either to corrosion or to fatigue cracking. Some of the older boats have been rebuilt twice.

WOOD

If wood were an isotropic material, extremely light wooden structures could be built. Plywood, which for practical purposes has nearly equal strength in all directions, can and does offer the possibility of very light weight, particularly if durability is not a consideration. If not all of the potential for weight savings is exercised, exceptionally high panel stiffness can be achieved. It is this fact that has made the conversion of some of the small, high-performance sailing dinghy classes so difficult. Those that had either large, flat panels or that were built by the cold-molding process are particularly obstinate.

Normal practice with regard to butt straps, scarfs and chine logs provides joint strength commensurate with the panel strength.

Plywood has better than average resistance to minor damage, but it is quite vulnerable to major damage. As with all wood, rot can be a problem.

In ordinary practice, the rough plank-on-frame construction of most workboats tends to end up as heavy as steel in order to compensate for the lack of connection between plank edges, the inefficiency of fasteners, the low strength of sawn frames, and the limberness of the structure as a whole. This is a very inefficient structural system. Durability is bought at a cost of ponderous masses or wood: thick planking, large and closely spaced frames, bulky knees, and tons of fastenings. The fact that these boats are necessarily slow helps to reduce the magnitude of the impacts which they must sustain.

This construction system does tend to distribute loads fairly well, and most heavy impacts will be absorbed by deflection of a large area of the hull, thus turning its flexibility into something of an advantage. However, the working of the hull under impacts tends to loosen joints and seams allowing leakage.

Double and triple diagonal planking has been used in order to approximate the properties of plywood. For larger moderate weight hulls such as PT, aircraft rescue, and high-speed yacht types this sophisticated structure has been successful. Resistance to minor damage is fairly good, but ultimate strength is lower that that obtainable in other materials.

In very light planked wooden constructions, the intrinsically low damage resistance can be somewhat improved by providing connections between plank edges such as in lap-strake, clinker, or edge nailed and glued strip planking. But none of these systems is the equal of plywood. The minor damage resistance of the strip planked and plywood systems may be very greatly improved through the application of a fiberglass covering. All these light weight systems are, however, extremely vulnerable to major damage.

Contemporary wood construction is severely hampered by a lack of suitable boatbuilding timber and of skilled craftsmen. It is essentially a dying art.

CONCLUSIONS

An attempt has been made here to look objectively at all the factors affecting materials selection and no simple conclusions as to the "best" choice have materialized. In fact, each material is best in some particular application. It is up to the designer to examine each design on a case basis. Hopefully the framework and tools for this analysis have been provided in the foregoing section. In the final analysis the design itself is the key. A given material for a single design will be best in some respects and poor in others. Where the material is deficient it is all the more important that the design compensate for these deficiencies.

There is very little direct competition between the various boatbuilding materials. The major properties of each suit a different type of boat and service:

> ALUMINUM is best suited for boats in moderate to rough service where speed is important but cosmetics are secondary, and where occasional major impact damage must be anticipated. Its adaptability makes it a good choice for one-of-a-kind or prototype craft.
>
> FERRO-CEMENT is a good substitute for heavy plank-and-frame wooden construction. Burdensome sail and displacement type power yachts are proper candidates.
>
> FIBERGLASS reinforced plastic is excellent for boats in light to moderate service where speed and appearance are important. In the hands of a reasonable careful operator, a well built fiberglass boat should last indefinitely, requiring little more than an occasional polish or coat of paint.
>
> STEEL is best in very rough service where speed, appearance, and corrosion are secondary considerations. It is approximately twice as heavy as fiberglass or aluminum when designed to equal deflections and any attempt to match their weight will create a tremendous upkeep problem. Its principal advantage is that it can stand up under extreme abuse.
>
> PLYWOOD is best for very light boats in light duty service where they get careful handling and tender loving care.
>
> Plank-and frame WOODEN construction really is not very good except for boats owned by die-hard timber sailors with the time and money to invest in upkeep, or for boats that are considered expendable and are quickly "written off". The shrimp fleet with an average wooden boat life of five years is a

ATTRIBUTE	ALUMINUM	FERRO-CEMENT	FIBERGLASS	STEEL	PLYWOOD	PLANK-AND-FRAME WOOD
SURVIVE MINOR IMPACTS	5	2	6	1	4	3
SURVIVE MAJOR IMPACTS	5	4	3	6	1	2
LIGHT WEIGHT	5	1	4	3	6	2
FLAT SHAPES	4	1	3	2	6	5
CURVED SHAPES	3	5	6	2	1	4
JOINT VS BASIC STRENGTH	4	2	3	6	5	1
FATIGUE RESISTANCE	2	1	3	6	4	5
WEATHERABILITY	4	6	5	3	2	1
REPAIR EASE	3	5	2	6	4	1
MATERIAL COST	1	6	2	5	3	4
LABOR COST	1	6	5	3	4	2
CAPITAL INVESTMENT & TOOLING COST	2	4	1	3	6	5

TABLE D - RANKING OF BOATBUILDING MATERIALS
(6 - BEST, 1 - WORST; HIGHEST TOTAL BEST)

good example of the latter philosophy.

The only overlap of applicability occurs in the case of fiberglass and aluminum. But even here the decision is easy to make. If appearance is important and if a small weight penalty can be accepted, and if many boats are to be built, fiberglass is the choice. If the duty is severe and ease of major repair and adaptability are important, or if only few are to be built, then aluminum is the choice.

Table D presents a series of rankings of the materials against various attributes. The material with the highest score for any set of operational and economic characteristics is the most suitable. If some particular attribute is more important than the others, its ranking numbers might be multiplied across the board by some factor appropriate to its status.

V. FERRO-CEMENT, STEEL & WOOD

In this section are presented detailed discussions of Ferro-Cement, Steel and Wood as applied to small craft construction. Fiberglass Reinforced Plastic and Aluminum are the subjects of separate chapters of this small craft design course.

FERRO-CEMENT

INTRODUCTION

Ferro-cement consists of several layers of wire mesh reinforcing in a mortar of sand and Portland cement. There is a tendency to compare the material to reinforced concrete, whereas in fact, it exhibits quite different properties. The basic difference in composition is that ferro-cement has a higher percentage by weight (over 15%) of steel reinforcing and the reinforcing material is more finely and evenly distributed through the material. The strength of the material is related to this weight and distribution of steel. A direct comparison may be made to FRP where the glass and resin perform the same relative fuctions as the steel and cement in ferro-cement. Ferro-cement has proven to be particularly applicable to thin walled structures, certainly a most unlikely use of ordinary reinforced concrete.

Ferro-cement has acceptable strength and stiffness, is water proof, fireproof, corrosion resistant, and the basic materials are very inexpensive. In addition the material lends itself readily to fabrication without expensive equipment or facilities by unskilled labor. In short, the perfect material for low cost "backyard" construction by amateur builders. However, quality control is a major problem and the plastering operation requires considerable skill. Never the less, it is within the amateur's reach where other materials may not be. This is the key to the material's current popularity. The success of several firms in producing ferro-cement craft at competitive prices proves that it can be done but the price advantage of the raw materials readily disappears in a commercial operation.

HISTORY

Ferro-cement has come into extensive use in boatbuilding only over the last five years though it has apparently been used for boat construction sporadically since 1849. The history of the material is amply developed in several references: (C-21, 37, and 44). To summarize: In France in 1849, Lambot patented the method under the name "Fercinent" and constructed a number of rowing boats. A ferro-cement boat constructed in Holland in 1887 is still in use on a pond in the Amsterdam Zoo. The process was revived in the early 1940's by Dr. P. L. Nervi as "Ferro-cement" in Italy where several small craft were constructed between 1943 and 1948. There was apparently no activity from 1948 until 1961 when the process was revived simultaneously in New Zealand and in England.

The material was introduced into the United States and Canada between 1965 and 1967. Today at least seven firms in the U. S. and four in Canada are engaged principally in the production of ferro-cement barges and small craft. Ferro-cement craft are also in production in England, New Zealand, Australia, Russia, China, Thailand, VietNam, Iran, South Africa, Spain, and France. Several hundred craft are in service including a number of small trawlers. Dr. Nervi's 38 Ft. ketch NENNELE, built in 1948, is reportedly still in service and in excellent condition. Several Universities, the Naval Ship Engineering Center, The Canadian Fisheries Bureau, and the FAO have conducted, or are conducting studies on the material.

It appears that ferro-cement is here to stay. The small craft designer should be prepared to design in the material. Considering the critical role of material selection and fabrication process in ferro-cement construction, the designer will be well advised to develop a thorough knowledge of fabrication details, not leaving his customer entirely to the builder's mercy. This material has certainly received a fair share of publicity. The problem is to sift the wheat from the chaff.

BIBLIOGRAPHY

The attached bibliography is considered to be reasonably comprehensive. Reference (C-37), a British Columbia Research Council report, is highly recommended. It appears to be a truly objective account of the state of the art. Included are results of a test program with samples of different composition. Reference (C-10), a translation of a Russian text is certainly the most comprehensive report to date on the material. This text presents analyses of the stress/strain behavior of the material and also data on creep, impact, water penetration, and freeze-thaw cycling. Design procedures are included.

John Gardner's articles in the National Fisherman (C-21 thru 29) are very informative, providing a running report of the material's introduction into the U. S. and Canada. Reference (C-28) is of particular interest in that it notes several problem areas with ferro-cement. Reference (C-50), "How to Build a Ferro-Cement Boat", is one of the first books describing a building method in detail. One of the leading exponents and developers of the material for boat construction has been W. Morley Sutherland of New Zealand. His recent book, (C-34), is one of the best references yet published on the material.

COMPOSITION

Sand/cement ratio varies from 1.5:1 to 2:1. Water/cement ratio should not exceed 0.35. This is approximately four gallons of water per bag of cement.

An alkali resistant Portland cement is used, generally type 5. Between 5 and 15 percent (of cement weight) of Pozzolan is added to the cement. Pozzolan is considered part of the cement weight for sand/cement/water ratios. Pozzolan is an amorphous silica. It is said to absorb the free lime during the setting, resulting in a denser, stronger, more waterproof material and to improve working qualities during plastering.

The sand used is of a sharp, fine grade with 100% passing a number eight sieve and 10-15% passing a number 100 sieve.

The steel reinforcement in ferro-cement commonly consists of a grid of 1/4 inch rod running fore and aft on two to three inch centers covered on each side with several layers of 19 or 20 gauge 1/2 inch square or hex wire mesh. The number of layers of mesh is determined by maintaining a steel reinforcing content of the material between 24 and 36 pounds per cubic foot (out of 150 pounds per cubic foot total density). In some methods of construction, 3/4 inch pipe transverse frames are added. High-tensile wire has been used in place of the reinforcing bars and expanded metal has been used in place of the wire mesh.

FABRICATION PROCESS

For detailed descriptions of construction methods the reader is referred to references (C-1, 8, 28, 34, 37, 44, 50 & 58).

Common to all processes are the problems of setting and cure time, hull weight support and continuous versus interrupted plastering. Before any work can be done following plastering the ferro-cement must set for 8-12 hours. Following this, a three to four week curing time is required during which the hull must be kept constantly damp. Temperature must be maintained above freezing and temperature variations from drafts or sunlight must be avoided. Careful consideration must be given to supporting the entire hull weight during plastering and setting. Wet cement is very heavy and the wire skeleton may sag disastrously before the cement is thoroughly set unless it is properly supported. Mortar that is too wet will flow out of the mesh. Continuous plastering of the entire structure is recommended. If the process is halted, an epoxy coating is applied to the faying surface before continuing with the plastering.

With careful planning, all main structural connections are fabricated with the hull. Wooden plugs are set into the wire skeleton wherever openings and penetrations will be located. Rawl plugs can be used to secure light loads. A carbide tipped drill is required. Bolted connections can be made but good bearing area should be provided on both sides through use of stiff backing plates. A certain amount of probing with the drill may result as the reinforcing bars are encountered. Modifications or additions after cementing is complete is very difficult. FRP bonding angles are sometimes used for connections. Deckhouses, and sometimes entire decks, are generally wood for weight reduction.

It would seem that quality control is a most serious problem. Thorough mixing and the sand/cement/water ratio are critical. The final thickness and the quantity and distribution of reinforcement are also areas of concern. There is virtually no way to check these factors in the finished product. Control must be exercised at the time of fabrication.

Plastering requires considerable skill and the whole process requires continuing conscientious application of effort to obtain an acceptable product. When an amateur is building his own boat in his backyard the problem of quality control resolves itself. But for the yachtsman having a hull built, or for the company building ferro-cement hulls on a production line, it is a matter of grave concern.

Construction methods may be classified into four basic systems:

Pipe Frame
Web Frame
Cedar Mold
Female Mold

<u>Pipe Frame</u> - In this system, 3/4 inch pipe is bent to the frame lines and a skeleton shell assembled by welding these pipe frames to keel and sheer members. The skeleton is then hung from the overhead and supported from below on the keel . Longitudinal 1/4 inch reinforcing bars are then tied with wire to the pipe frames on two to three inch centers, followed by transverse reinforcing bars tied on three to six inch centers. Several layers of mesh are next wired on to each face of the pipe and reinforcing bar skeleton. The wire mesh is fair on the outside and molded over the pipe frames on the interior. Care must be taken to insure even distribution of the wire in the final matrix. Pipe through-hull connections, shaft logs, flanges for bulkheads, frames and foundations, etc. are fabricated of bar and mesh and welded or wire laced into the shell before plastering.

The plastering is generally accomplished by applying the mortar from the inside and trowelling it smooth on the outside (Sutherland (C-34) recommends application from the outside). Fairness may be checked by battens on the outside during the trowelling. In order to avoid surface cracks in unreinforced cement, the mortar must only just barely cover the mesh. Hulls are often finished by grinding though Sutherland does not recommend this. Surface preparation for painting is accomplished by etching with muriatic acid and neutralizing with caustic soda.

Web Framework - This is a variation on the pipe frame system. Pipe framing is eliminated and replaced with temporary plywood webs. When the reinforcement is in place, the webs are removed. A steel channel is commonly used as a keel shoe. This is welded to the transverse reinforcing bars, thus providing much of the support for the hull during cure.

Cedar Mold - In the cedar mold method a male plug is fabricated with planking of cedar or other soft wood. The plug is covered with plastic sheeting or tar-paper as a vapor barrier. The wire mesh, longitudinal and transverse reinforcing bars, and then additional layers of mesh are nailed to the mold. Mortar is applied and trowelled into the reinforcement to the required thickness. Vibrators are sometimes used to reduce void content. After cure the hull is inverted and the mold stripped out. Claims for this system are that the hull is fairer and the reinforcement may be assembled more rapidly.

Female Mold - This method, developed by Fibersteel Corp., employs a permanent female mold. Expanded metal and/or reinforcing rods are added layer by layer, interspersed with concrete applied at high velocity from a gun. With this system hull thickness is not limited to the thickness of reinforcement through which mortar can be forced. This system would seem to have numerous advantages: smooth mold surface on the hull exterior, better distribution of reinforcement, faster fabrication, and simplification of the hull support problem. The disadvantages would be mold costs and equipment costs for applicator guns.

DESIGN

General - Ferro-cement construction in the present state of the art has certain limitations. This is a relatively dense material at 150 pounds per cubic foot. Though hulls have been built of less than 1/2 inch thickness, current construction averages over 3/4 inch. This corresponds to an area density of approximately 10 pounds per square foot. Even if framing is largely eliminated this is unlikely to produce a hull weight competitive to wood or steel in craft under 40 ft. in length.

The material in its present form is generally not recommended for large flat areas and consequently not for hard chine or high speed craft. Since ferro-cement has been used successfully for slab sided barges, this is not always true but relates to weight and material quality. The flat surface problem is related to panel stiffening. Stressed skin shells are generally built, relying on the arch or dome effect to keep the material predominately in compression.

The key to ferro-cement's strength properties, assuming a proper mortar mix, is the type, quantity, and distribution of steel reinforcement. The surface area of the steel for adhesion as well as the total cross section area for strength and stiffness are critical. There appears to be an upper limit to the cross section area of the individual strands of steel reinforcements. This limit is related to the adhesion bond strength at the mortar/wire interface. In the extreme case where steel channels are encased, Sutherland has noted that adhesion cannot be maintained and that serious corrosion and loss of strength will result. It would seem that an optimum diameter for rods and mesh could be determined experimentally. As the diameter goes up, of course, the surface area for a given diameter of reinforcement decreases. On this basis the contribution of 3/4 inch pipe in the pipe frame system is seriously questioned.

Current practice is largely a result of expediency in fabrication and has received little scientific analysis. It is entirely possible that material properties could be appreciably improved without undue cost increase. Reference (C-37), for example, notes that compressive samples failed by splitting between the layers of mesh indicating the need for a better system of cross connecting the mesh layers.

With a K factor of 69, ferro-cement reportedly experiences sweating problems (see Table B for comparison to other materials). Styrofoam bonded to the inner hull surface is suggested by ferro-cement builders. (Spraying polyurethane foam into the inside of a hull constructed by the cedar mold method is a very neat way of disposing of the problem of the thousands of nail points that remain after the wood is stripped out.)

Structural Design - Theoretically the criteria, safety factors, and techniques outlined in Sections II and III, with the design stresses from Table B of Section IV, could be applied to the structural analysis of ferro-cement. In practice, this analysis would not apply to the large unsupported panels of double curvature in the typical ferro-cement craft. If treated as flat panels these shells would show excessive deflections and stresses under the design loads, when in fact they may be acceptable because of their shape. It is believed that the theory used for the design of large architectural thin shell structures could be adapted to ferro-cement boat hulls, but this is beyond the scope of this chapter and the knowledge of this writer. It is suggested that a flat panel calculation be made since, if it meets these requirements, there is no question that it will be stronger in a curved surface. Or a comparison can be made empirically to the shape, span and thickness of panels in existing craft of ferro-cement or other materials.

Table B lists suggested design stresses not including safety factors. There is some controversy regarding all the figures except that for modulus of elasticity. For example, ultimate tensile test results published in (C-37) ranged from 450 to 900 PSI depending on type and amount of steel reinforcing. Reference (C-37) reports that these figures are consistent with those of Nervi (1956) and Byrne and Wright (1961). They are in notable disagreement with Lloyds report of "Seacrete" samples (C-44) which gives a figure of 1690 PSI. In the same manner, compression, flexural, and shear strengths show major disagreement. It is suggested that the figures of the British Columbia Research Council (C-37) are best documented and that the lower figures of Table B derived from these values be retained until further test results are available.

COSTS

The issue of ferro-cement costs has been clouded by the considerable publicity accorded the low basic materials costs. As in any type of boat construction, labor costs are the major element. From Table A, ferro-cement basic material cost equals 8¢ per pound, and the total cost per pound equals 47¢. The cost index of Table A (row 11) indicates that a given hull cost should be lower in ferro-cement than in any of the other four materials but by nowhere near the ratio of basic materials costs.

FUTURE

It is clear that improvements in the strength and stiffness/weight ratio of ferro-cement can realistically be expected in the near future. Considerable improvement should be attainable simply by optimizing the type and distribution of the steel reinforcement with no other basic material change.

STEEL

HISTORY

Though iron was used in shipbuilding as early as 1787, it was not until 1875 that mild steel was available and used in shipbuilding. The subsequent use of steel in ships needs no recounting. Use of steel in small commercial craft followed the lead of the material in larger ships.

Pleasure craft are another story. Though steel was the material for the palatial yachts of the early 20th century, smaller pleasure craft were not produced in quantity in steel until after World War II. Between 1946 and 1952, Steelcraft Company of West Haven, Connecticut produced 2000 steel power boats (S-4). Several other firms picked up production of steel power craft. The market for these craft lasted into the 1960's but has since given way to Aluminum and FRP.

Production steel yachts are the exception today although the material is still competitive in the houseboat market. Many custom yachts are still built in steel, particularly in the larger sizes. Steel dominates the field for commercial craft such as workboats, tugs, fishing craft, etc. The crew boat market seems to have swung to Aluminum, but many crew boats are still constructed in steel. With Navy craft: tugs, large landing craft, workboats, and barges are still predominantly steel though there has been some shift to aluminum.

BIBLIOGRAPHY

There is no shortage of references on steel ship construction. This is not the case with steel small craft as the abbreviated bibliography on steel at the end of this chapter will testify. Tim Graul's SNAME paper, reference (S-4), is highly recommended. Reference (S-1), the "Steel Construction Manual", is a good general reference.

ATTRIBUTES

Steel has extraordinary strength and toughness in boat construction. It is easily repaired and modified. Steel craft are essentially fireproof. Full strength welds are easily accomplished. The material is cheap and readily available.

On the other hand it corrodes severely, is noisy, and is expensive to form into other than developable surfaces. If the density of steel could be reduced by a factor of three and if its corrosion resistance and acoustic damping were improved it would be something like the ideal hull material.

FABRICATION

Assembly and welding is generally accomplished with the hull inverted, beginning with the frames. In some cases craft have been fabricated in a rotating jig (see reference (S-4)).

Quality control in steel construction is not a serious problem. Fabrication techniques are relatively unsophisticated and require skills that are readily available. Several non-destructive methods are available for inspecting weld quality.

DESIGN

The criteria and safety factors of Section II, procedures of Section III, and stresses of Table A should be applied.

Flat bar longitudinal framing with flanged plate webs are common. Tee longitudinals are more efficient and less prone to buckling. Pipe is often used at chine and sheer. See reference (S-4) for typical details. Welding in slamming and high load areas should be continuous. In selection of plating it is best to err on the heavy side in favor of reduced distortion and improved welding and impact resistance.

COSTS

See Table B of Section IV for cost comparisons. The steel cost data should be reasonably reliable.

FUTURE

Steel seems to have an assured future in small craft. Where weight and appearance are not critical it is clearly the most cost effective material. Higher strength steels (HY-80, etc.) are available and are currently in use in large ship structures. However, since strength is usually less of a problem than deflection, the fact that these high strength steels have little or no increase in modulus of elasticity over the garden varieties limits their potential benefits in small craft.

WOOD

BACKGROUND

From ancient times until the twentieth century wood was THE material for small craft construction. In fact, the demise of wood as the leading material for small craft has occurred only in the last fifteen years. There are few designers without a fond regard for this strong, clean, natural material from our forests from which have been created the lovely traditional craft of our heritage.

Many of the new generation of designers, however, this writer among them, bred on the new materials, have insufficient understanding of wood, its potential, and applications. Wood is still the principal building material in many countries of the world, though it is becoming scarce even in Scandinavia and Southeast Asia. In the United States it still offers an excellent solution to the dilemma of the amateur or small yard building custom craft. The more sophisticated forms of construction: double planking and laminated structure, still offer an attractive stiffness/weight ratio for high speed craft, as evidenced by the many wood patrol craft in world service.

THE INDUSTRY TODAY

In the construction of production small craft hulls, wood will soon become a rarity. An advertisement in the August 1969 Motor Boating for the Matthews "45" in fiberglass signalled the fall of one of the last bastions of wood production yachts. There are, however, scores of yards in the U. S. still building custom wood yachts.

Maintenance of the thousands of wood pleasure craft throughout the country has provided a steady business in repair and upkeep. Small fishing craft and trawlers constructed in the U. S. are still predominantly in wood though steel, aluminum, FRP, and even ferro-cement have all entered this market.

Relatively poor durability (decay, high maintenance, vulnerablilty to damage) is probably the quality most responsible for replacement of wood by fiberglass and aluminum, and now ferro-cement. Wood also suffers on a weight basis in comparison to aluminum and in some cases to FRP. Another steadily increasing handicap to wood is the high price and low availability of good boatbuilding woods and skilled labor.

BIBLIOGRAPHY

Not surprisingly, there is no shortage of good references on all phases of wood boatbuilding. Many are listed in the Bibliography at the end of this chapter. Applicable references will be cited in the following discussion.

ATTRIBUTES

The reader is referred to references (W-51), "The Timber Design and Construction Handbook", (W-24), "The Wood Handbook", and (W-52), "Wood, A Manual for its Use as a Shipbuilding Material", for comprehensive discussions of this subject. Several items of particular interest are discussed below.

Hardwoods and Softwoods - This is a somewhat misleading classification which has nothing to do with the hardness of the wood. Hardwoods are the trees with broad leaves, softwoods are the evergreens or conifers.

Moisture Content - Moisture content is generally expressed as a percentage of the weight of the oven-dry wood. "Air-dried" lumber may range in moisture content from 6% to 24% depending on the locality of the air drying. Average moisture content for air dried wood is 12 to 15 percent. Kiln dried lumber runs from 4 to 12 percent. Moisture content is inversely proportional to most strength properties, the drier the wood, the stronger it is. Moisture contents for green wood range from 30 to 200 percent depending on the species.

Decay - Wood decay is produced by fungi, organisms which live on the wood substance. They must have certain amounts of moisture, air, and a specific temperature range in order to grow. Lack of moisture or complete immersion will prevent decay as will lack of air or extreme high or low temperatures. Even "dry rot" requires more (over 20%) moisture than is contained in air dried lumber. Decay will progress between 40° F. and 100° F., most rapidly at 75° to 85° F. It is generally believed that decay is more rapid with fresh water than with salt water.

The best protection against decay is to use decay resistant species of wood since it is virtually impossible to prevent decay conditions from occurring. Second choice is to apply preservatives. Heartwoods are more decay resistant than sapwoods which are subject to decay in almost any species of wood. The following species are listed in their order of resistance to decay (best first-from (W-37)):

1. Live Oak
2. Juniper
3. Cypress
4. White Oak
5. Yellow Bark Oak
6. Gray Oak
7. Yellow Pine (dense)
8. Douglas Fir (dense)
9. White Pine (Eastern)
10. Hackmatack
11. Douglas Fir (average)
12. Larch
13. White Pine (Western)
14. Ash
15. Red Oak
16. Beech, Maple & Birch
17. Spruce

Marine Borers - Marine borer activity rises with the water temperature. These organisms are active on all coasts of the U. S., though less so in the North. All woods are attacked by marine borers. Protection consists of keeping the surfaces underwater completely covered with paint. Worm shoes are often added on the keel as paint is easily removed by groundings.

Acoustic Properties - Wood has a superior ability to damp vibration and consequently may be considered the best of the boatbuilding materials for inherent acoustic insulation properties.

Directional Strength Properties - Wood fibers are oriented in a pattern parallel to the tree trunk called "grain". Strengths of wood parallel to the grain vary greatly from properties across the grain. Compressive strength parallel to the grain is 5 to 10 times this property perpendicular to the grain. The ratio for tensile strength is even higher. Modulus of elasticity may vary by a ratio of 100. Strength properties perpendicular to the grain do not vary greatly when measured radially or tangentially to the growth rings. For strength properties of common boatbuilding woods the reader is referred to the references cited above and to Table B.

WOOD SPECIES

Only the principal boatbuilding woods will be mentioned here. See reference (W-52) for a detailed discussion of other species.

Oak - White Oak is best for primary structure such as frames or floors. Durability is excellent and strength is high. Black Oak is similar to White Oak. Red Oak and Gray Oak are generally unacceptable from a decay resistance standpoint though they have been used successfully after pressure treatment with preservative. Live Oak is at least equal to White Oak but is no longer available.

Elm - American Elm and Rock Elm are used for bent frames and interchangeably with White Oak for keel, stem, etc. Decay resistance of Elm is not as good as White Oak.

Juniper - Newfoundland Juniper has been used for entire vessels. It has good decay resistance.

Cypress - This wood has good decay resistance as planking but tends to swell and shrink excessively.

Long Leaf Yellow Pine - This wood has good strength and rot resistance and is widely used for planking and structurals.

Douglas Fir - Douglas Fir is strong, moderately hard, and has moderately good decay resistance. It is used widely for structurals and also planking. The material must be carefully selected as quality varies greatly with locality of growth.

Eastern White Pine - This wood is knotty and is used principally for decking.

Hackmatack - This wood is considered superior to White Oak but it is generally unavailable.

Mahogany - Mahogany is expensive but is widely used in yacht construction. It has good strength and decay resistance.

Greenheart - This wood has excellent strength, hardness, and decay resistance.

Black Locust - Black Locust is strong, heavy, hard, and decay resistant. This wood was used extensively for "treenails".

Teak - Teak is strong, hard, heavy, extremely decay resistant, very expensive, and difficult to work (because particles of silica trapped in the grain ruin cutting edges).

Western Red Cedar - This wood is used on the West Coast for planking. It is somewhat soft and weak but has good decay resistance.

Port Orford Cedar - This is the heaviest and strongest of the cedars. It is used for planking.

PLYWOOD

This material is widely used in the construction of small craft. It is particularly suitable for amateur construction, though lines are limited to developed surface. Generally Fir plywood is used in this country though plywoods are also available in several African woods such as Utile, Gabon and Khaya, as well as in Philippine Mahogany.

Fir plywood is manufactured in two general types, Interior and Exterior. Only Exterior grade is suitable for use on a boat. Marine Exterior is a premium panel which is all Douglas Fir (or Larch) and has tightly joined cross plys virtually eliminating the core voids which may occur in regular Exterior grade. There are three veneer grades used in Exterior plywood. Panels are available with grade A veneer on one face and grade A, B or C on the other. Where both sides should be smooth and tight A-A or A-B should be used. A-C would be acceptable for decking or floorboards.

FABRICATION

There are many excellent references on wood boatbuilding. Chappelle's "Boatbuilding" (W-15), for example, gives a clear, detailed, well illustrated description of all of the conventional building methods. This section will summarize the types of wood construction.

Carvel Planking - This is the most common planking system. The hull may be V or round bottom. Planking runs fore and aft over bent or sawn frames. In "batten seam" construction all planking seams are backed by wood battens which are let into the frames. Batten seam construction is good for construction of power boats subject to vibration and slamming which would tend to open the seams.

Cross Planking - This method is common to many indigenous flat or V bottomed power and sailing craft such as the Skipjack and Sharpie. Planks run from keel to chine, raked slightly aft, or in flat bottom boats directly from chine to chine with only an outer plank keel on centerline.

Lap Strake - Lap Strake construction produces a strong, rigid and very light hull. Boats of lap strake construction are used as surf boats in many parts of the world because of these qualities. Each plank is lapped over and fastened to the plank below. Pine, cedar, and mahogany as well as oak and elm are used for lap strake planking. Lap strake planks are difficult to repair and difficult to keep tight once the seams have opened. Lap strake hulls were in the past commonly built to lengths over 50 feet.

Strip Planking - Strip Planking involves the use of narrow, often almost square in section, planks, edge fastened and sometimes glued as well as fastened to the frames. Edges must be beveled or alternately rounded and cut with a concave edge to provide a tight seam. This method is unpopular with professional builders because of the excessive number of fasteners required. Repair is difficult. Strip Planking with planks up to 3 inches square has been accomplished.

Double Planking - There are three basic forms of double planking: 1) The "Ashcroft" system with two plies of thin diagonal planks at about 45 degrees to the keel running parallel but with seams staggered. 2) Double Diagonal - two thin layers set perpendicular to each other, each at 45 degrees to the keel. And 3) Diagonal and Fore and Aft - This system involves a thin inner diagonal ply and a heavier fore and aft outer layer. All of these systems provide a strong, lightweight structure. The system is excellent for high speed power craft. Double planking may be set in glue or various bedding compounds. This is an expensive system and a system difficult to repair.

Plywood - Plywood is particularly popular with amateur builders. Hull lines should be developed surface. Plywood produces a strong, lightweight, rigid structure. Glued joints are commonly used. See references (W-57) and (W-58) for good descriptions of plywood fabrication processes. In larger craft, plywood is commonly used for decks, bulkheads, and deckhouses. Plywood is the best form of wood to be covered with fiberglass as it does not shrink and swell as much as solid planking.

Molded Plywood - This system involves the fabrication of plywood "in place" by stapling and glueing strips of veneer in alternate diagonal layers over a male mold and curing with heat and pressure. This method of construction has largely been replaced by FRP. It had the principal advantage of not being limited to developed surfaces.

FASTENINGS

The key to successful wood construction lies in the fastenings. Common boatbuilding woods listed in the order of their ability to hold fastenings (best first) are (W-37):

1. Beech
2. White Ash
3. Elm
4. Yellow Pine
5. Douglas Fir
6. Cypress
7. White Pine
8. Port Orford Cedar
9. Spruce

In general all fasteners require a slightly undersize hole. Ends of fasteners are puttied or sometimes counterbored and bunged.

Nails - The hot-dipped galvanized iron boat nail, rectangular in cross section with a large oval head, is an excellent and durable fastener if used in large enough sizes (W-15) with ample galvanizing. Bronze or monel serrated nails are often used today. These tend to be more slender than iron nails and have less resistance to side loads. Clench nails of galvanized iron or copper are used, often as rivets over burrs (tight fitting washers).

Screws - Bronze and galvanized screws have better holding power than nails. Galvanized screws are less likely to wring off, but have less holding power than bronze. Brass screws should not be used on a boat as they corrode badly and have poor strength.

Bolts - Galvanized or bronze bolts are used in many high strength applications. Thick washers must be used at both ends to prevent the heads or nuts from being drawn into the wood.

Glue - Resorcinol and other glues have been used widely in recent years in boat construction. In some cases craft to 100 ft. in length have been constructed with all-glued connections and a very minimum of fasteners. Some pressure is necessary but glueing can be done effectively at room temperature. A large advantage of resorcinol glues is that tools used with them can be cleaned in water before the glue sets, though it is impossible to remove without scraping after it cures.

DESIGN

The criteria and procedures set forth in Sections II and III may generally be applied, though for conventional construction the several scantling rules cited in the Bibliography should be consulted.

For plywood, the many publications of the American Plywood Association should be consulted. For molded plywood, cross planking, and other more advanced forms of wooden construction, as well as for sheet ply construction, the calculation methods in this chapter will be the best approach. The wood manuals should be consulted for stress data.

FUTURE

Though wood technologists are still hard at work devising new ways to use their material, wood is getting scarcer along with the skilled boat carpenters who put it together. The future for wood in boat building is not bright. It is still a competitive, if not superior, material in many applications, but it is ceasing to be a "popular" material.

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This bibliography presents approximately 250 references. They are divided into six categories:

Aluminum	(A)
Ferro-Cement	(C)
Fiberglass Reinforced Plastic	(F)
Miscellaneous	(M)
Steel	(S)
Wood	(W)

Material comparisons, basic strength of materials and general structural articles are included under Miscellaneous.

An attempt has been made to include only material of direct interest to the small craft Naval Architect, i.e. pure materials technology and highly sophisticated design or construction procedures have been excluded.

Comments are included with a number of entries. These were simply added at random when they seemed appropriate.

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M-11 HANSON, P.S.,
"A Lightweight Durable All-Metal Yacht" SNAME, New York Metropolitan Section, January, 1966.

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M-13 HUDSON, RAPLH G.,
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M-14 JASPER, N.H.,
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M-15 <u>KILGORE, ULLMANN,</u>
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M-17 <u>ROARK, RAYMOND J.,</u>
"Formulas for Stress and Strain", 4th Edition (1965) McGraw-Hill Book Co., Inc.
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M-18 <u>SHIP STRUCTURE COMMITTEE,</u>
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M-19 <u>SILVIA, P.A.,</u>
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Principally covers wood construction, through steel aluminum, and GRP are included. Nevin's and Heneshoff's rules are covered in detail.

M-21 <u>SNAME,</u>
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M-22 <u>TIMOSHENKO, S. & MacCULLOUGH, GEASON, H.,</u>
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M-23 <u>TRAUNG, JAN-OLOF, & GULBRANDSEN, OYVIND</u>,
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M-24 <u>VERWEIJ, D.</u>,
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GRP (simple skin and sandwich) is compared to steel, aluminum, and various woods for strength, weight, durability and cost.

STEEL

S-1 AMERICAN INSTITUTE OF STEEL CONSTRUCTION
"Steel Construction Manual"

S-2 BUREAU OF SHIPS
"Strength of Structural Members-Design Data Sheet", DDS1100-3.

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"Structural Design of Flat Plating and Stiffeners Subject to Water Pressure-Design Data Sheet", DDS1100-4.

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"Steel and Wood Scantling Tables (West Coast of U.S.A.)" Pages 137-145 of Fishing Boats of the World: 2 (1959), Edited by Jan-Olof Traung, Food and Agriculture Organization of the United Nations, Published by Fishing News (Books) Ltd., London.

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W-13 BUREAU VERITAS,
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W-15 CHAPELLE, HOWARD I.,
"Boatbuilding, a complete Handbook of Wooden Boat Construction", W. W. Norton & Co., Inc. New York.
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W-18 DOYLE, D.V.,
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W-25 FOX, UFFA,
"Seamanlike Sense in Powercraft", (1948), Peter Davies, London
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W-26 FREAD, A. D.,
"Factors Affecting Strength and Design Principles of Glued Laminated Construction", (1956) Forest Products Laboratory report 2061, Madison, Wisc.

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"Figures and scantling tables are given for small fishing vessels not covered by bodies such as Lloyds and A.B.S. They are for wooden boats of from 30 to 90 ft. with bent frame construction and for those of from 30 to 125 ft. with sawn frames. They also cover V-bottom wooden boats of from 30 to 90 ft. and welded steel vessels of from 30 to 130 ft. in length."

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W-34 LORD, LINDSAY,
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Interesting discussion of modern practices in wood construction. Design philosophy is discussed at length. Sketches of examples are presented.

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W-36 LOVELL, R. E. L.,
"Fast Patrol Boat Hulls- The Case for Wood (Construction Methods in a Hampshire Shipyard)", Ship and Boatbuilder International, June, 1966

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"Wood as a Fishing Vessel Construction Material", paper presented at Conference on Fishing Vessel Construction Materials, Montreal, October, 1968.
Excellent discussion by two of the real old timers in the field. Various wood species are discussed and listed both in order of ability to resist rot and in ability to hold fastenings. A list of construction do's and don'ts is provided.

W-38 OTSU, YOSHINORI, et al,
"Structural Testing of Small Craft", pages 146-151 of Fishing Boats of the World: 2, (1959), edited by Jan-Olof Traung, FAO, Published by Fishing News (Books) Ltd., London.
An interesting account of a loading test on a typical 36 ft. wooden hard chine fishing craft in which deflections are measured and stresses calculated.

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W-40 Pedersen, Gunnar,
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An excellent discussion of material properties and design considerations for wooden fishing craft structure. Design proposals are made for optimum use of the material.

W-41 PHILLIPS-BIRT, D.,
"Motor Yacht and Boat Design", (1953), Adlard Coles, Ltd., London.
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W-42 PHILLIPS-BIRT, D.,
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Discussion of construction in various materials. Excellent discussion of glues for wood construction. Coverage on FRP and aluminum now outdated.

W-43 POTTER, STANLEY,
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W-44 SAETHRE, J.,
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W-49 STEWARD, ROBERT M.,
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W-50 TARBOX, LUTHER H.,
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W-51 TIMBER ENGINEERING CO.,
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W-52 U. S. BUREAU OF SHIPS,
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Excellent source of material properties data. Available from the Government Printing Office, Washington.

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W-54 WATTS, C. J.,
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"Designing With Wood in Small Boat Construction", student paper, New York Metropolitan Section, SNAME, December, 1956

W-56 WHITE FISH AUTHORITY,
"Standard Specifications for the Construction of Scottish Fishing Vessels", U. K.

FIBERGLASS REINFORCED PLASTIC

Notes Prepared for

Course in Small Craft Design

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I. INTRODUCTION

The use of fiberglass reinforced plastics as a boatbuilding material began about 25 years ago, with the construction of a class of 28 foot Navy personnel boats. These early boats proved to be strong, lightweight, water-tight and easy to maintain, and led to a rapid and steady increase in the use of the material, to the point that it is now the most popular material for building small boats.

Despite this popularity, fiberglass is still considered to be a relatively "exotic" material in many circles, and the structural design of fiberglass boats is often more of an art than a science, for several reasons. Many designers have difficulty in utilizing the extensive amount of literature existing on the behavior of fiberglass as a structural material, which is often too complex for their use or difficult to compile into a useful form. Also, most builders of small boats are content to use a rule-of-thumb approach to design, backed up by full-scale testing.

This paper compiles the basic design information that a small boat designer would need to apply a logical yet simple engineering approach to the selection of fiberglass materials and scantlings for small craft. Although the term "small craft" is somewhat limiting, the information in this paper will be useful in designing structures for fiberglass boats of any type: power or sail, commercial, pleasure or military, up to perhaps 100 feet in length.

II. FIBERGLASS AS A BOATBUILDING MATERIAL

BASIC PRINCIPLES

The term "fiberglass", as commonly used to describe the material we are concerned with, is actually a misnomer, since the fiberglass is just one part of a two-component structural matrix, the other being a thermosetting liquid resin which, after being dispersed through the glass, is cured into a hard plastic by chemical action and heat. Hence the name "fiberglass reinforced plastic" (FRP) or "glass reinforced plastic" (GRP), or more simply "fiberglass".

The fiberglass reinforcement is composed of very thin glass filaments, and is available either as a felt-like mat or woven into a fabric. Successive layers of reinforcement are individually impregnated with resin prior to or during its layup against a supporting form or mold of the desired shape. The resin is allowed to cure, forming a strong, rigid structural laminate with the exact shape and surface texture of the mold. The strength of the laminate is controlled by the number of plies and type of reinforcement within a given thickness of laminate.

FRP is truly a synergistic material, in which the combination of the two materials has superior characteristics than either material individually. The plastic resin portion of the matrix has relatively poor physical properties, and would not perform well as a structural material. The glass portion, though composed of individual glass filaments of immense strength, is utilized in a fabric-like form which has no structural capabilities except in tension. The combination of these two materials, however, produces a matrix or "laminate" with excellent physical and mechanical properties, which is impervious to the degrading effects of a marine environment.

The matrix of glass and resin is similar in principle to reinforced concrete, wherein the steel reinforcing bars, like the fiberglass reinforcement, are the main load-carrying members. The resin performs a function similar to the concrete in supporting and positioning the reinforcement so that it can perform effectively.

ADVANTAGES AND DISADVANTAGES

The potential advantages of FRP over other materials for small craft construction are as follows:

Resistance to the Marine Environment

FRP does not corrode, rot or otherwise deteriorate when exposed for extended periods to salt air or water. It is equally unaffected by fuels or pollutants often found in rivers and harbors. Contrary to the popular misconception, FRP will become fouled with grass and barnacles as readily as wood or metal, and thus requires antifouling bottom paint in salt or brackish waters.

Light Weight

With proper design and control in the shop, FRP structures can be fabricated which are about one-half the weight of equivalent steel or wood structures, and about equal in weight to equivalent aluminum structures.

High Strength

The inherent strength of FRP is quite high relative to its weight, and long exposure to salt water has little effect on its properties.

Seamless Construction

FRP hulls are generally fabricated as a one-piece molding, without seams or laps, and are thus leakproof.

Chemically Inert

FRP does not react to salt water or most chemicals, and is not susceptible to electrolysis.

Ability to Orient Fiber Strength

The nature of FRP reinforcement permits the glass fibers to be oriented in the direction of maximum stress, thus providing the designer with the ability to economically optimize strength-weight relationships to a greater extent than with metals.

Ability to Mold Complex Shapes

FRP materials can be molded into a wide variety of complex shapes with relative ease and economy.

Flexibility

The low modulus of elasticity of FRP is beneficial in absorbing energy from impact loads, such as slamming. However, this flexibility can also be a design constraint.

Competitive Cost

Although the cost of FRP materials is usually considerably higher than wood or steel, the over-all cost of an FRP boat is usually only slightly higher than the equivalent wood or steel hull providing the number of hulls being built in FRP are sufficient to amortize the cost of molds and other tooling. Higher costs are to be expected for prototype or one of a kind FRP hulls. FRP is generally competitive with, or slightly cheaper than, aluminum construction for high-volume production.

Ability to Mold in Colors

The plastics used to form FRP laminates can be provided in a wide variety of colors, thus eliminating the need to paint the boat for many seasons. Eventually, however, the colors may fade or chalk, requiring cosmetic painting.

Repairs

FRP structures are relatively easy to repair.

Low Maintenance

The non-corrosive nature of FRP generally results in much lower hull maintenance for smaller craft. The corresponding savings for larger hulls may be less, since antifouling painting is required at the same intervals as with hulls of other materials, and painting of topsides will eventually be required to cover up scrapes, gouges and color fading.

Durability

Recent surveys of U.S. Navy and U.S. Coast Guard small boats indicate no degradation in laminate properties after as long as 15 years service. With proper maintenance and reasonable care, FRP boats would appear to have an indefinite life, though substantiating data is presently unavailable since the material is relatively new.

These advantages are offset by a number of potential problems, which must be considered in designing FRP boats, including the following:

Stiffness

The modulus of elasticity of conventional FRP laminates is usually less than 2×10^6 PSI, compared to 30×10^6 PSI for steel, and 10×10^6 PSI for aluminum. The use of unidirectional FRP laminates with a greater percentage of the glass oriented in the direction of the load can increase the modulus to about 4×10^6 PSI, but FRP is still at a disadvantage in deflection-critical applications.

Hull Strength

Although the basic short term strength of FRP is quite satisfactory, its fatigue strength is generally low, which must be considered in selecting design loads and safety factors. In addition, the notch toughness of FRP structures must be evaluated to determine the problems associated with stress concentrations such as at hatch corners, endings of stiffeners or decks, and other discontinuities. The low buckling strength of FRP also warrants consideration in evaluating the basic structural concepts.

Creep

FRP has a tendency to creep if subjected to long-term loading and if the laminate stresses are high.

Vibration

The low modulus of elasticity of FRP could lead to problems with structural vibrations, particularly in way of reciprocating machinery and propellers.

Abrasion

The abrasion resistance of FRP is less than that of metals, though better than wood. This necessitates the use of bumpers or chafing plates in areas where abrasive loads might occur.

Vulnerability to Fire

The conventional FRP laminate is fabricated with a type of resin which is flammable and will support combination with about the same intensity and flame spread rate as plywood. There are fire-retardant types available which are self-extinguishing after removal of the source of flame; however, they are still combustible to some degree, and the laminates rapidly lose strength at high temperatures. The fire-retardant resins also generate toxic fumes in the presence of fire.

The unquestioned success of FRP as the dominant material in small boat construction indicates that its advantages greatly overshadow the disadvantages. The extensive experience gained in designing, building and operating FRP boats over the past 25 years has produced satisfactory and economical means of coping with the material's disadvantages, which are discussed in detail in subsequent sections.

III. HISTORY OF FIBERGLASS BOAT CONSTRUCTION

The history of FRP boats is well documented in a number of books and technical papers, and will not be covered here in detail. However, a brief review is of interest, and is helpful in gaining a perspective on the material's development.

As noted previously, FRP was used initially for boat construction about 25 years ago by the Navy for personnel boats. Since then, the Navy has continued to rely heavily on FRP for the construction of thousands of small boats from 12 feet to 50 feet in length, including landing craft, utility and personnel boats, line handling boats and whaleboats. Perhaps the most famous Navy fiberglass boat is the 31 foot PBR River Patrol Boat, which has seen extensive service in Southeast Asia.

The U.S. Coast Guard has employed FRP for the construction of a wide variety of utility and patrol boats up to 40 feet in length. Recent examination of an early FRP 40 footer which had seen nearly 20 years of continuous service showed her to be in excellent condition, with no apparent degradation in structural properties.

The history of FRP in pleasure boats could be the subject of a paper by itself. The first uses of FRP were in small runabouts and sailboats, with both the size and number increasing with each year until today 60 percent of all powerboats and 90 percent of all sailboats built in this country are of fiberglass construction. The largest FRP yachts in series production are now about 85 feet long, and the trend is toward even larger boats. The highly competitive nature of the pleasure boat industry has resulted in numerous design and production innovations to improve the performance and reduce the cost of fiberglass structures, including the concept of a drop-in molded FRP hull liner into which berths, galley components and decorative surfaces are integrally molded. This concept greatly reduces the time and cost of fitting out the boat. Other innovations include molded-in buoyancy form and non-skid deck patterns and one-piece molded bottom grillages. The ability to easily mold complex shapes permitted the economic development of a number of new hull forms, such as the cathedral and trihedral hulls, which would be extremely difficult to shape in either wood or metal.

The development of large fiberglass fishing trawlers began about 10 years ago in South Africa with the construction of a series of 63 foot long pilchard trawlers, Reference(1). The success of these vessels led to parallel developments in this country, primarily in the shrimping industry, as noted in References (2) through (5). The first such vessel was the 72 foot trawler R.C. BRENT, launched in Florida in 1968. Today, there are several builders marketing FRP shrimp trawlers about 75 feet long, and service experience with these boats, though limited, is excellent. The largest FRP fishing trawler now in production is a 93 foot stern trawler being built in Peru. Recent studies, Reference (6), indicate the feasibility of FRP trawlers up to 110 feet long, and there is no reason to believe that this is the upper limit on size.

The development of FRP minesweepers was begun simultaneously by the United States and British Navies in the early 1960's. The non-magnetic nature of FRP makes it an ideal material for such a vessel, being both lighter and lower in life cycle cost than conventional wood construction. The U.S. Navy studies, summarized in Reference (7), indicated the feasibility of building FRP minesweepers up to about 190 feet long and led to the construction of a full scale midship section which was recently tested for acoustic characteristics and shock resistance. The British studies and tests were sufficiently successful that a prototype 153 foot FRP minehunter is now under construction, and is to be launched soon. When completed, it will be the largest FRP boat in existence.

FRP has been used for a number of other marine applications over the years, including submarine fairwaters and sonar domes, deckhouses, tanks, masts, hatch covers, buoys, etc. as noted in Reference (8). These applications are generally based upon the light weight, corrosion resistance and durability of FRP. One of the most interesting such applications is the use of FRP for construction of LASH (Lighter Board Ship) barges. A 60 foot prototype FRP barge was recently successfully tested, and is expected to be in production in 1971. The light weight of the FRP barge permits the carrying of more cargo than a steel barge without exceeding the 500 ton lifting capacity of the shipboard crane.

It is expected that fiberglass will continue to maintain a dominant position in small boat construction in the future, including a greater percentage of the one-off or limited production market where other materials have historically had a competitive cost advantage. This is due to recent developments in limited-production technology, discussed later, which have substantially reduced the cost of tooling.

IV. BASIC FIBERGLASS MATERIALS

In this section, the basic materials used in FRP boat construction will be described, as well as the structural concepts utilized. The discussion is basically of state-of-the-art materials, though mention will be made of newly-developed materials which will be used increasingly for small boat construction in the future.

The three basic categories of structural materials to be considered are resins, glass reinforcements and core materials used in sandwich construction.

RESINS

The types of resins used for construction of fiberglass boats are of the thermosetting type which once hardened can not be softened by the application of heat. The selection of resins involves consideration of the following variables:

Polyester vs. epoxy

Rigid vs. semi-rigid or flexible

Fire-retardant vs. general purpose

Gel coats

Air inhibited vs. non-air inhibited

Fillers, including thixotropic additives and pigments

Curing cycles and catalyzation systems

Polyester vs. Epoxy

There are two basic types of resins, polyester and epoxy. Under ideal conditions, epoxies have very high bonding strength, particularly to metals. However, polyesters are used almost exclusively in FRP boat construction for the following reasons:

They are less expensive.

They have adequate strength. Although epoxies will result in higher strength laminates under controlled conditions, this potential is not as significant in field applications where cure is taking place at room temperature and without pressure.

Most epoxies have a tendency to lose viscosity as the heat of cure, or "exotherm" increases, and will drain from vertical or inclined surfaces.

Polyester resins allow the use of the simplest and most versatile production techniques of all thermosets, and do not present the personnel hazards of epoxies.

Good chemical resistance.

Better mold release.

Somewhat better heat resistance.

Epoxies possess superior abrasion resistance, less water absorption, greater bonding strength and much lower shrinkage. In addition, they provide somewhat greater flexibility in imparting desired mechanical or resistance properties than polyesters. However, these advantages are not considered sufficient to offset the disadvantages of epoxies, particularly with regard to cost.

Rigidity

The use of flexible or semi-rigid resins offers potential advantages in increasing the resistance of laminates to impact loads, such as hull slamming. However they offer relatively little advantage for primary hull structure, due primarily to the increased overall hull flexibility. Therefore general purpose resins are generally used for structural laminates, though a more resilient formulation would be desirable for gel coats.

Fire Retardancy

As noted previously, polyester resins are available which are classed as fire-retardant. These resins do not support combustion when the source of flame is removed, and are harder to ignite. This property is imparted to the resin chemically or by additives such as antimony trioxide. In the presence of flame, fire-retardant resins generate chlorine gas which smothers the flame. They have not become popular in commercial boat construction, due to higher cost and specific gravity, as well as greater difficulty in laying up. At this time, their use is required in all Navy and Coast Guard boats, as well as lifeboats. However, it is doubtful whether use of fire-retardant resins will become common for pleasure boats unless required by Federal regulations.

Gel Coats

A gel coat is a specially formulated resin mix applied to the mold, prior to layup of the first layer of reinforcement. This coating duplicates the mold surface, forms the outer surface of the part, and provides protection against water penetration and weathering.

Air Inhibited vs. Non-Air Inhibited

Polyesters are basically air inhibited resins, and will not cure fully in the presence of air. To affect cure in air, paraffin is often added to the resin, which floats to the surface of the resin as a result of the heat of cure, sealing it from the air. Such resins, called non-air inhibited, are the most commonly used in boat production. The wax film presents potential problems in either bonding to the surface or painting it, generally requiring sanding or solvent washing to remove the wax.

Fillers

The use of fillers, such as silicon dioxide to make the resin thixotropic, i.e. increasing its viscosity when at rest to prevent running on vertical surfaces, is recommended for those components of the hull structure that must be fabricated in a vertical or inclined position. Thixotropic resins are available pre-compounded from the manufacturer. Fillers are added to gel coat resins to reduce shrinkage, minimize crazing and to improve surface finishes. Laminates containing fillers may be opaque, making visual inspection difficult. Pigments may be added to both the resin and gel coat to impart permanent color. Although this impairs visual inspection of the laminate, this is not generally objectionable.

Curing Cycles and Catalyzation

Fiberglass reinforcement and properly catalyzed resin can be cured to a hard structural laminate by either the application of heat from an external source, or by the addition of an accelerator to the resin-catalyst mixture to produce sufficient internal heat to cure the laminate at room temperature. Heat cure has been used to produce small parts with superior physical properties on a mass produced basis. Due to the rapid cure cycle, cost of the heated molds and the cost of the large external power supplies, the use of heat cure for larger layups such as boat hulls is generally impractical.

For a room temperature cure, the curing cycle or "gel time" of a resin is a function of the type and concentration of the catalyst and accelerator. By adjusting the percentages of catalyst and accelerator, the fabricator can adjust cure time to provide adequate time for impregnation and layup of the reinforcement prior to the start of resin hardening. For normal boat layups, with laminate thicknesses of one-half inch or less, gel times as short as 30 minutes are common. However, for thicker laminates, the heat of cure, or exotherm, would be so great with such short gel times that laminate distortion and poor quality would result. Accelerators and catalysts will only work together in certain combinations. The following combinations are most commonly used for layups of polyester resin:

Catalyst: Methyl Ethyl Ketone Peroxide (MEK)
Accelerator: Cobalt Naphthanate

Catalyst: Cuemene Hydroperoxide
Accelerator: Manganese Naphthanate

The former combination should not be used for gel times exceeding four hours.

Recent advances in ultraviolet (uv) curing permit the curing of pre-impregnated reinforcement under direct exposure to uv energy. Since the cure cycle is directly dependent on the application of uv energy, it is possible to eliminate pre-cure and to control the cure cycle very closely. In addition, no appreciable exotherm results, and cure times can be considerably reduced with thin laminates. However, present uv cure technology is primarily based upon vacuum bag curing of relatively small, thin laminates under closely controlled conditions. Manufacturers of uv prepregs do not feel that the technology is presently applicable to the cure of large FRP components, or that a technological breakthrough can be expected in the near future.

REINFORCEMENTS

Reinforcing materials are made from very thin glass filaments drawn together to form continuous bundles, known as strands. The strands are used to make various types of reinforcements such as cloth, woven roving, mat, and unidirectional rovings. The glass filament used in boat hull construction is a lime-alumina borosilicate E glass of low alkali content, which has high chemical stability and moisture resistance. The higher strength S glass is not used because of its high price. Reinforcements are generally sold in rolls, varying in width from thin tapes 3 or 4 inches wide up to as much as six feet. Successive layers of reinforcement are impregnated with resin until the desired thickness is achieved.

Cloth

Cloth is a plain square open weave material, used primarily in small boat construction for surfacing the exposed areas of hulls and superstructures and for repairing laminate defects. It improves appearance, but is expensive and builds up thickness too slowly to be economical for general construction. The dry weight of the more commonly used cloths varies from 6 to 10 ounces per square yard, the latter requiring about 40 or 50 plies or layers to build up a laminate thickness of one inch.

Woven Roving

Woven roving reinforcements consist of flattened bundles of continuous strands woven into a heavy plain weave with a slightly greater number of strands in the "warp" direction, parallel to the length of the roll of material, than in the "fill", perpendicular to the roll. Woven roving is commonly used as a reinforcement for marine applications. When layup is by the contact or hand layup molding method, woven roving has the following advantages:

Has good drapeability and handling characteristics.

Builds up laminate thickness rapidly.

Provides higher strength and stiffness than mat.

Has directional physical properties for orientation in high stress areas.

Has good resistance to impact because of the continuous, untwisted strands in the individual bundles.

The most commonly used woven roving for boat construction weighs 24 ounces per square yard dry, and consists of 5 bundles per inch of width in the warp direction and 4 bundles per inch in the fill direction. This material builds up thickness at the approximate rate of 25 plies per inch. A lighter 18 ounce woven roving is also used, though to a lesser extent.

Woven rovings weighing up to 40 ounces per square yard (compared to the 24 ounce per square yard woven roving in general use today) are within the state-of-the-art capabilities of reinforcement manufacturers. The use of these heavier woven rovings is being considered for laying up the thick laminates required for larger hulls. Mechanical impregnating and material handling systems are also suggested in order to insure proper wet out and quality control. Mechanical impregnation will provide greater control of the glass-resin ratio, increase wetting of the glass fibers, reduce resin wastage and will permit the use of polyester resins of higher viscosity. The cost of additional equipment should be offset by lower resin wastage and labor costs. A mechanical impregnation of this type was used successfully in laying up the midship test section for the U.S. Navy FRP minesweeper program. Thus the technology required to develop such equipment is now available.

Mat and Chopped Strand

The chopped-fiber type of reinforcement is available as a prefabricated mat made from short randomly oriented chopped strands of fiberglass held together with a soluble resin binder, or the glass strands may be chopped, mixed with resin and simultaneously deposited in the mold with a chopper-spray gun. Mat reinforcement has the following advantages:

Lower cost per pound and unit thickness than fabrics.

Homogeneous material with equal physical properties in all directions.

Good interlaminar bond due to the interlocking action of the fibers.

Can be molded into more complex surfaces and shapes than fabrics.

Easy to wet out.

Preformed mats are available in weight of from 3/4 to 4 ounces per square foot (note that mat weights are specified on a square foot basis rather than on a square yard basis). The most commonly used mat weighs 1-1/2 ounces per square foot dry and builds up thickness at the rate of about 20 plies per inch.

Mat laminates have a lower glass content than fabric laminates with a resulting lower strength and modulus of elasticity. Thus mat laminates must be thicker in order to have the equivalent properties of a fabric laminate.

Although chopped strands deposited with a chopper gun produces a reinforcement with properties equivalent to prefabricated mat reinforcement, it is difficult to accurately control laminate thickness.

Unidirectional Materials

There are presently several manufacturers producing inexpensive unidirectional materials suitable for marine applications using hand layup procedures. These materials consist of continuous parallel strands of fiberglass either sewn together or bonded to a light mat backing to form a roll or bolt of reinforcement. In addition to the pure unidirectional material, with all fibers parallel to the warp, there are a number of possible variations with bundles of glass in the fill direction as required to suit strength requirements. The percentage of glass in the warp and fill direction can be varied over a wide range. These materials offer high strength and stiffness in the warp direction, and maximum freedom to optimize weight-strength relationships. They are generally somewhat more expensive than woven roving, though purchases of large quantities of material would reduce this differential. To date, the primary use of undirectional reinforcements of this type for marine applications has been in the production of large sailboat hulls, particularly in Canada. No attempt has yet been made to mechanically preimpregnate and lay down these unidirectional reinforcements, though this would not appear to be a problem.

Sizes, Finishes and Binders

Sizes and finishes are chemical treatments applied either during the manufacture of the fiberglass filaments or to the reinforcement after it is woven into cloth and cleaned to improve the chemical bond between the molding resin and the glass filaments. For use with polyester resins, silane or chrome type sizes and finishes can be used, although the silane types are recommended for marine applications since greater laminate wet strength is obtained. Highly soluble polyester resin binders are used to hold together the short randomly oriented chopped strands of mat reinforcement during handling and layup.

GRP Composites

A composite fiberglass reinforcement, consisting of alternating plies of mat and woven roving, is used extensively in commercial small boat hull construction. They may be layed up individually, or in combination where several plies are sewn or bonded together. This composite reinforcement provides improved interlaminar bonds between successive plies, reduced porosity, and allows several plies to be layed up at one time. In addition, the resultant weight-strength and weight-stiffness characteristics appear to be ideal for small boat hulls except where minimum weight is required for high performance. The most common such composite consists of 24 ounce woven roving and 1-1/2 ounce mat, which builds up thickness at the rate of about 12 plies per inch.

Preimpregnated Reinforcements

Preimpregnated reinforcements are reinforcements preloaded with polyester or other molding resins which are either layed up immediately or stored for later use. The preimpregnating is usually done by machine in order to better control the glass to resin ratio. In addition to greater control of the glass-resin ratio, preimpregnated reinforcements provide increased wetting of the glass fibers, reduced resin wastage and allow the use of high viscosity resins. The additional equipment and storage facilities required, the reduced storage life and handling difficulties during layup due to the tackiness of the resin are the major disadvantages of preimpregnating, and have limited its use in FRP small boat construction.

CORE MATERIALS

Many materials are used as structural cores for stiffeners and sandwich panels including wood, foamed plastics and honeycomb. The selected core material should have good shear strength and rigidity; ability to bond adequately to the facings with a minimum of difficulty; resistance to deterioration due to water, fungi, and decay; light weight; and sufficient crushing strength to withstand loading loading.

Wood

Hard woods, plywood and balsa are some of the typical types of wood used as core materials. Plywood has good strength, rigidity and ability to withstand local loads and is commonly used for bulkheads and deep girders. However, plywood is relatively heavy and should be of exterior grade only. Hard woods are not generally used since they have a tendency to swell and crack the covering laminate and do not bond well to FRP. Softer woods, such as pine, are used for some applications. Although they can also cause swelling problems, they bond well to FRP. Woods should not be treated with preservatives which will prevent adhesion of polyester resin. Because of possible rotting, swelling and degradation, the use of wood cores in areas below the waterline or adjacent to tanks is not recommended unless special precautions are taken to protect the wood.

Balsa wood, weighing between 6 and 9 pounds per cubic foot, is the most common light weight core material used in small boat construction. In end-grain configuration, with the grain perpendicular to the bond surface, the bond strength is very high. End-grain balsa is sold in the form of small blocks, about 3 inches square, bonded to a light scrim backing, which will drape over curved surfaces. It is also sold in plank form, for use on flat surfaces.

Foamed Plastics

Foamed plastics such as cellular cellulose acetate (CCA), polystyrene, polyurethane and polyvinyl chloride (PVC) offer the advantages of light weight and resistance to water, fungi and decay. Low compressive strength, especially of the very light weight foams, makes then susceptible to damage from local impact loads. Low foam shear strength often dictates the use of FRP shear webs between faces to avoid excessive core thickness on highly-loaded panels. Polystyrene is not recommended, since it will be attacked by polyester resins.

While CCA and polyurethane are rigid materials which will generally not conform to surface curvature, PVC can be obtained in a thermoplastic form which, when heated in an oven to 200 degrees F, will soften sufficiently to be draped over curved surfaces. When it returns to room temperature, it regains its hardness. This tendency to soften when heated can cause problems if the ambient temperature is high, such as on a deck exposed to intense sunlight or over an engine compartment.

The structural grades of foam are generally of 6 to 8 pounds per cubic foot density. Lighter densities can be used for some applications, though physical properties diminish rapidly as density decreases.

Honeycomb

Honeycomb cores of aluminum, fiberglass laminates, cotton duck, waterproof paper and nylon are available in various sizes and weights. They have light weight, good rigidity, poor resistance to concentrated local loads and require highly developed fabrication techniques to produce good bonding between core and facings. Imperfect core-to-facing bonds will permit water travel throughout the core in the event of a leak. The use of honeycomb cores in marine construction is usually limited to interior decks, flats and bulkheads where light weight is essential.

Microballoons

Light weight hollow glass or gas-filled phenolic spheres and polystyrene beads embedded in resin are examples of the high density, trowelled-in-place type of core material presently being used in certain areas of some small boat hulls. In general, their high cost has limited their use to local areas where high core strength is required, such as in way of engine mounts, etc. Alternatively a local core insert of vermiculite and resin (80 per cent resin by weight) can be used.

Buoyancy Foam

Polyurethane or polystyrene foams of about 2 pound per cubic foot density are commonly used for flotation in small boats. These foams may be installed as precured blocks, or, in the case of polyurethane, foamed in place. Foam-in-place polyurethane is made by mixing a polyol and toluene diisocynate (TDI) by either hand or machine and depositing the liquid in the cavity to be filled. The reaction of the components causes the mixture to rise and cure. Since the increase in volume is generally in a ratio of about thirty to one, it is very important to control the quantities of components to prevent under or overfilling the compartment. The cure process is extremely sensitive to variations in temperature, percentages and age of the components as well as the temperature of the hull into which they are poured and expanded.

V. STRUCTURAL CONCEPTS

There are two basic types of construction used in fabricating FRP boats - single skin and sandwich.

SINGLE SKIN CONSTRUCTION

Single skin construction is quite similar to conventional wood or metal construction, utilizing a single thickness of fiberglass laminate supported by frames which reduce panel sizes and provide overall rigidity to the hull. This type of construction is considered the most simple to fabricate, and is used extensively for shells, where it derives considerable strength from the curved shapes which occur in most small boat hulls.

Framing

The framing system used to support the single skin can be either longitudinally or transversely oriented, or a combination of both orientations. In general, longitudinal framing is favored for the bottom of powerboats, utilizing the engine stringers as the main supporting members. The longitudinal stringers are supported by either transverse floors or bulkheads which in turn transfer the loads to the sideshell in shear. The sideshells of powerboats are usually unstiffened, since the combination of shape, built-in berths and other furniture and bulkheads provide sufficient strength. If framing is required, transverse framing is generally shallower in depth, thus causing less interference with internal arrangements. On the other hand, transverse framing is usually somewhat heavier than longitudinal framing, and can not be as easily aligned with built-in furniture.

The hulls of sailboats generally have relatively little framing, due to their pronounced shape. In larger keel boats, it is usually necessary to provide at least two bottom longitudinals, tied into a series of transverse floors to support the keel.

Types of Frames

The methods used by the boatbuilding industry to construct framing systems are almost limitless in number. A few of the more common types are shown in Figure 1, and include the following:

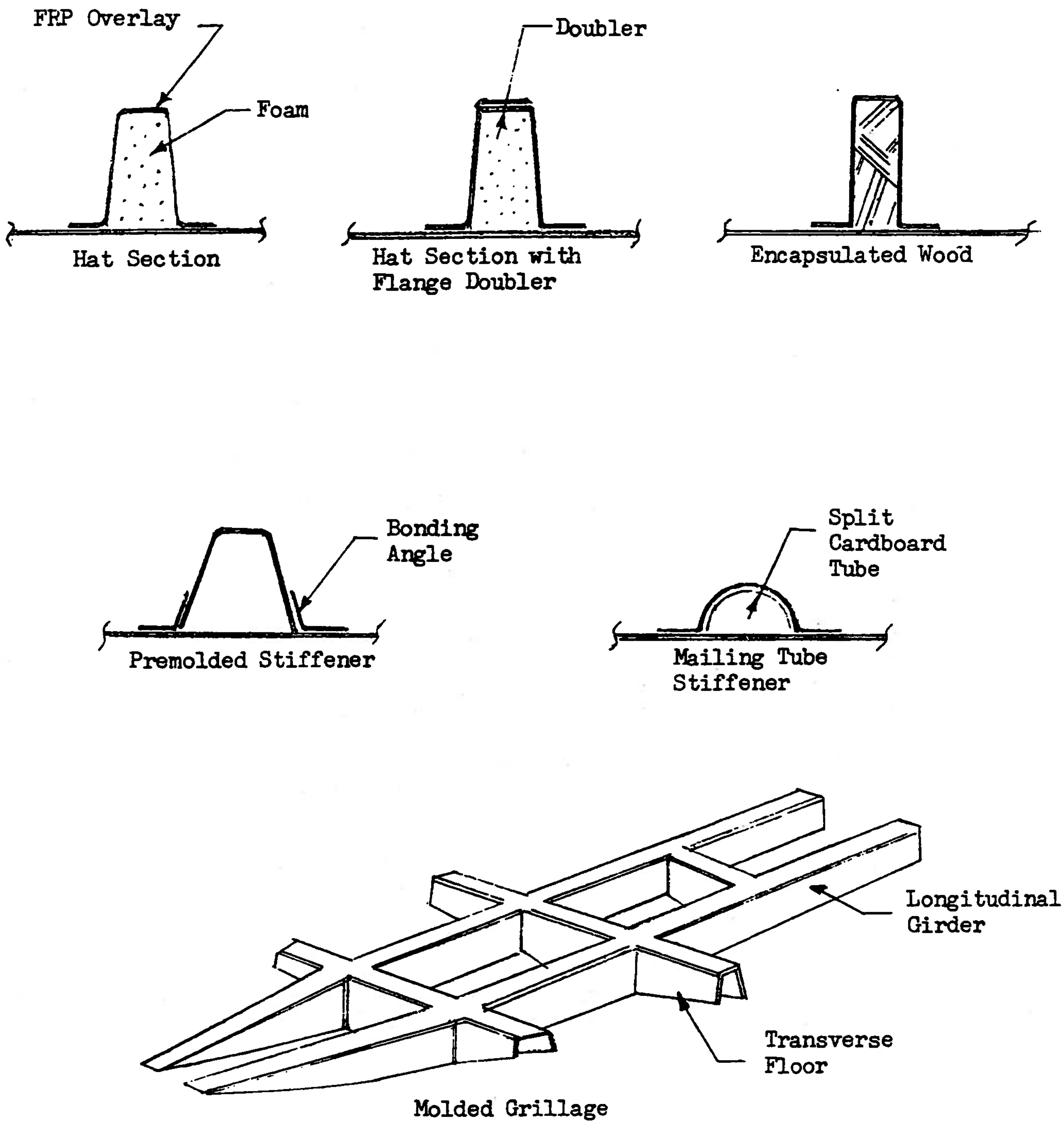


FIGURE 1

TYPICAL FRAMING MEMBERS

(1) Conventional hat section, in which a non-structural foam core is bonded in place and successive layers of reinforcement are layed over the core and overlapped onto the skin. Variations on this type include the use of very light premolded plastic or FRP hollow formers in lieu of foam for a core.

(2) Similar to the hat section described above, but with a number of layers of unidirectional reinforcement on the top flange to increase strength and stiffness.

(3) Encapsulated wood or plywood. This type of stiffener must be designed for the strength of the wood, since the elastic moduli of wood and FRP are quite similar. Thus the FRP is primarily for protection and attachment to the skin. The use of encapsulated wood is questionable in the bottom of boats, because of possible problems with rotting and swelling if the wood gets wet. However, this is fairly common practice in the industry, though most builders use plywood rather than timber because of its better dimensional stability. With wood-cored stiffeners, it is important to properly scarph and overlap joints in the wood to maintain full strength.

(4) Premolded stiffener. This type offers the advantage of close control on dimensions for such critical areas as engine foundations, and precludes the need for a core. Premolded stiffeners are generally installed with FRP bonding angles, which lap onto both the stiffener and skin. An option is to mold horizontal faying flanges onto the stiffener, and to bond the stiffener to the hull with an FRP putty or adhesive. The integrity of such a bond is questionable, however.

(5) Mailing tube. This is a variation on the hat section, using a split mailing tube as a core. These stiffeners are relatively inefficient and are generally used as panel stiffeners on lightly loaded structures.

(6) Molded grillage. Several manufacturers of small powerboats have developed a molded structural grillage incorporating both transverse and longitudinal members, which is bonded to the hull with FRP bonding angles. The underside of the grillage is often foam-filled for flotation.

Framing members are to be run continuously through the structures which support them whenever possible, and rigidly bonded to the supports with small bonding angles. Where this is not possible, the end connection should be carefully designed to minimize peel loads on the fiberglass laminates transferring shear loads from the stiffener to the support.

Bulkheads

The number and location of structural bulkheads provided in small boats is generally determined by arrangements rather than structural considerations. In small powerboats, using outboard or inboard/outboard engines, bulkheads are seldom fitted. As the size grows, and inboard engines are required, it is customary to provide forepeak and engine compartment bulkheads and, in larger sizes, additional bulkheads are provided as arrangements permit. The hull receives additional support from lighter joiner bulkheads if they are well tied into the hull. If arrangements dictate a long span between structural bulkheads, perhaps 15 or 20 feet, it is generally necessary to provide an intermediate transverse floor to support bottom longitudinals unless they are very deep.

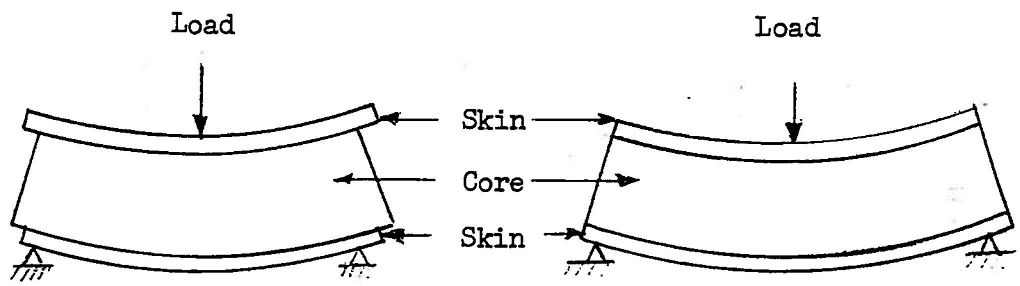
The number of structural bulkheads in a sailboat is quite critical, due to the unique type of loading the hull encounters under full sail in heavy weather. Larger boats used in racing are now often fitted with bulkheads or web frames on 8 to 10 foot centers.

Plywood is almost universally used for bulkheads in FRP boats, since it is relatively strong, rigid and inexpensive. They are normally not framed except in very large boats, with required strength being provided by variations in thickness. The thickness of bulkheads may vary from about 1/2 inch in 20 to 30 foot boats up to a double layer of 3/4 inch plywood in large fishing trawlers. Although this type of construction is heavier than the FRP sandwich panels discussed below, their low cost is an overriding consideration.

SANDWICH CONSTRUCTION

The purpose of this type of construction is to increase the rigidity of a panel by increasing its thickness with relatively little increase in weight. This is achieved by the use of thin FRP skins bonded to a thicker light weight core such as foam or balsa wood. Sandwich panels function similar to an I-beam, in that greater structural efficiency is achieved by placing the material further from the neutral axis. The skins resist bending while the core supports the load in compression and transfers it to the supports.

In the bonding of sandwich panels, a high sliding shear force is developed in the bond between the skin and core. The strength of this bond is extremely important to the performance of the panel. Without this bond, the faces act independently, as indicated in Figure 2(a). With this bond, the faces and core work together, as shown in Figure 2(b), increasing the strength and stiffness of the panel. For the loading shown in Figure 2(b), the top skin is in compression, and the bottom skin is in tension. The core is in compression directly under the load and over the supports, and carries shear loads.



(a) No Bond

(b) Bond Between Core and Faces

FIGURE 2

INTERACTION OF CORE AND FACES

There are three basic types of core materials in general use today, as illustrated in Figure 3:

> Those incorporating light weight cores of foam or balsa, in which the bending is resisted almost entirely by the skins, due to the very low modules of the core.

Those incorporating cores which are effective in bending, such as plywood, which has a modulus of elasticity similar to that of FRP. For this type, the strength of the panel must be based on the lower strength of the plywood.

Those incorporating thin FRP webs to separate the faces. This type of construction permits the use of thinner panels, since the shear strength of the webs is far higher than that of foam or balsa. The voids between shear webs are generally filled with light density foam (2 pounds per cubic foot) both to provide a mold surface for layup of the webs, and to prevent their buckling.

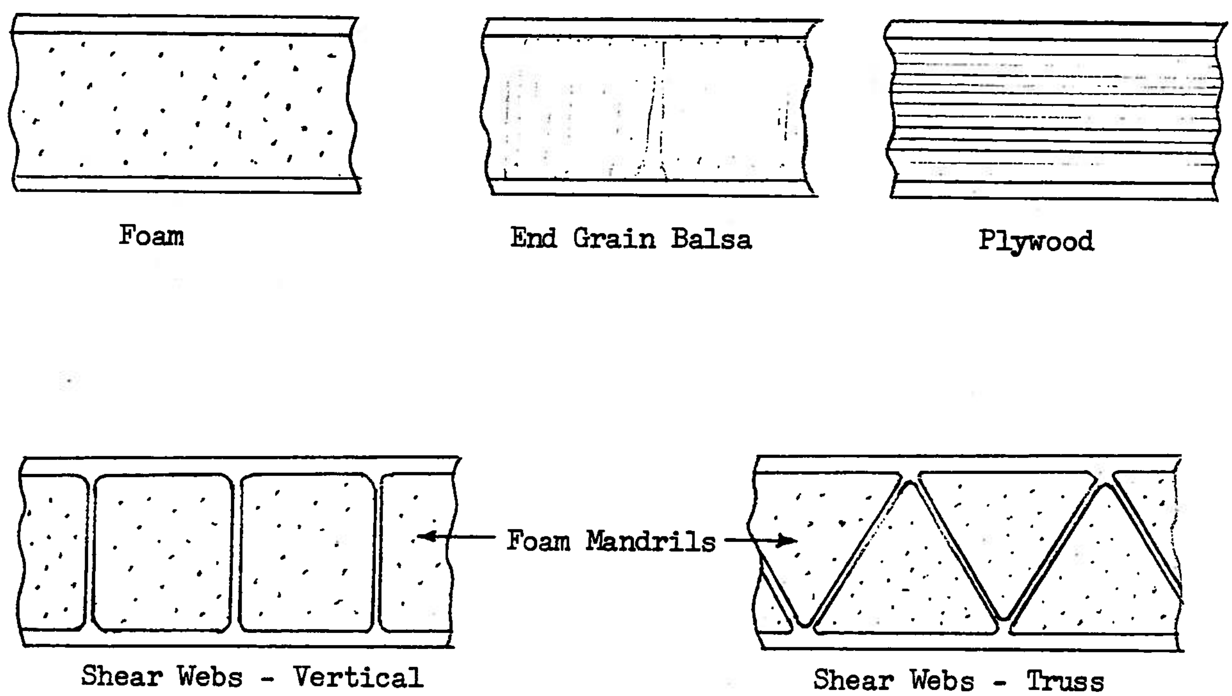


FIGURE 3

TYPICAL CORE CONSTRUCTION

Construction of sandwich panels is generally more difficult than with single skin because of the steps necessary to ensure a good bond between the skins and core, as discussed later. However, for equal stiffness, a sandwich panel will be both lighter and requires less depth than a single skin with frames. Because of this, sandwich construction is generally limited to large flat surfaces such as decks, bulkheads, cabin tops and other areas where single skin construction would be either heavier or would result in a structure whose depth would infringe on headroom.

The stiffness of sandwich panels is particularly advantageous in constructing walking surfaces, where the flexibility of thin single skin FRP panels would be unacceptable. Unfortunately, most people associate strength with stiffness, and feel that a deck with "spring" or "sponginess" is weak. With fiberglass, this is not necessarily so - witness the large deflections of FRP fishing rods - but the boatbuilding industry has had to accommodate this concern for deflection of decks by using either plywood or sandwich construction for walking surfaces as a preferable alternative to thicker single skins or uneconomically close frame spacing.

Because of the relatively low compressive strength of light weight core materials, it is necessary to provide higher strength core inserts in way of through bolts or fittings. These inserts can be of plywood or the microballoon or vermiculite and resin mixture discussed in Section IV. If the fitting loads are relatively light, it is often possible to avoid core inserts by providing large backing plates in way of the bolts, In way of through-hull fittings, it is preferable to taper the core away gradually and utilize single skin construction locally. This prevents possible soaking of the core and subsequent loss of bond strength.

TYPICAL SECTIONS

The structural concepts discussed above are illustrated in Figures 4 through 9, typical midship sections of a variety of FRP boats. These concepts are discussed in greater detail later.

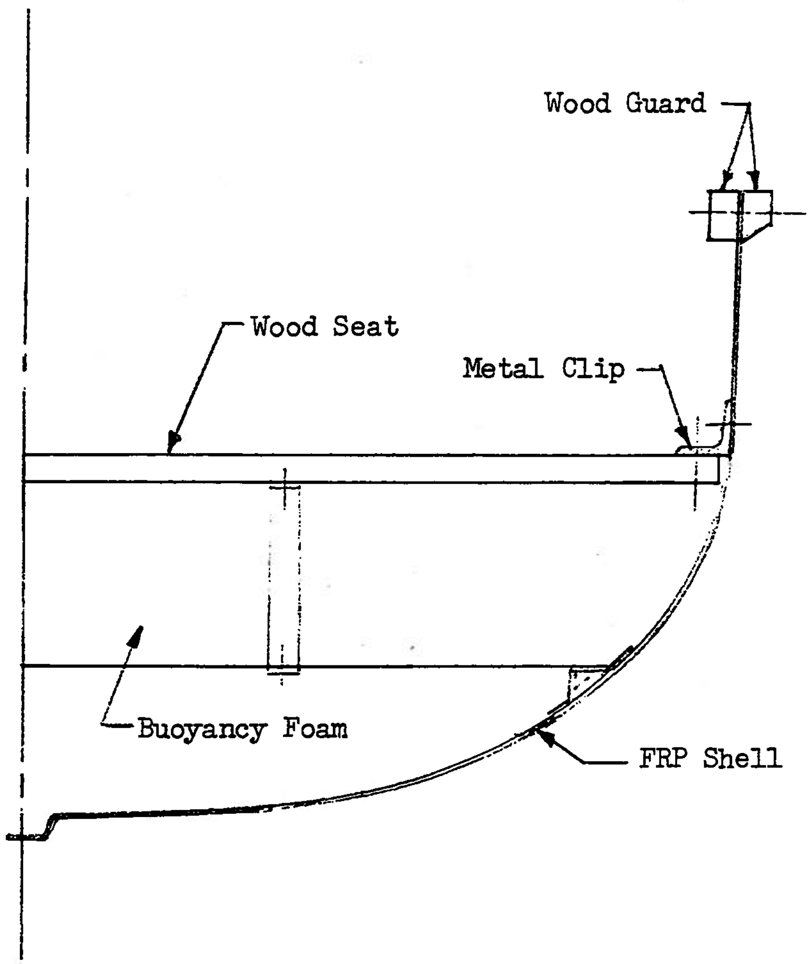


FIGURE 4

SMALL DINGHY

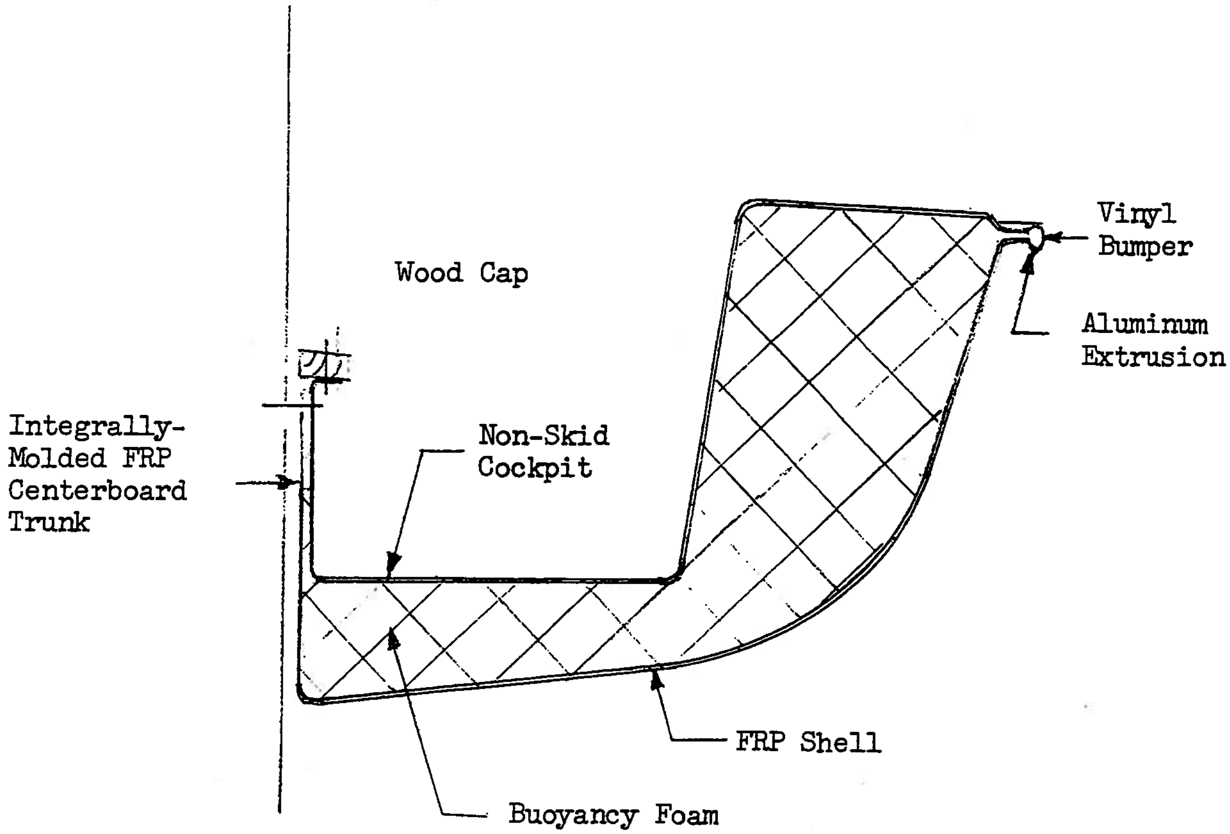


FIGURE 5

SMALL DAY SAILBOAT

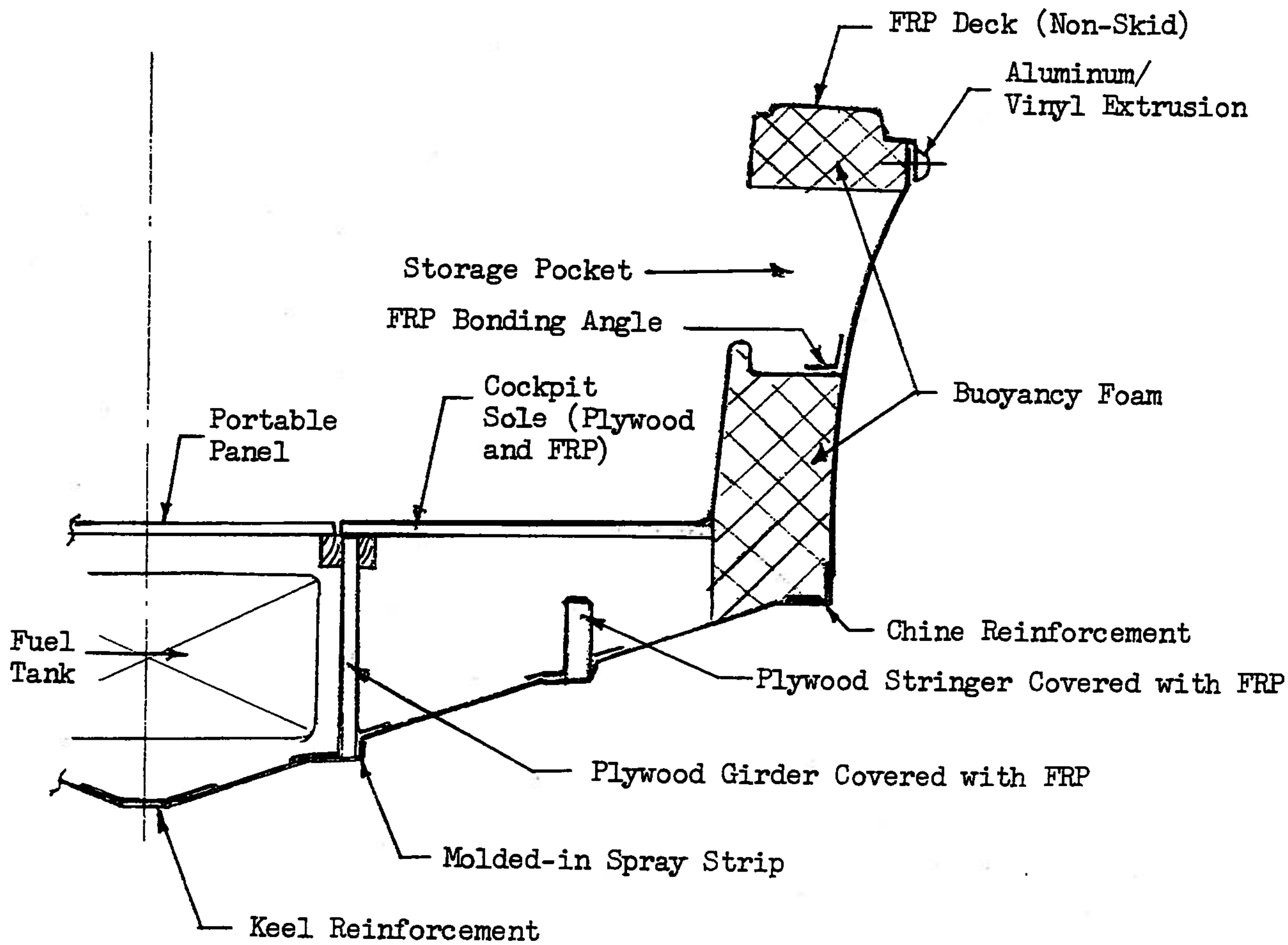


FIGURE 6

INBOARD/OUTBOARD POWER CRUISER

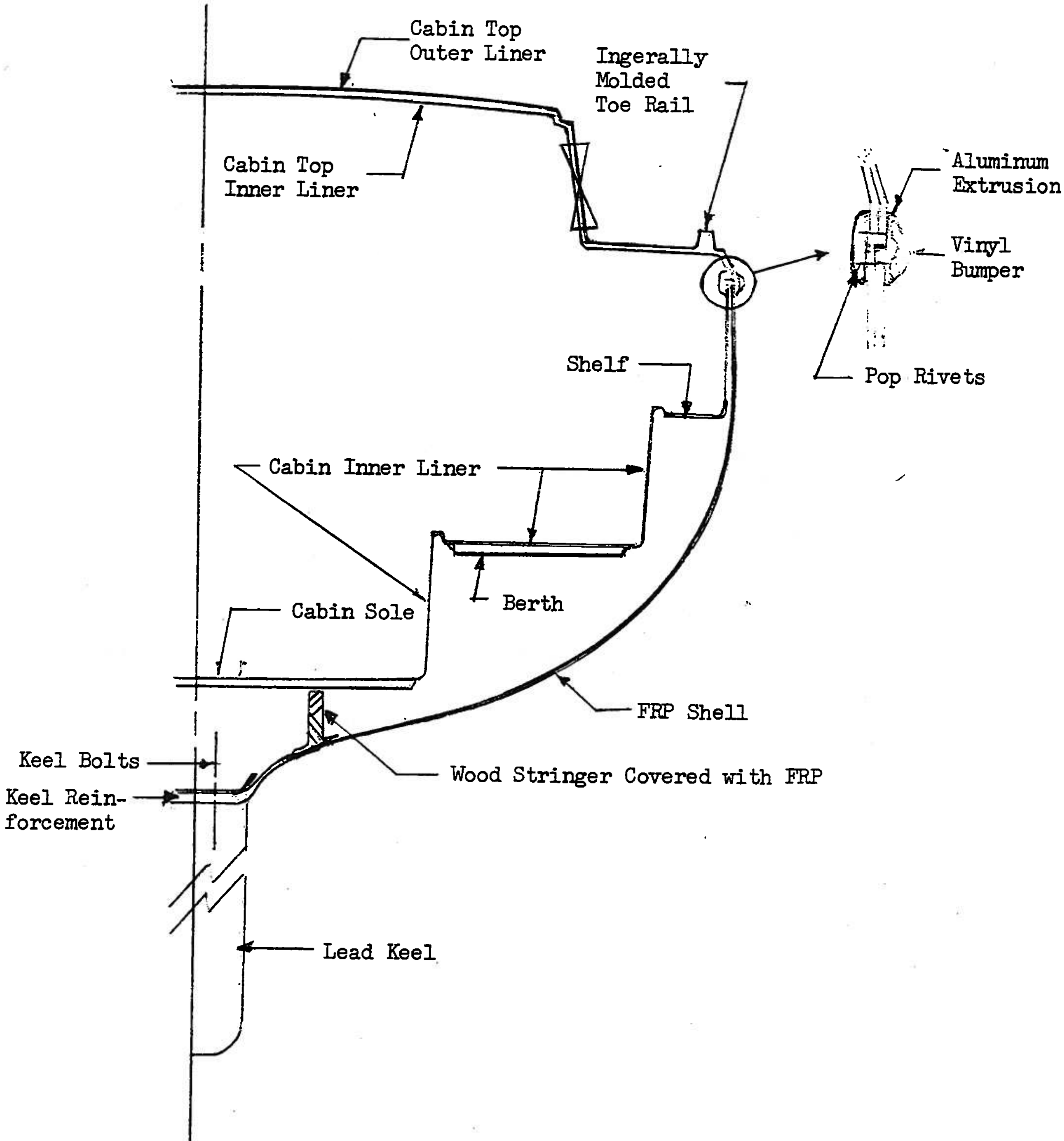


FIGURE 7

OCEANGOING SAILBOAT

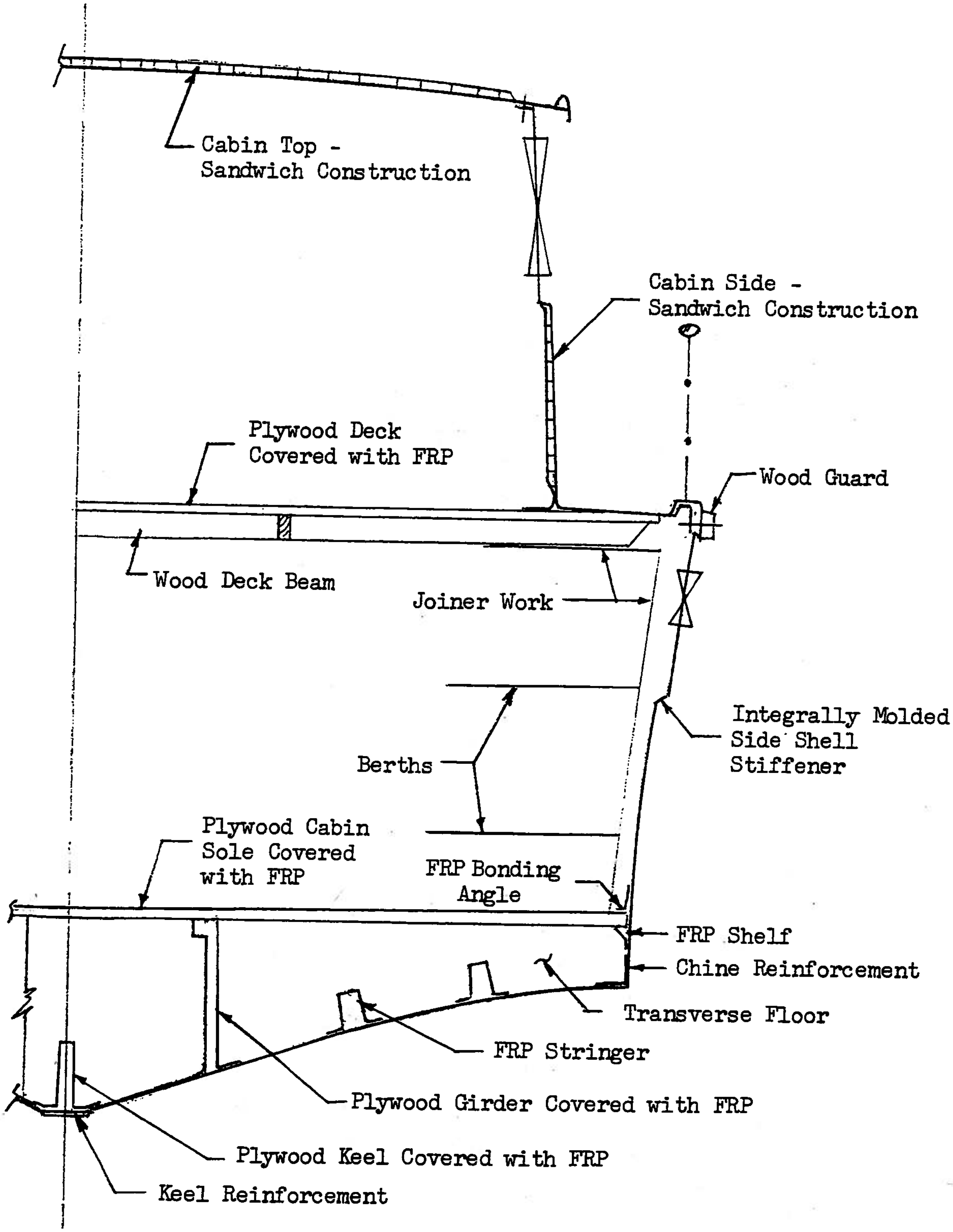


FIGURE 8

LARGE POWER YACHT

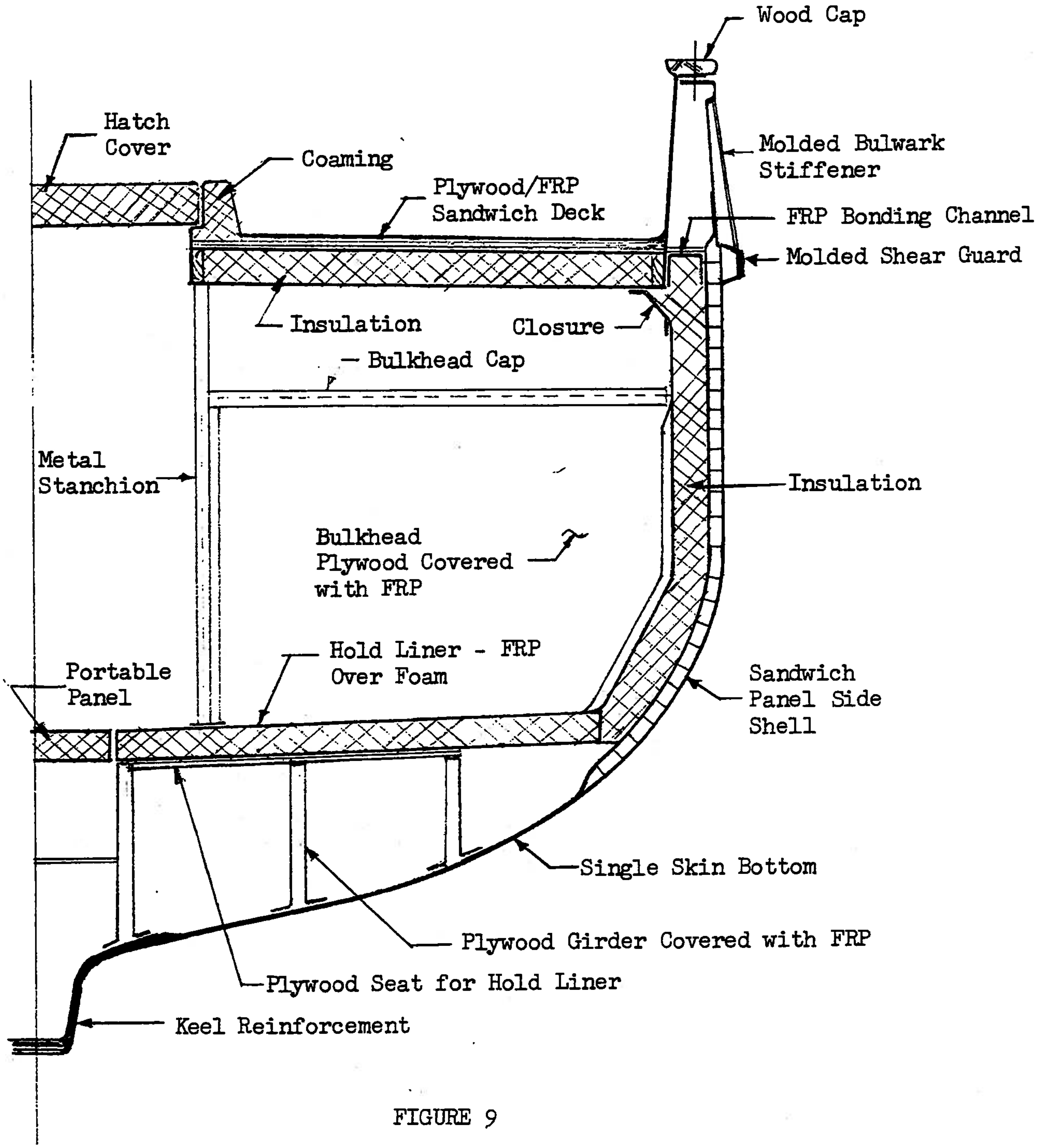


FIGURE 9

SHRIMP TRAWLER

VI. DESIGNING WITH FIBERGLASS

Fiberglass reinforced plastics have a number of rather unusual characteristics which must be understood and considered in conducting structural analysis. However, experience in designing boats of this material has shown that, in most cases, it is possible to develop simplifications which permit the use of conventional design techniques. One of the fundamental reasons for this is that the overall and local loads on small boat hulls are not well defined, and in many cases must be approximated. Thus, a detailed classical engineering analysis of small boat structures is seldom justifiable. In fact, the design process often involves calculating the approximate load-carrying capabilities of boat scantlings which have been derived empirically and which have proven satisfactory over a long period of time, and applying these capabilities to later designs.

The danger in such a process is, of course, the possibility of perpetuating overly conservative designs. In the small boat industry, however, this does not appear to be the case, since the competitive nature of the business has caused the builders to cautiously reduce scantlings from the early conservative designs until failures began to occur in the field. When a clear pattern of failures has occurred, the builders have provided additional strength, to the point that today's FRP small boats are a good compromise between required durability and minimum cost. Naturally, it is impossible to make an FRP boat "idiot-proof". Invariably someone will over-power a boat and thereby induce structural failures. However, economic considerations prohibit the design of boats to suit this fringe element.

In this section, we will look at the characteristics of FRP which are unique, and develop material properties and methods of design which are reasonably easy to apply. For those who wish to investigate the structural design of FRP boats in greater detail, there are a number of excellent books and technical papers available, including References (8) through (14).

REGULATORY BODY REQUIREMENTS

At this time, Regulatory Bodies in Great Britain, Norway, Italy, France and Germany have published Rules for the design and construction of FRP boats, References (15) through (20). In the United States, these Rules have received relatively limited use, since the type of laminates and construction methods presented are not generally used, and many boatbuilders consider them to be overly conservative and inflexible. In addition, English translations of the Norwegian, French, German and Italian regulations are not easily available.

The American Bureau of Shipping is presently in the process of preparing Rules for fiberglass boats from 30 to 120 feet, covering both yachts and workboats. The ABS Rules are expected to provide greater flexibility and responsiveness to the needs of the U.S. boatbuilding industry, and should receive wider acceptance, particularly for larger boats where there is an economic justification for classification. It is somewhat questionable whether they will be widely used for smaller boats, though current popular and Government concern over water safety points up the need for an acceptable guideline on scantlings for small FRP boats.

FRP LAMINATE PROPERTIES

Basic Principles

As noted previously, fiberglass laminates have some rather unique characteristics when compared to metals, which are discussed below.

Orthotropicity

FRP laminates which utilize woven or fabric type reinforcements are not isotropic. As noted previously, the number of fibers in the warp and fill direction differ, with corresponding variations in properties. This phenomenon, discussed in detail in Reference (8), represents one of the primary advantages of FRP - ability to orient fiber strength with the direction of principle stresses. For a balanced fabric reinforcement such as woven roving, the strength in the fill direction is generally less than 20 percent below the maximum, or warp strength. However, at 45 degrees, i.e. diagonally across the woven pattern, the laminate strength is considerably reduced. This can be understood if you grasp a piece of cloth, such as a handkerchief, and pull it either longitudinally or transversely relative to the weave. The strength is relatively high, and about equal. However, if the material is pulled on a bias, the fibers tend to slide over each other, and the piece of cloth distorts into a parallelogram relatively easily. The same behavior is observed with fiberglass laminates of woven material as shown in Figure 10.

In contrast to woven roving or cloth, mat laminates are essentially isotropic, due to the random nature in which the individual glass fibers are deposited during the manufacturing process. Composites of mat and woven roving show a loss of strength at 45 degrees, but not as pronounced as an all-woven roving laminate.

Unidirectional laminates have very high strength in the warp direction since all of the glass is working in the direction of the stress. The strength in the fill direction is very low, corresponding to that of the resin. For general use in boat construction, such a situation would be intolerable, since the stresses in panels are never in one direction only. Thus it is generally necessary to lay up some cross plies or diagonal plies in conjunction with the primary unidirectional laminate.

Non-Yielding

Fiberglass laminates do not have a yield point, but respond elastically until failure occurs. Thus the stress-strain curve is a nearly straight line from zero load to failure. This lack of a "plastic" zone between yield and ultimate strength should be reflected in design safety factors.

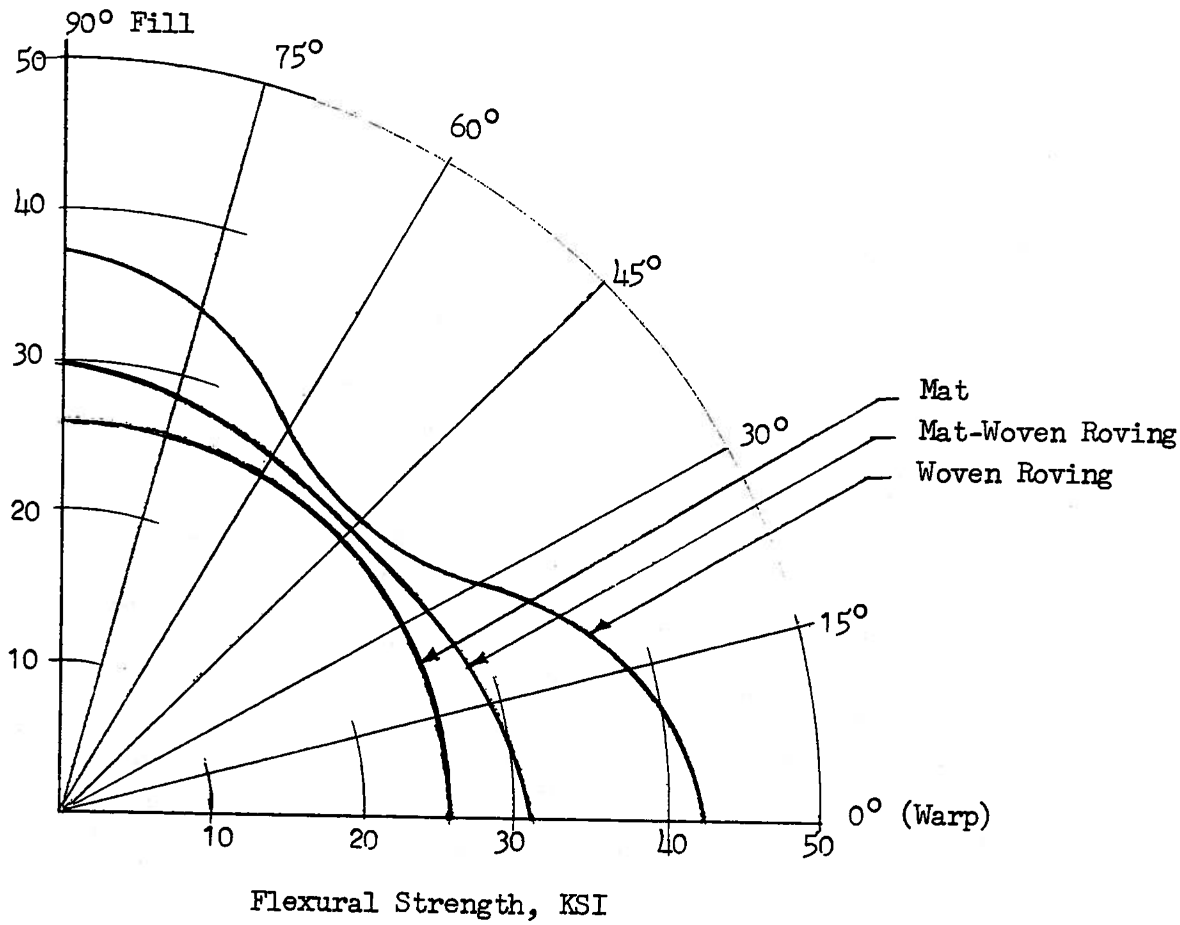


FIGURE 10

DIRECTIONAL STRENGTH OF FIBERGLASS

Effect of Glass Content and Orientation

The strength of an FRP laminate is essentially a function of glass content, as discussed in detail later. In addition, the orientation of the glass relative to the direction of load application greatly affects properties. A "balanced" reinforcement, such as woven roving, will produce laminates with less strength and stiffness in the warp direction than a unidirectional, since nearly half of the glass is at right angles to the load, and is thus ineffective. Conversely, the strength of a unidirectional laminate is very low in the fill direction, perpendicular to the direction of the load.

Variability in Properties

The physical characteristics of a laminate are dependent to a large degree on the skill of the individual laminator, and tend to vary widely for a given type of laminate. Thus it is harder to maintain quality control than with other materials such as steel or aluminum, where physical properties are predictable within very close limits.

The causes of variability have been evaluated in detail, Reference (21), and include the human element, as noted above, as well as the quality of the raw materials, rate of cure, temperature and humidity during layup, misalignment of reinforcement and the distribution of the resin through the glass. For example, one laminator may work the resin through the glass very well, compacting the glass and squeezing out all excess resin, while another may use an insufficient amount of resin, resulting in a loose, "dry" laminate. Though both laminates would have the same glass content, the latter would have lower physical properties than the forner.

Difference in Tensile, Flexural and Compressive Properties

The strength and stiffness of a laminate is different when loaded in tension, flexure and compression. The reasons for this are related to the microstructure of the materials and in particular the glass-resin interface. Flexural properties are generally highest, often as much as twice those in tension and compression.

Laminate Properties

The design physical properties of mat, woven roving and mat-woven roving composite laminates are shown in Figures 11 through 35 and Tables 1 and 2 which are reproduced through the kind permission of Owens-Corning Fiberglas Corporation. Strength and stiffness properties presented in these graphs are based on the laminates in the "wet" condition, which simulates the slight loss in these properties when the laminates have been exposed to water for a long period. "Dry" strengths and stiffnesses would be expected to be between 10 and 15 percent higher. However, for general design purposes, the use of the "wet" data is recommended.

Properties are presented for the warp (zero degree), fill (90 degree) and 45 degree direction of woven reinforcement. Since mat laminate is essentially isotropic, its 0 degree, 90 degree and 45 degree properties are identical.

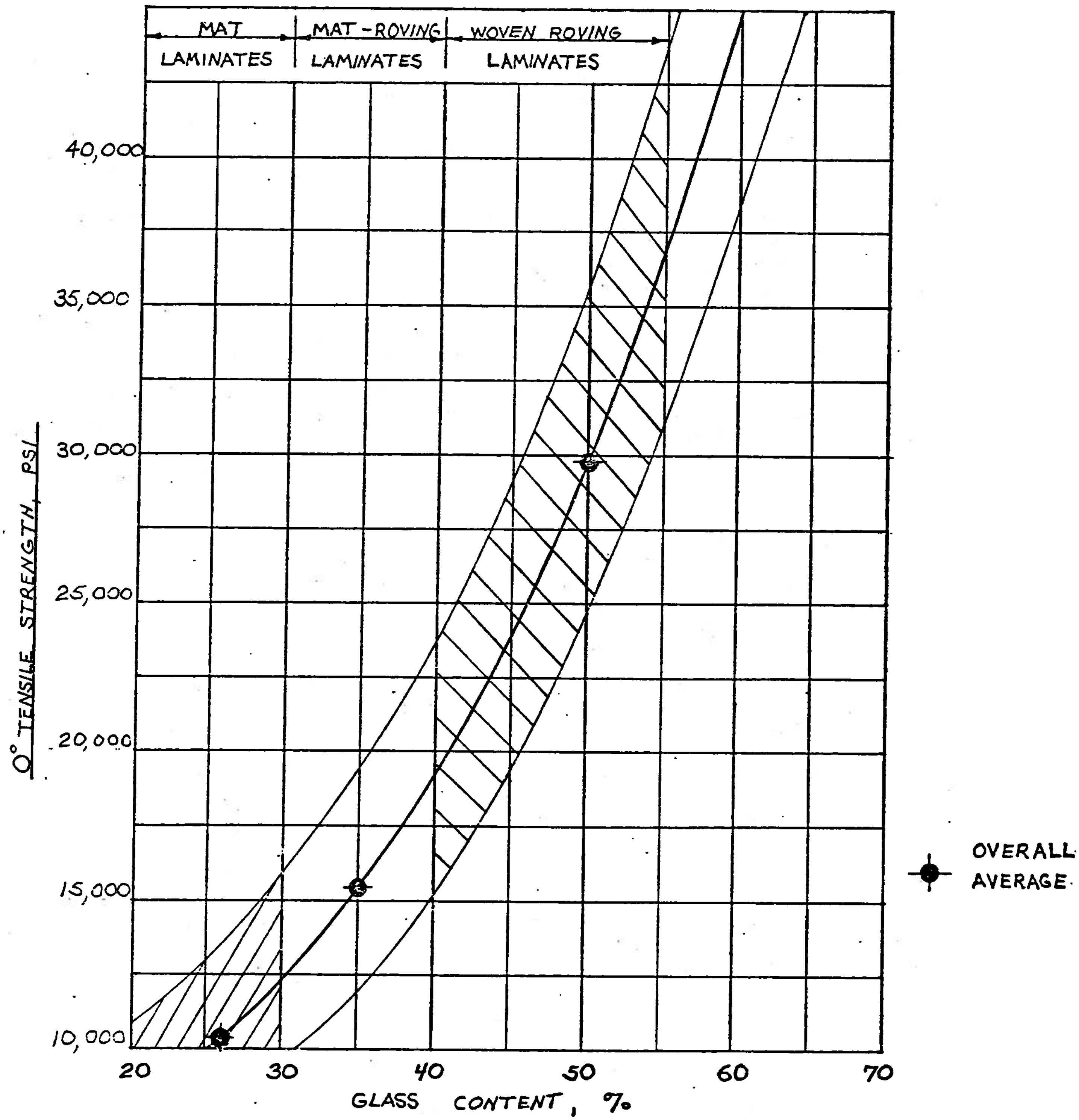


FIGURE 11

TENSILE STRENGTH AT 0 DEGREES (WARP)

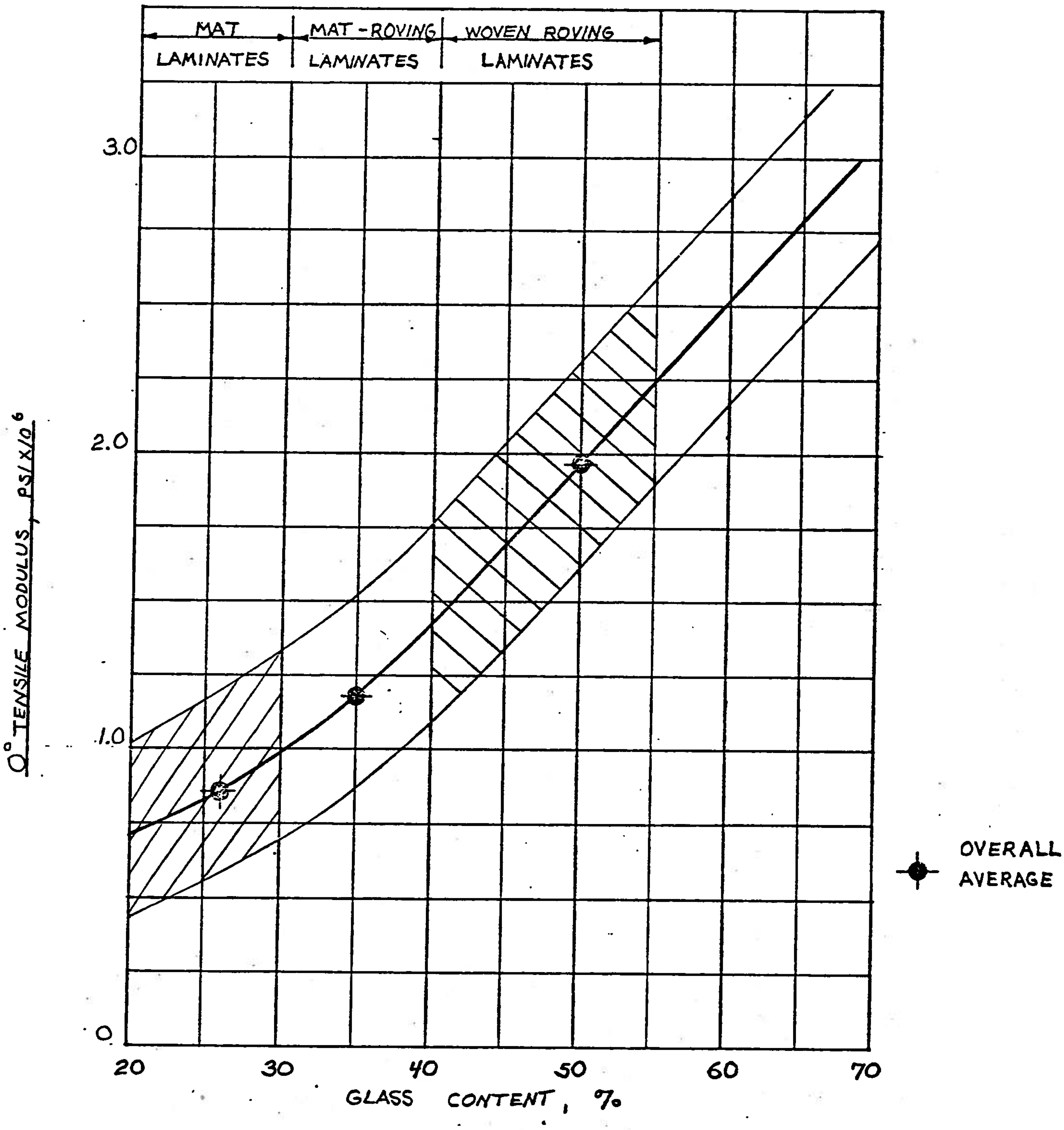


FIGURE 12

TENSILE MODULUS AT 0 DEGREES (WARP)

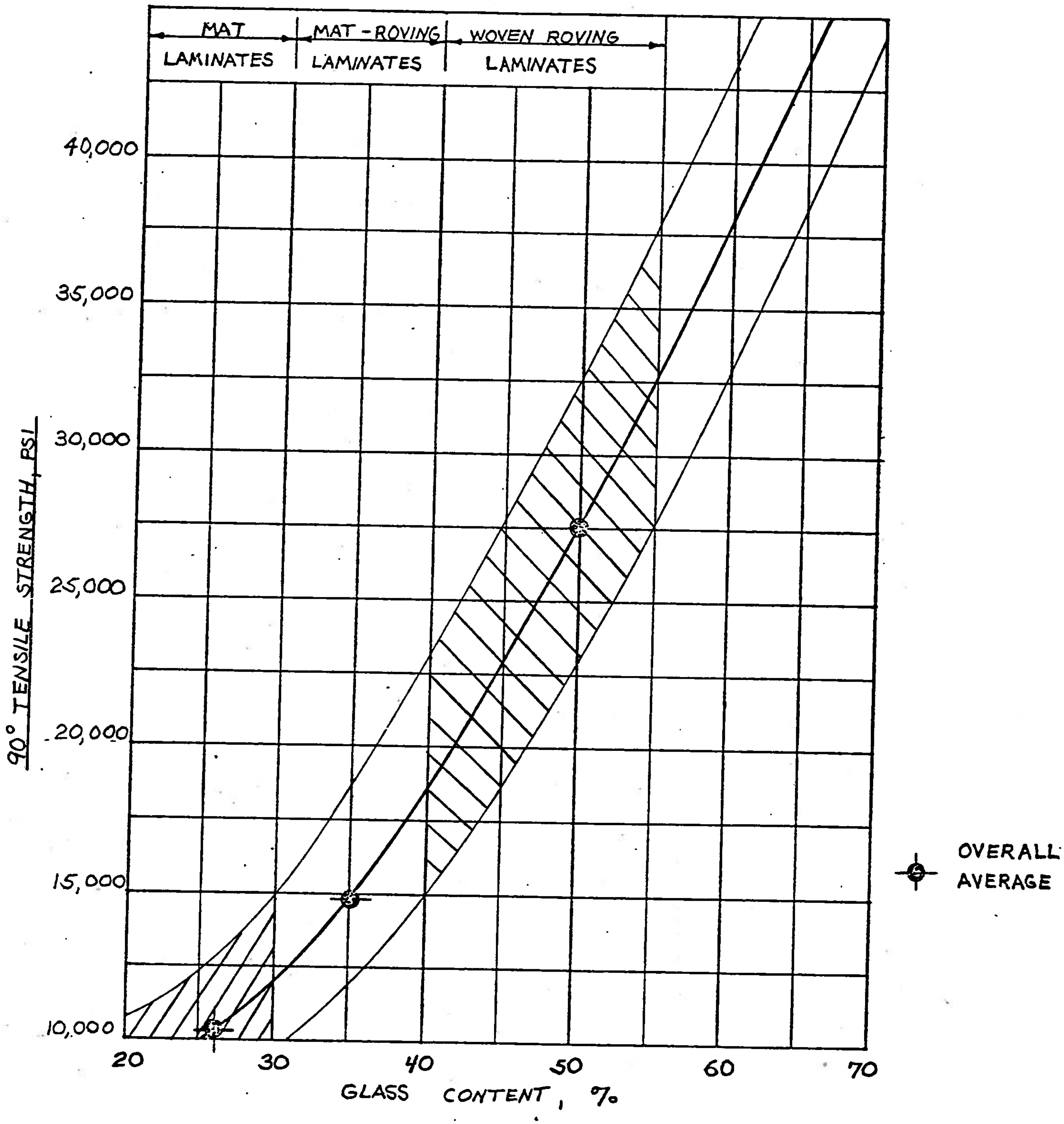


FIGURE 13

TENSILE STRENGTH AT 90 DEGREES (FILL)

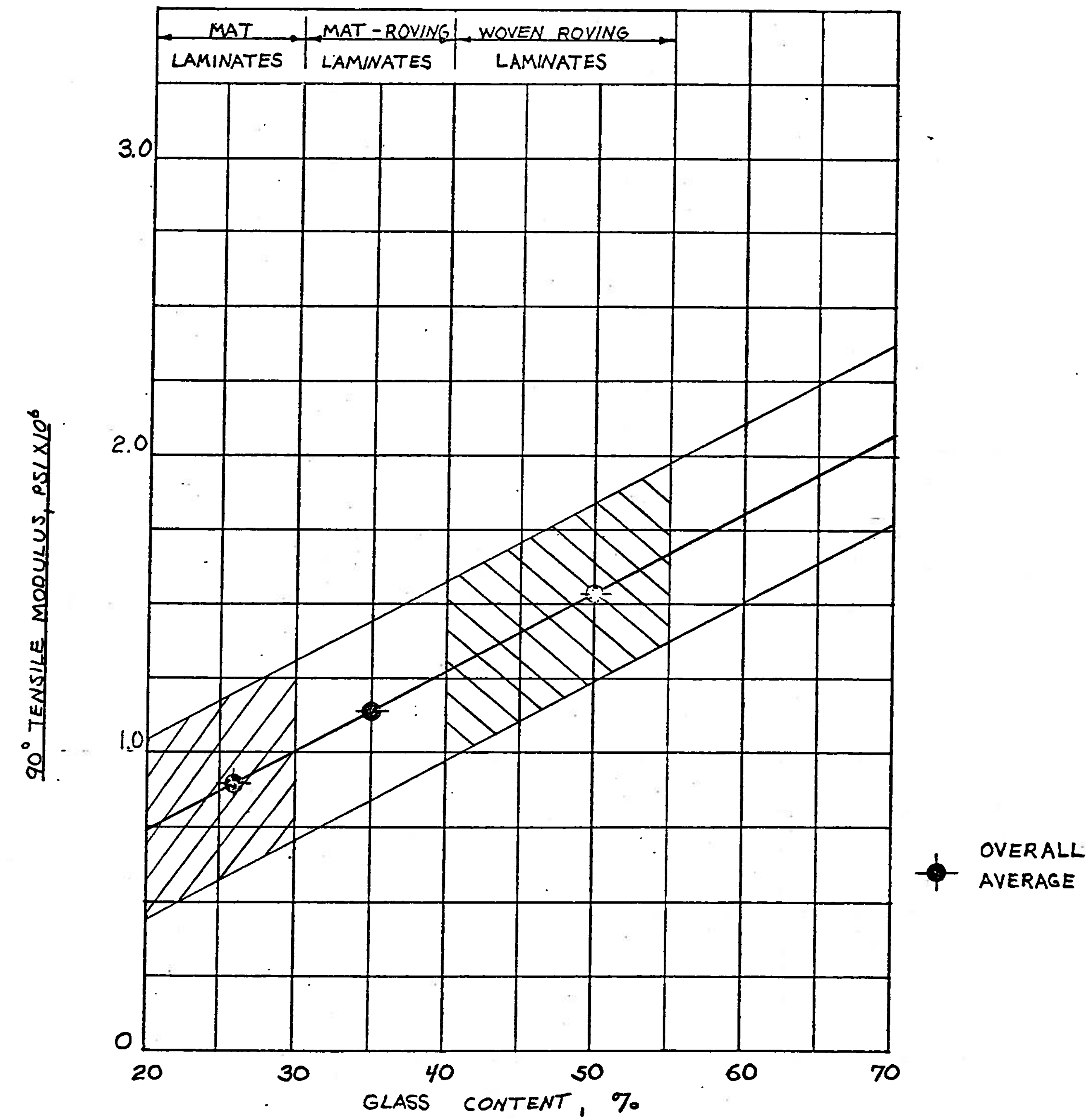


FIGURE 14

TENSILE MODULUS AT 90 DEGREES (FILL)

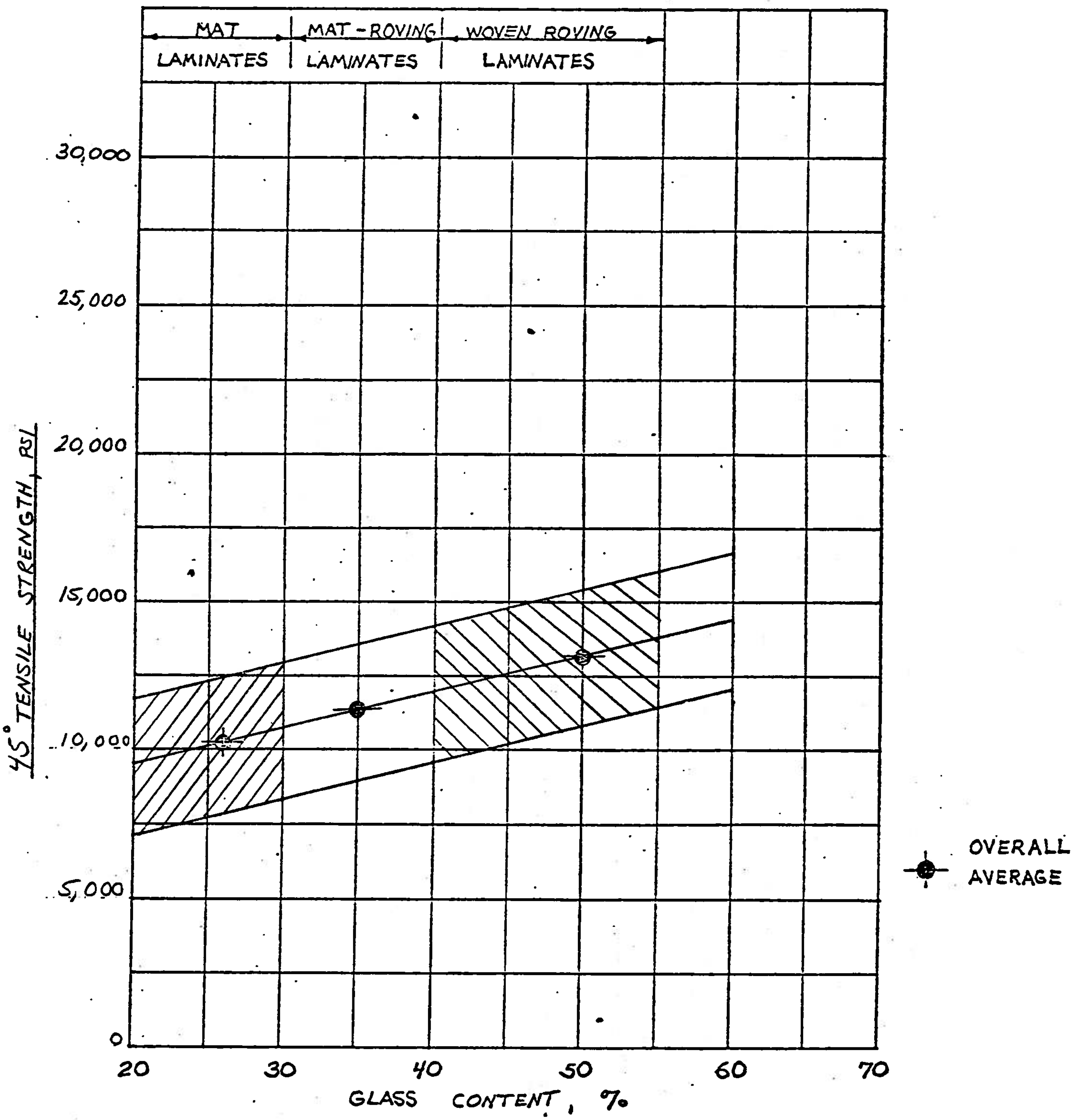


FIGURE 15

TENSILE STRENGTH AT 45 DEGREES

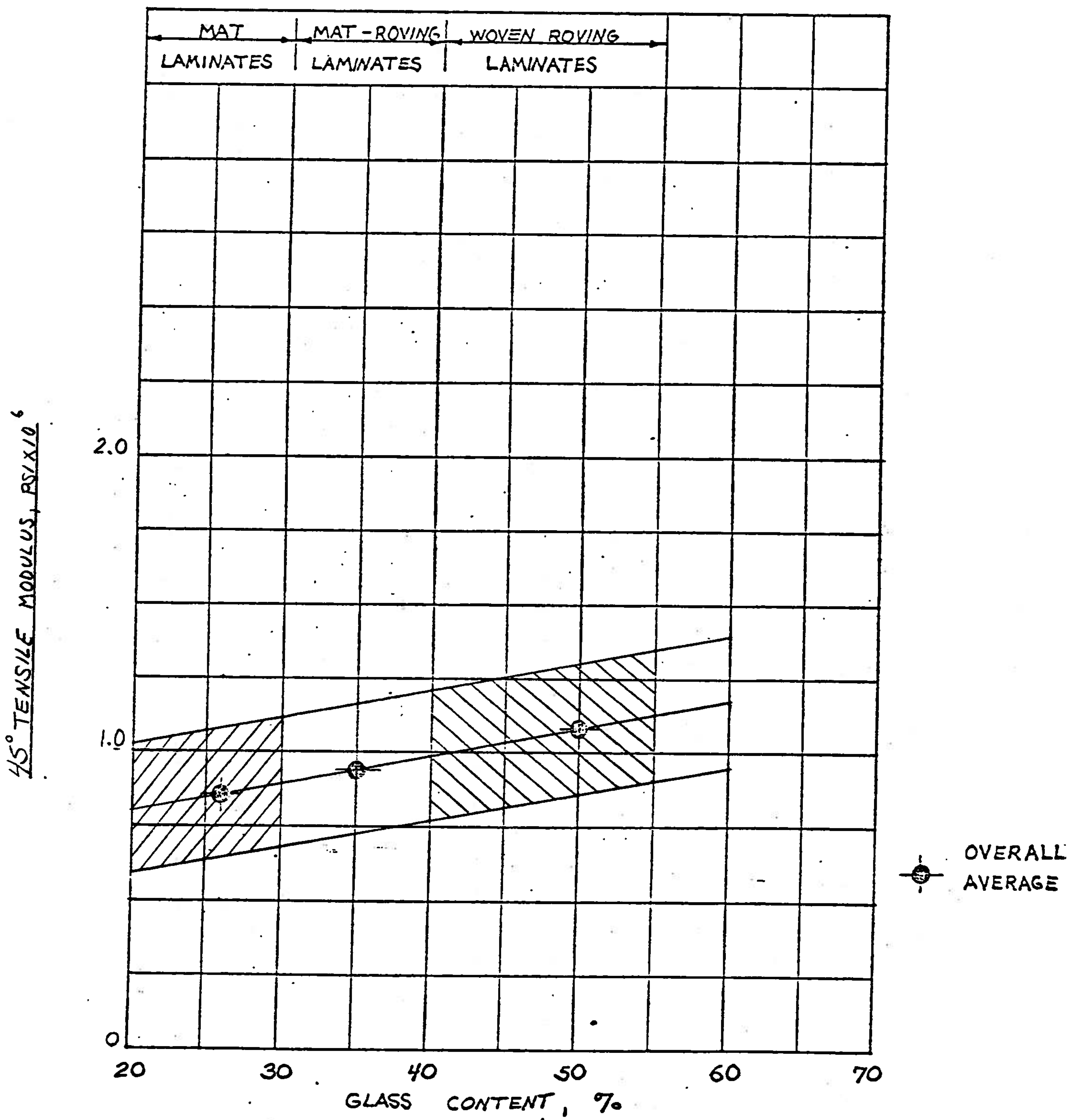


FIGURE 16

TENSILE MODULUS AT 45 DEGREES

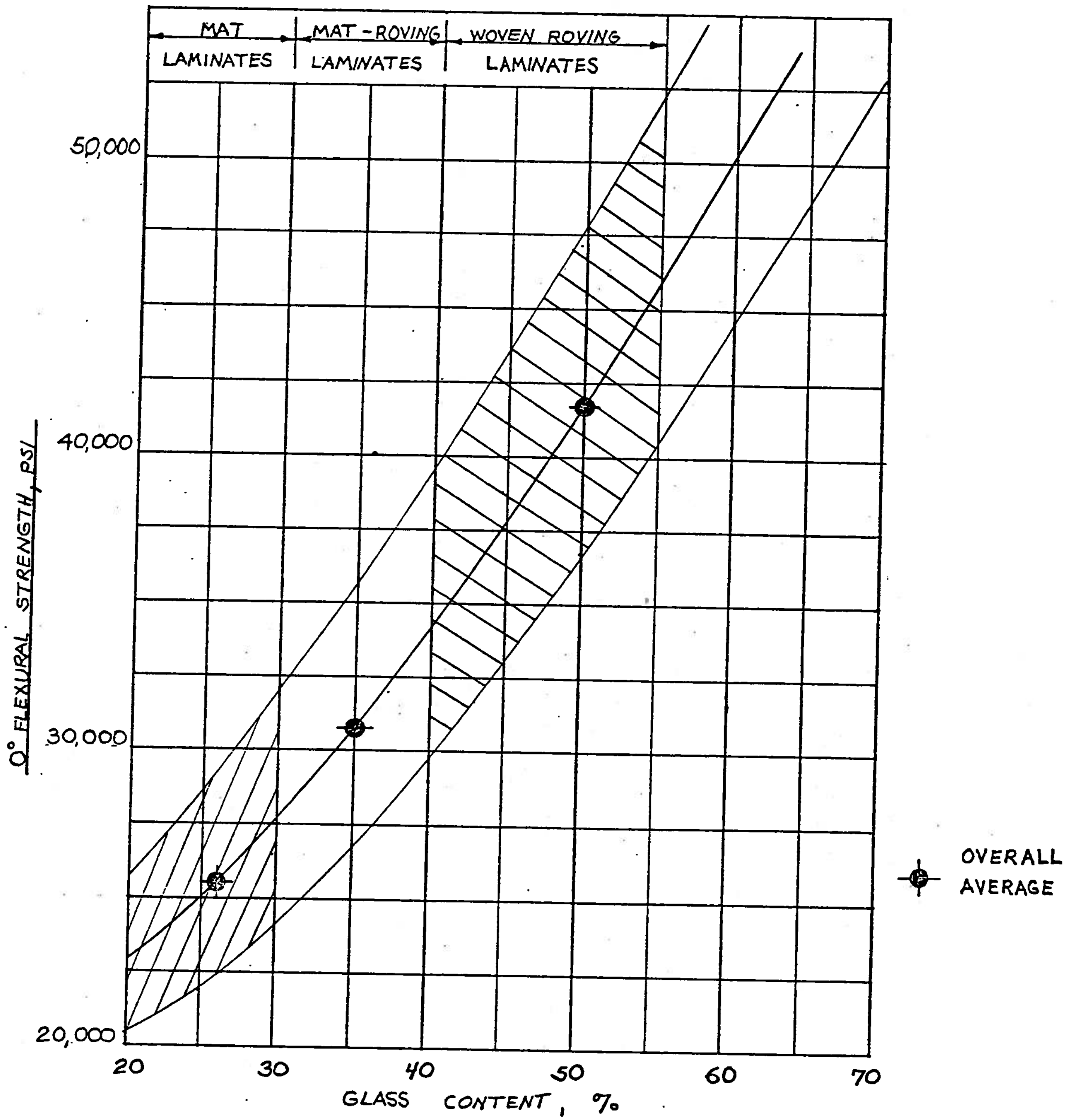


FIGURE 17

FLEXURAL STRENGTH AT 0 DEGREES (WARP)

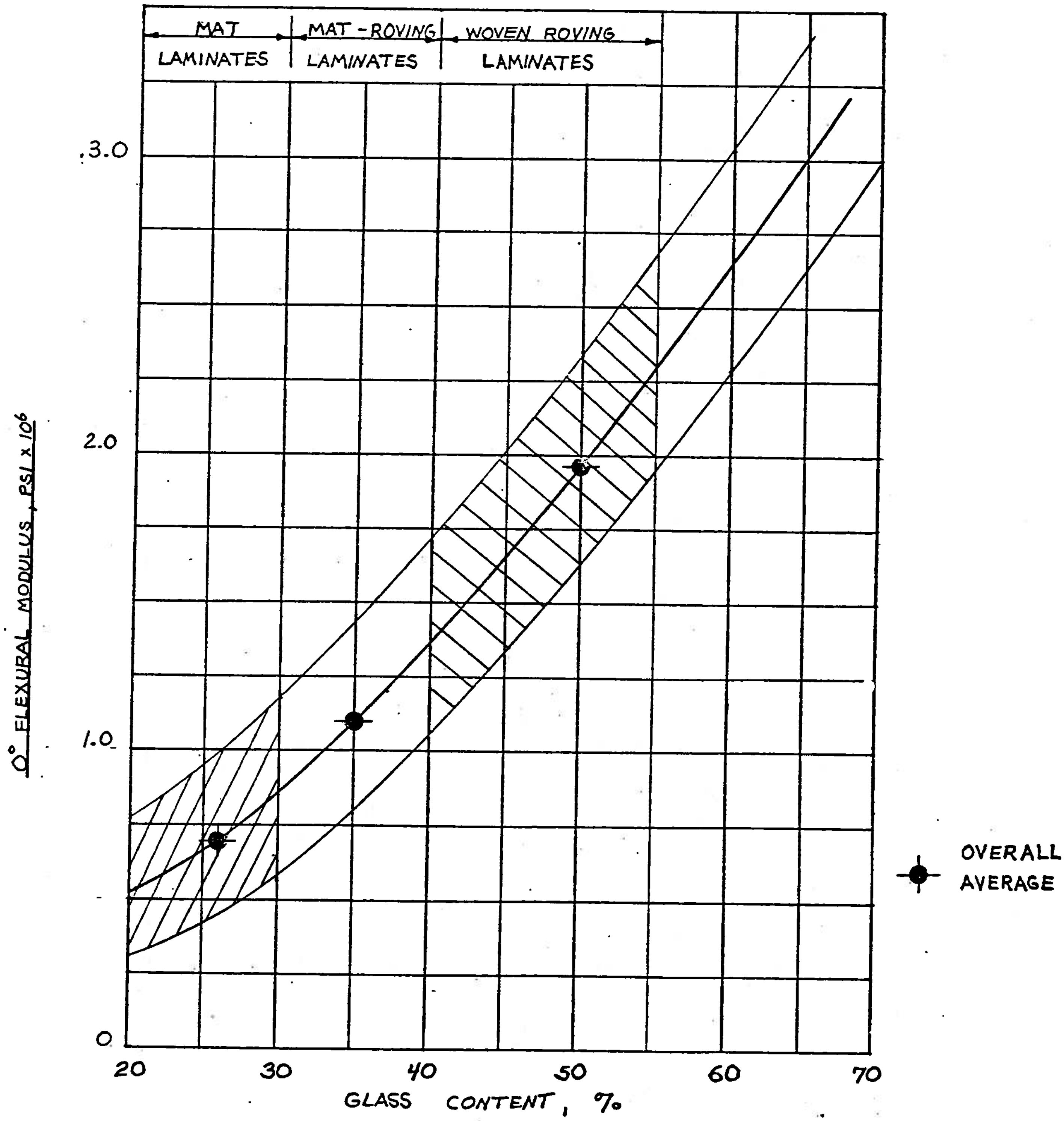


FIGURE 18

FLEXURAL MODULUS AT 0 DEGREES (WARP)

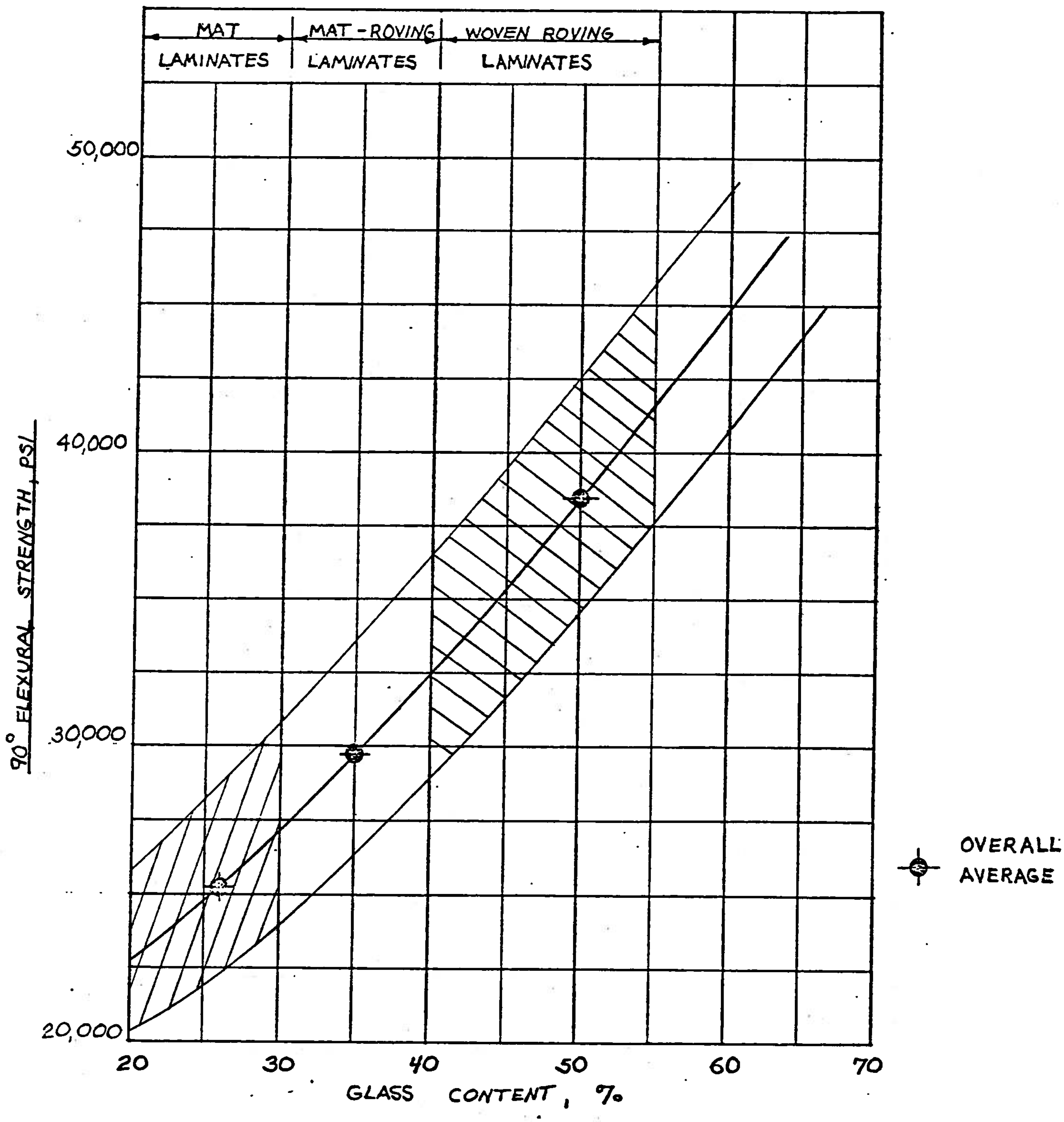


FIGURE 19

FLEXURAL STRENGTH AT 90 DEGREES (FILL)

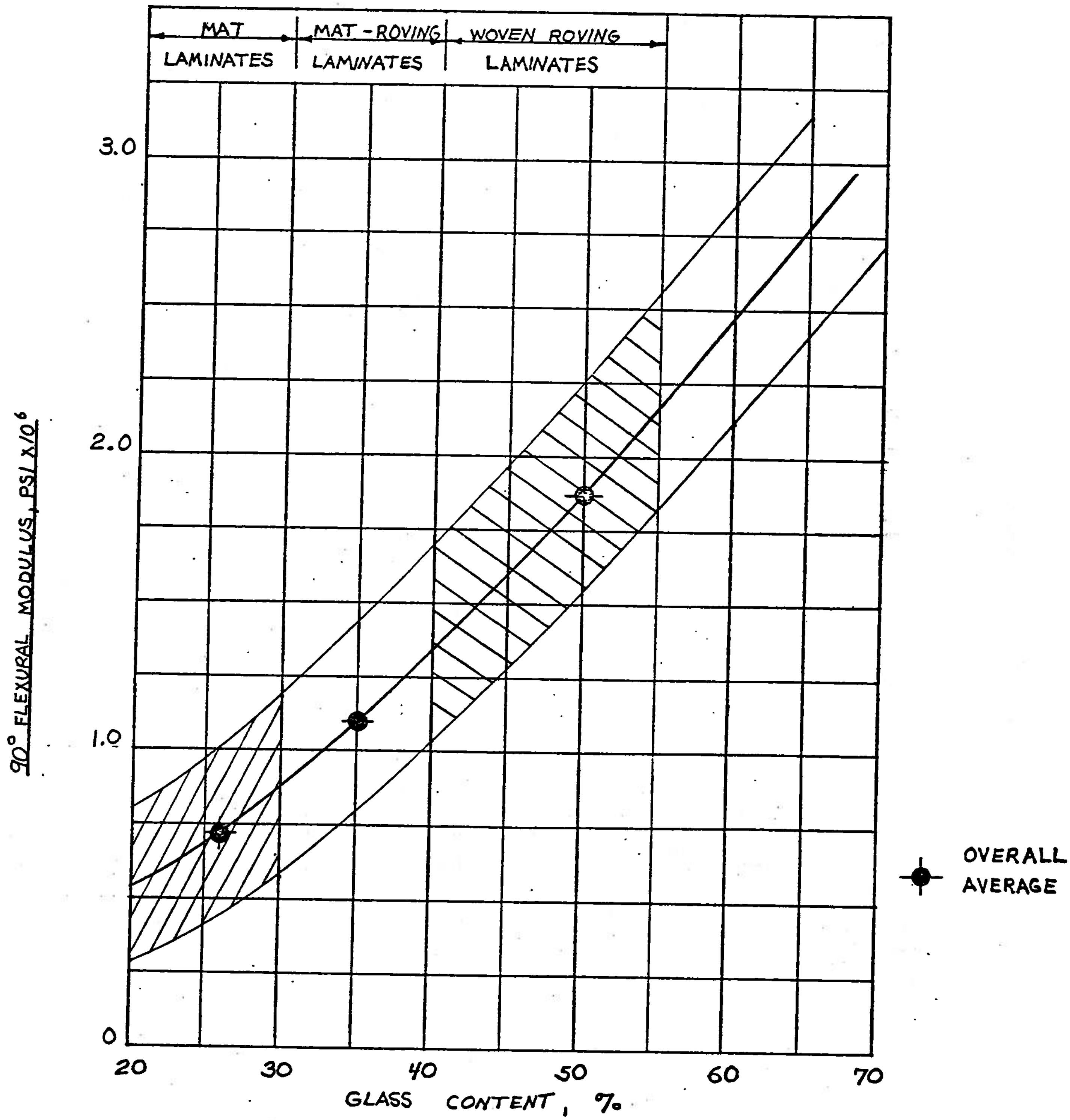


FIGURE 20

FLEXURAL MODULUS AT 90 DEGREES (FILL)

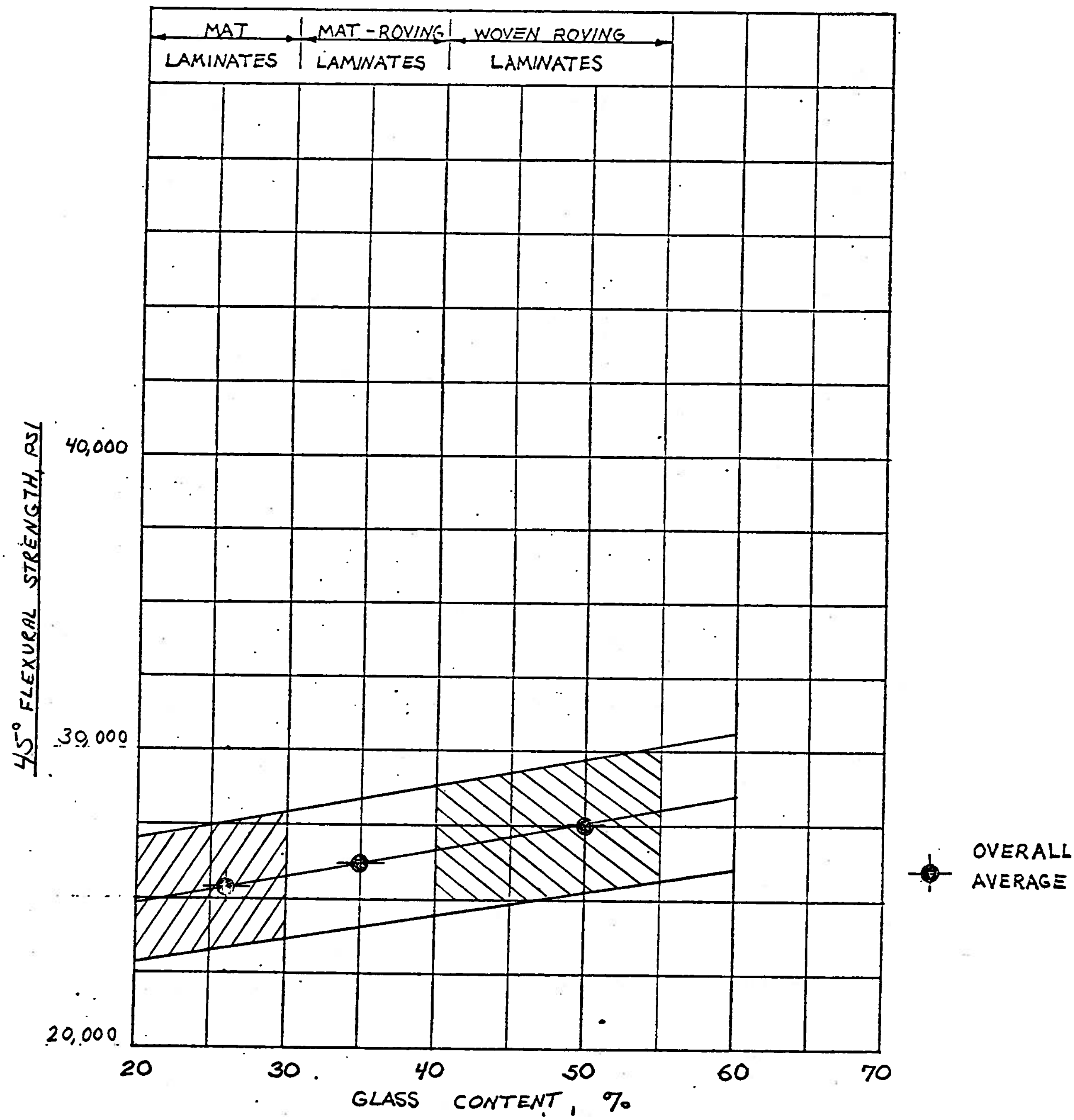


FIGURE 21

FLEXURAL STRENGTH AT 45 DEGREES

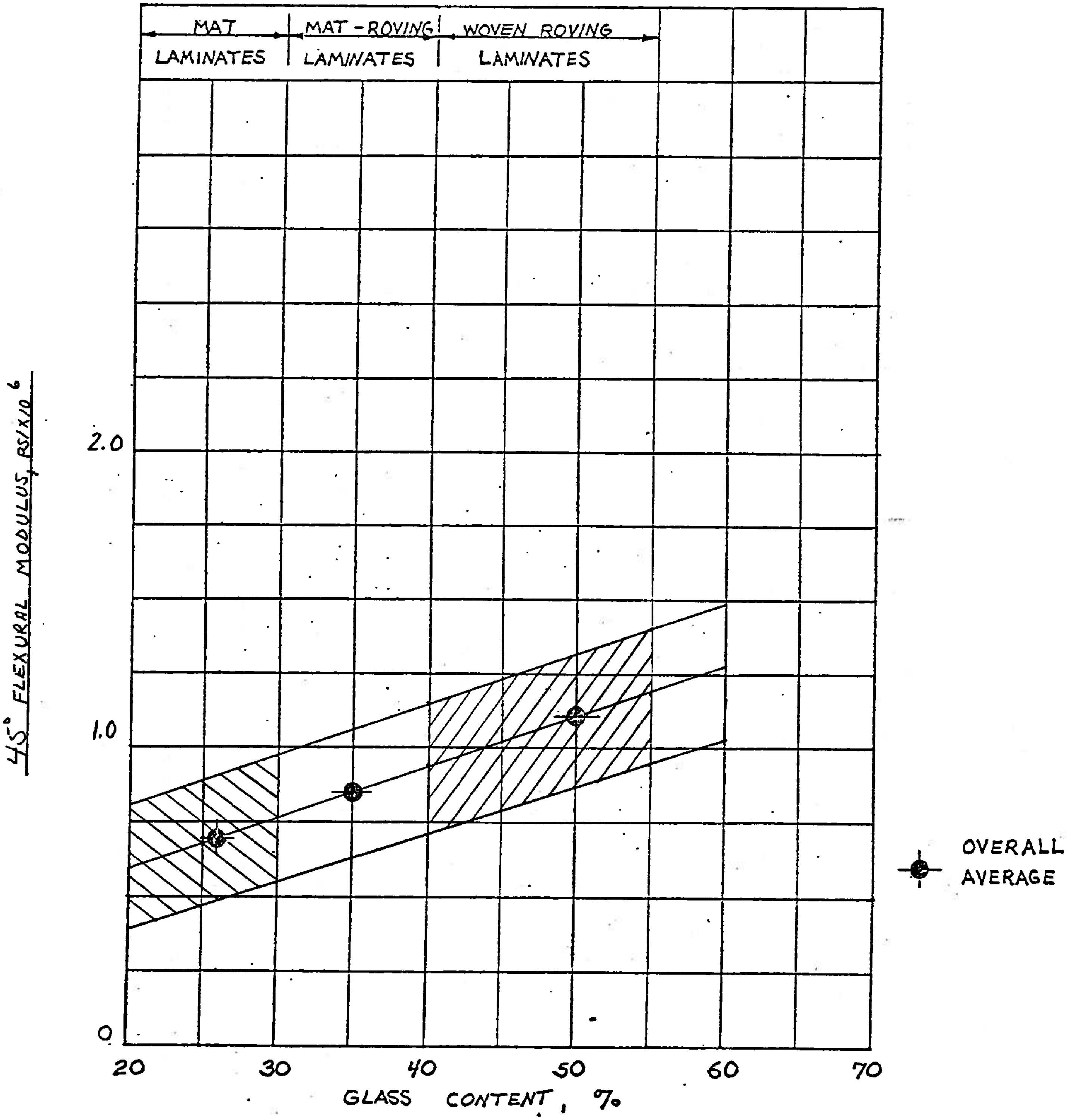


FIGURE 22

FLEXURAL MODULUS AT 45 DEGREES

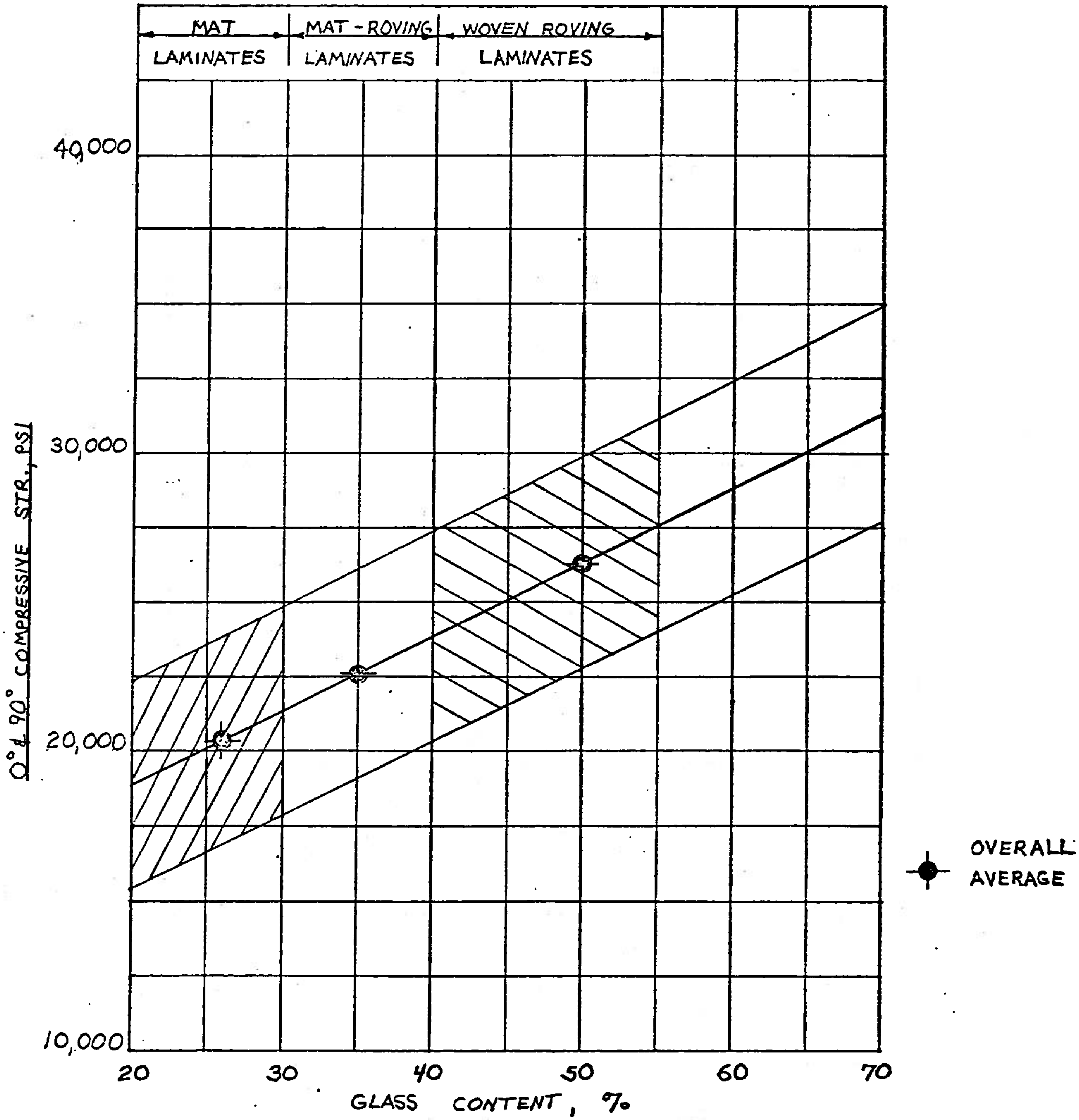


FIGURE 23

COMPRESSIVE STRENGTH AT 0 AND 90 DEGREES

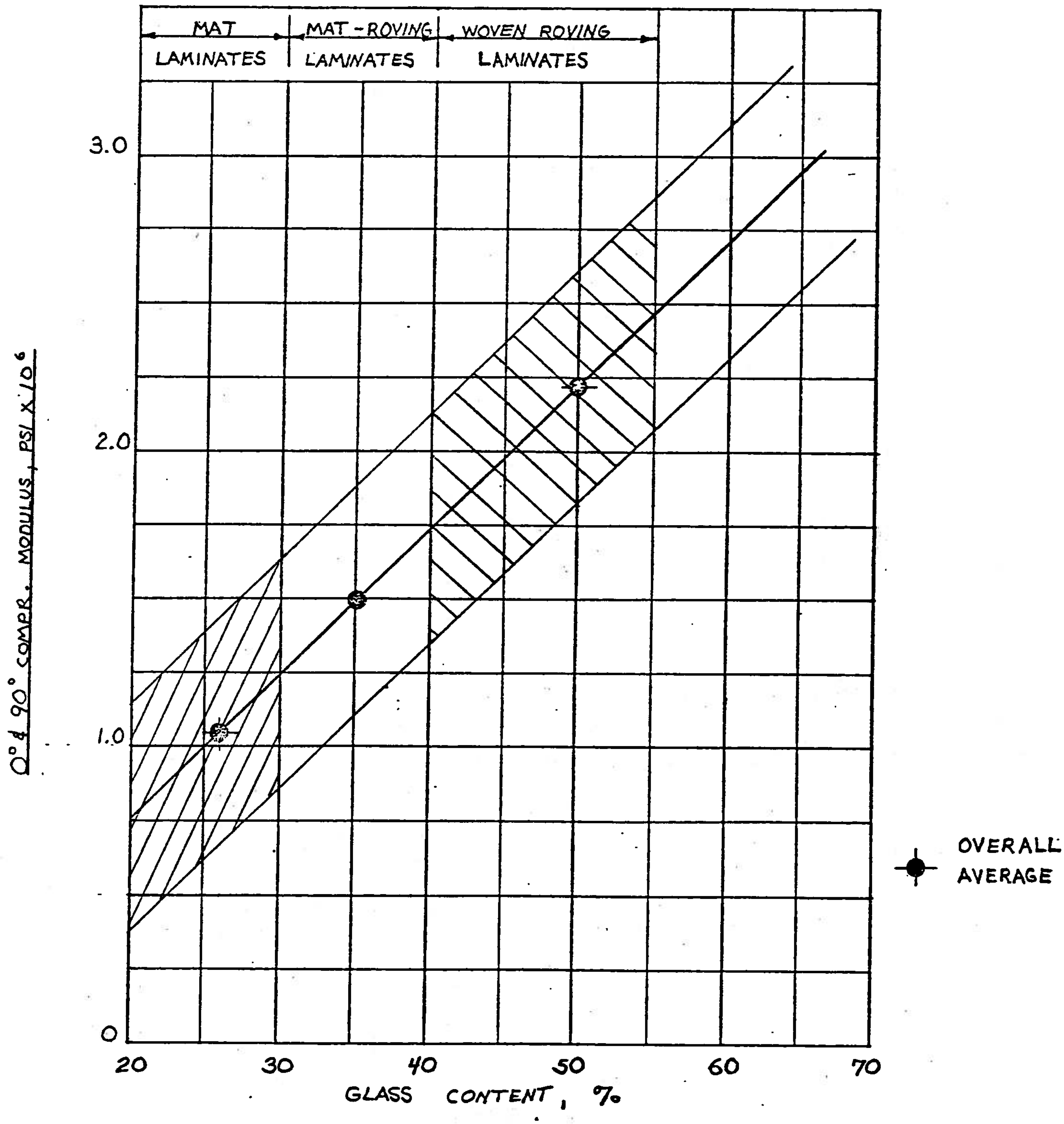


FIGURE 24

COMPRESSIVE MODULUS AT 0 AND 90 DEGREES

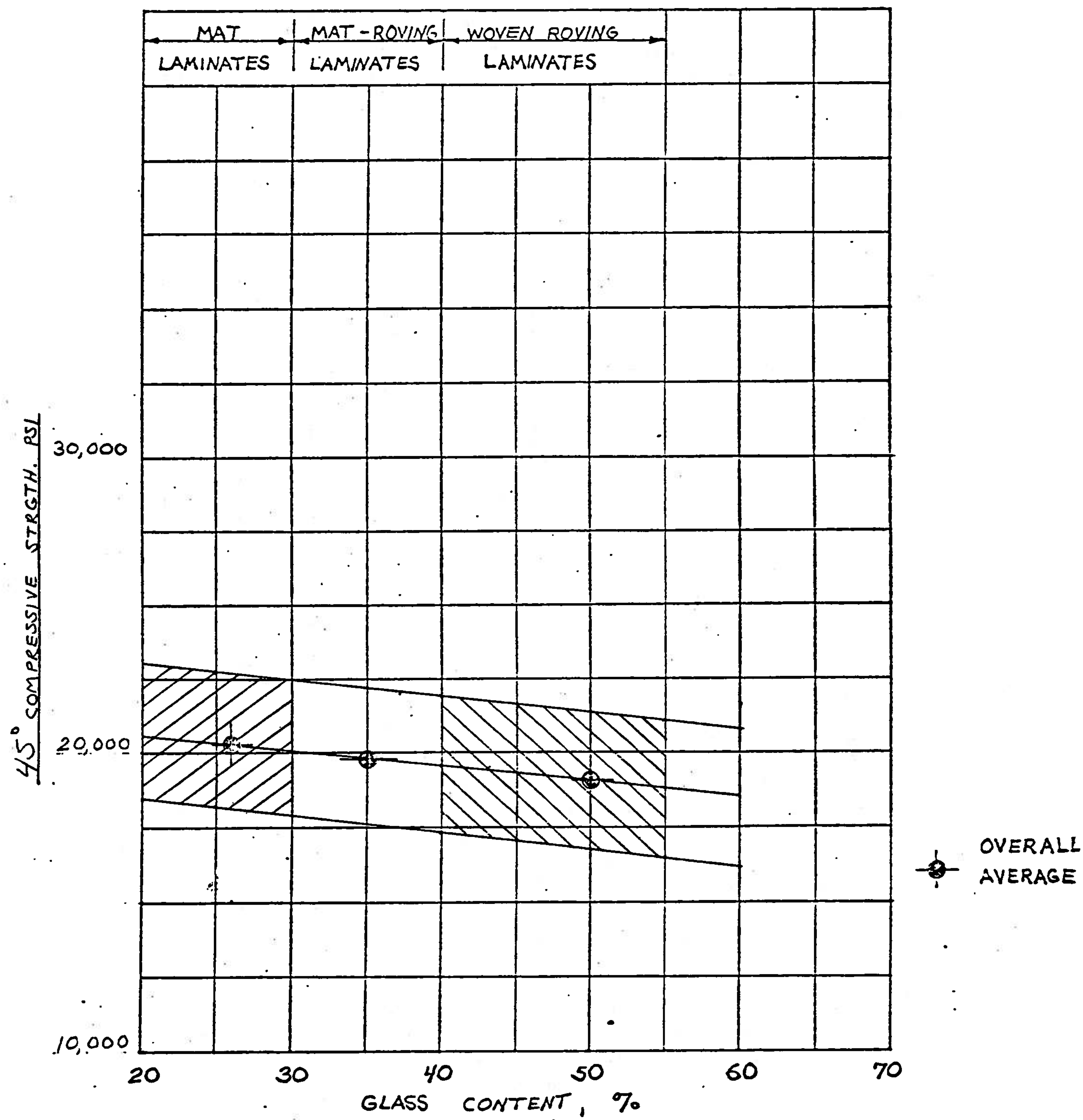


FIGURE 25

COMPRESSIVE STRENGTH AT 45 DEGREES

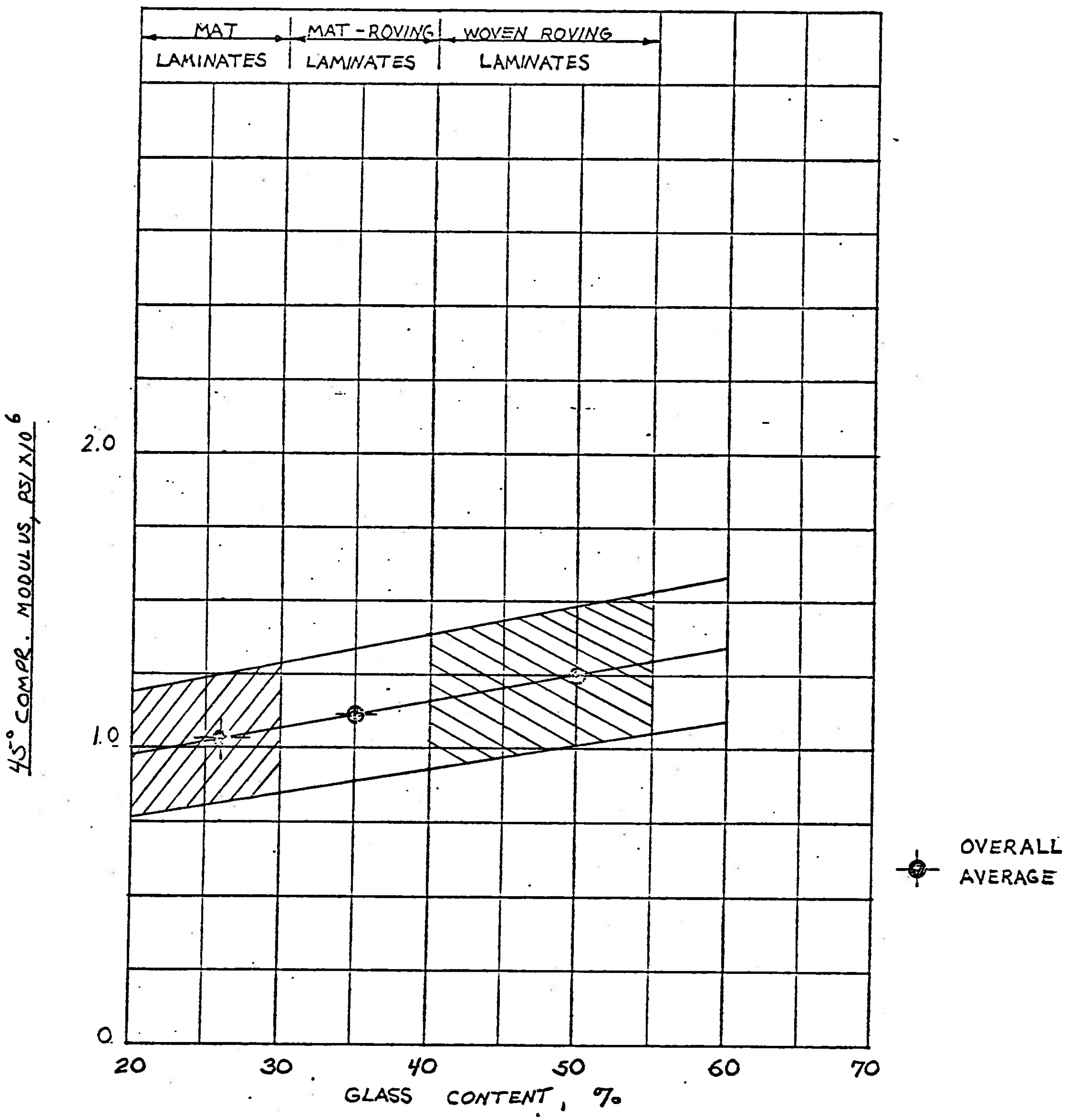


FIGURE 26

COMPRESSIVE MODULUS AT 45 DEGREES

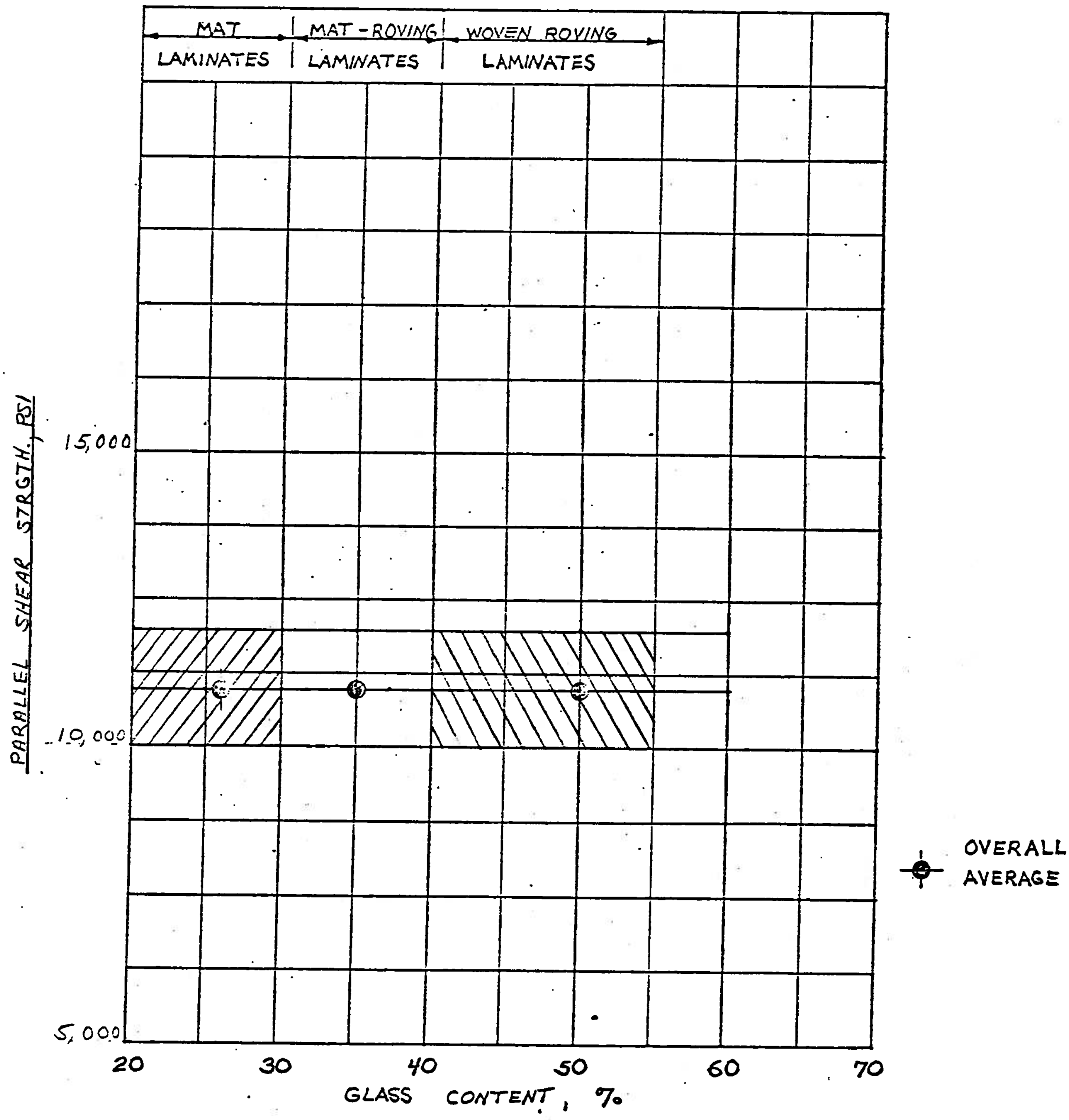


FIGURE 27

PARALLEL SHEAR STRENGTH

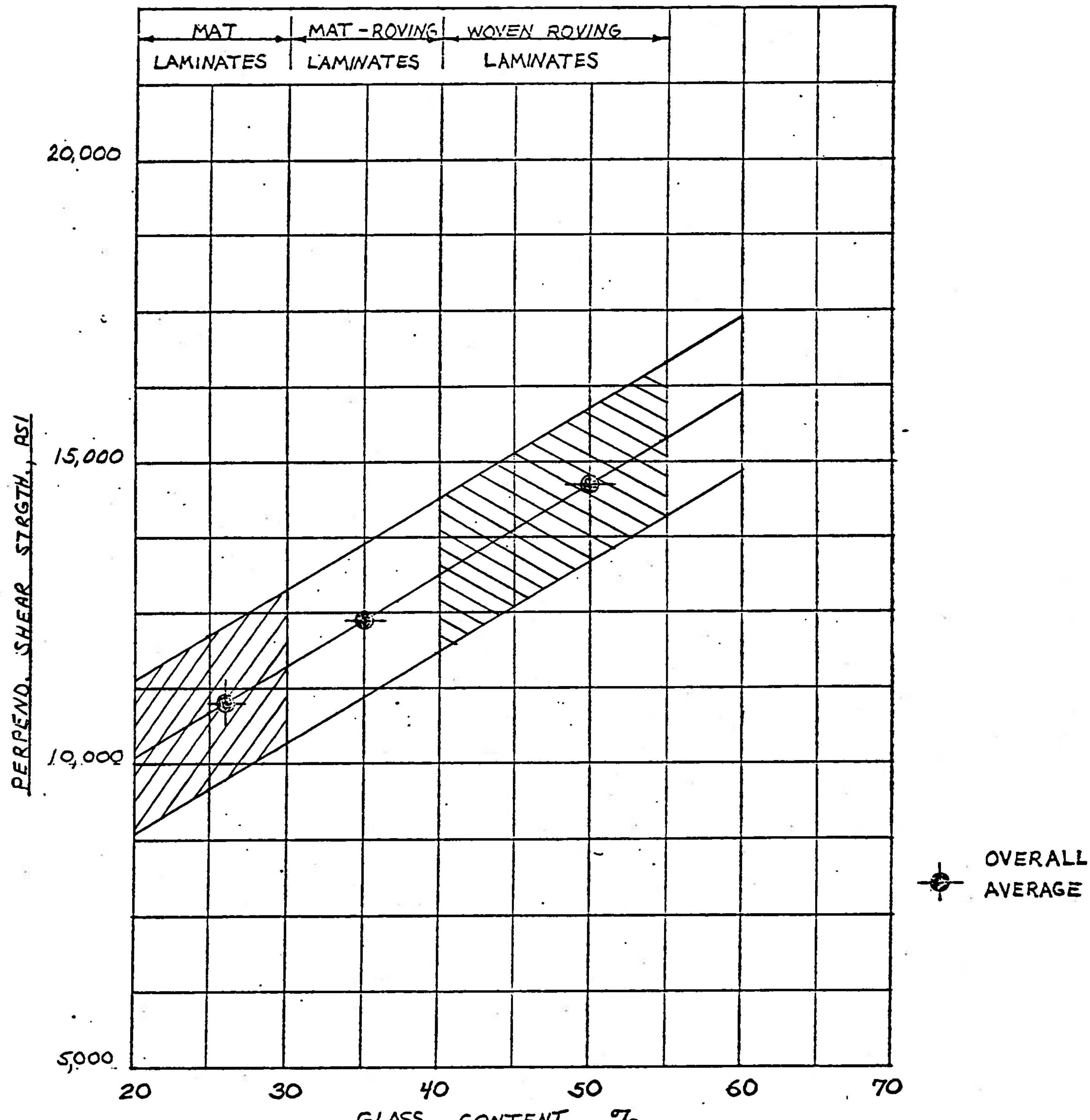


FIGURE 28

PERPENDICULAR SHEAR STRENGTH

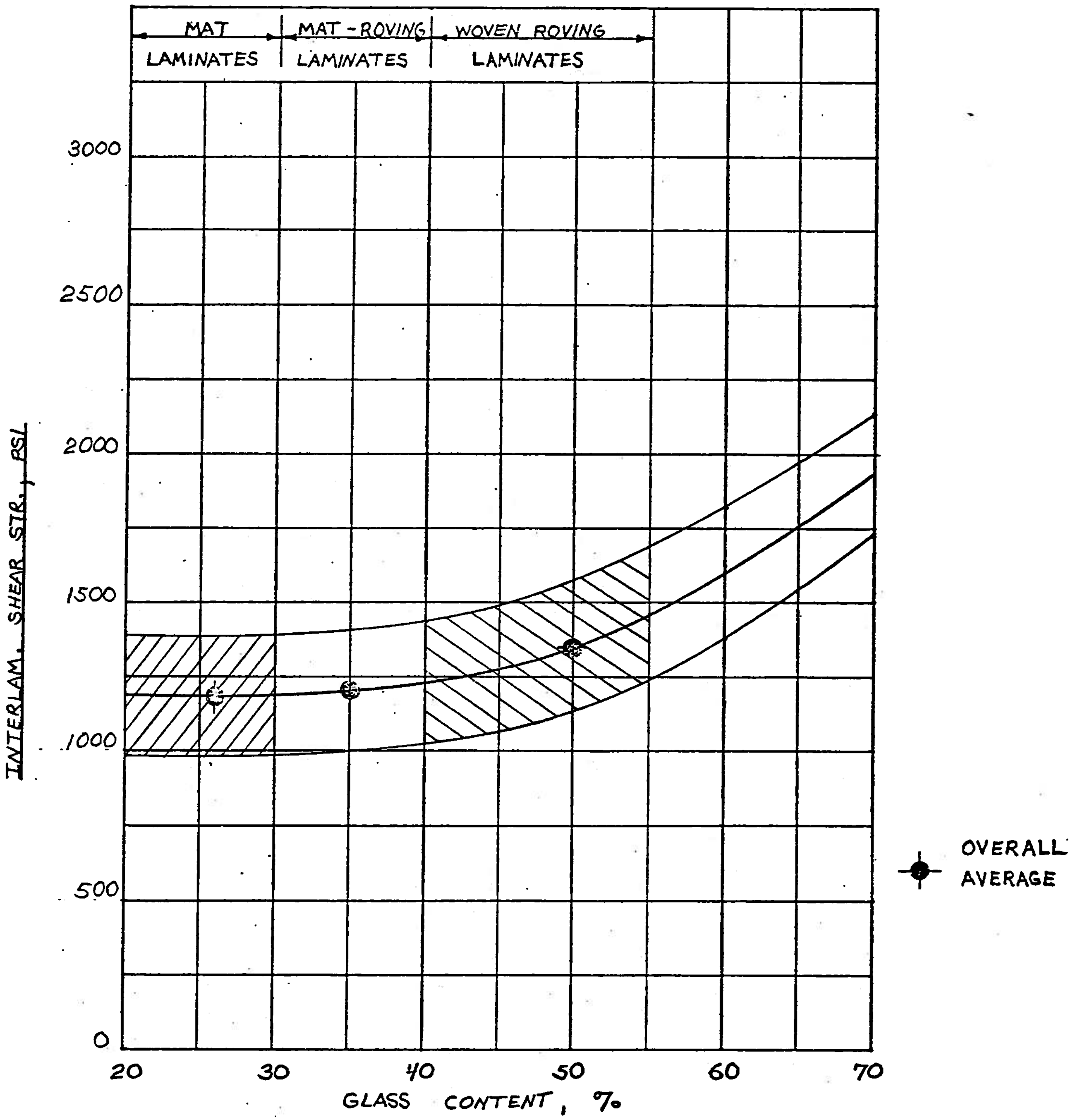


FIGURE 29

INTERLAMINAR SHEAR STRENGTH

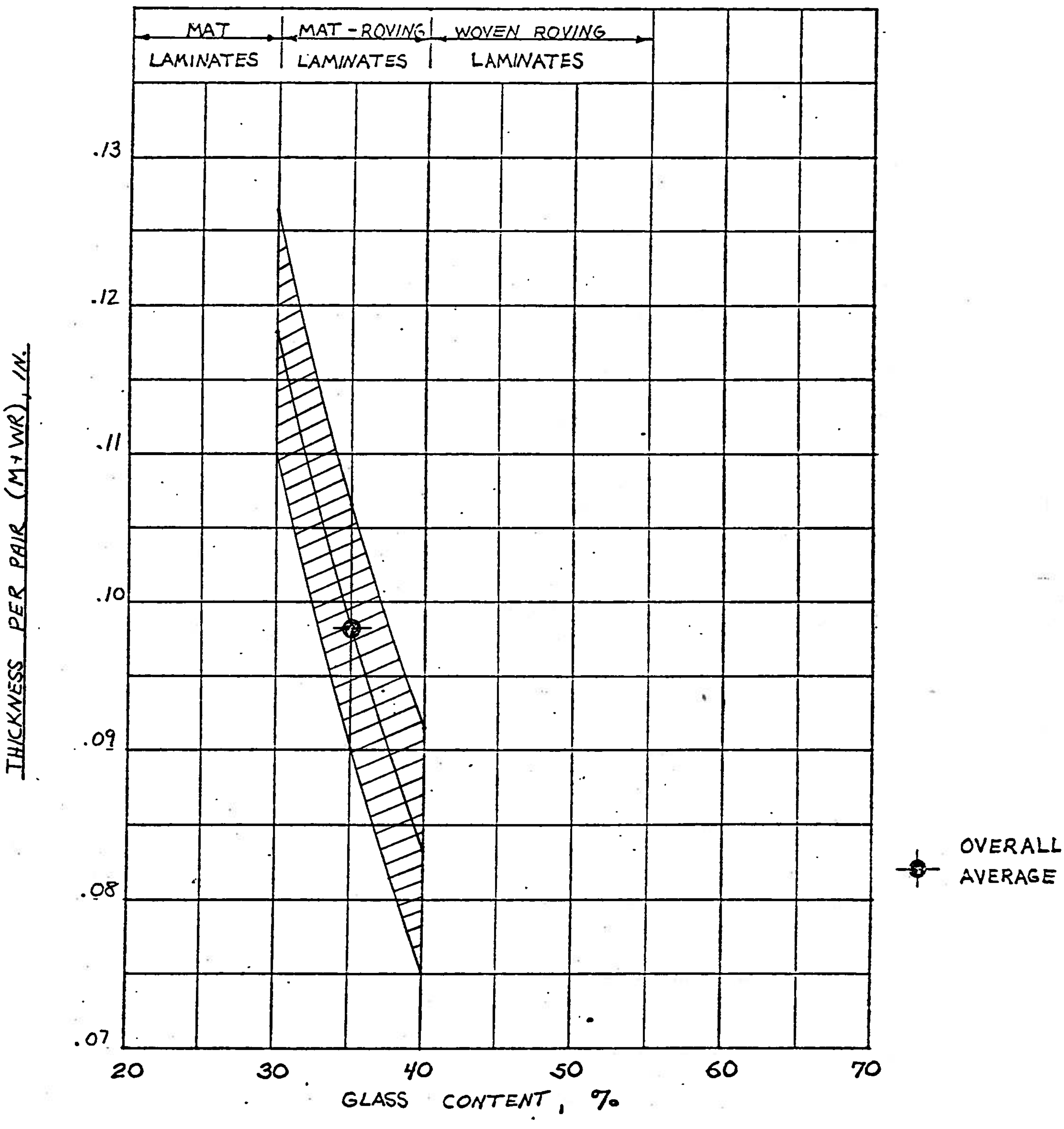


FIGURE 30

THICKNESS PER PAIR - ALTERNATING PLIES OF 1-1/2 OZ. MAT AND 24 OZ. WOVEN ROVING

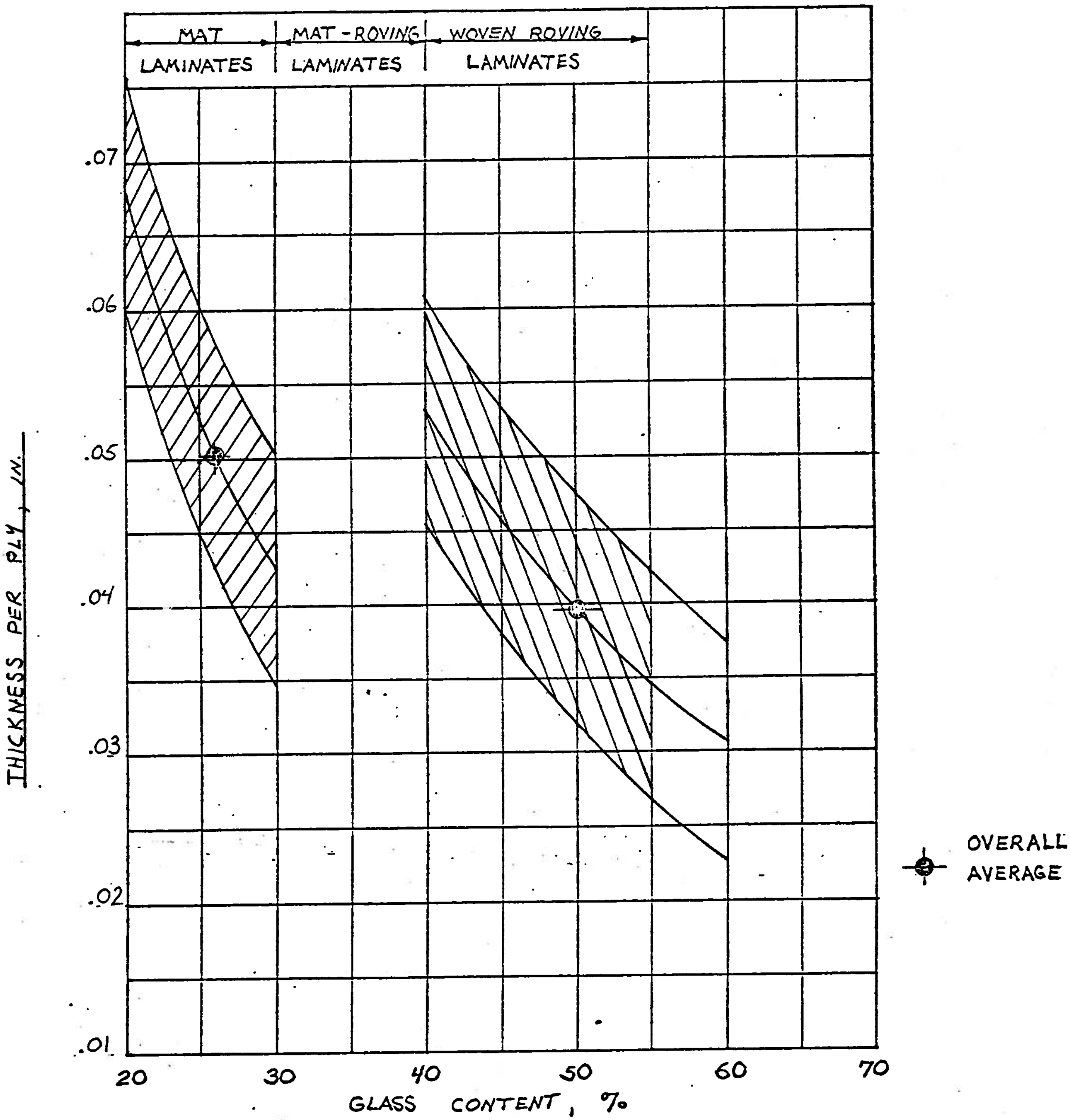


FIGURE 31

THICKNESS PER PLY - 1-1/2 OZ. MAT
OR 24 OZ. WOVEN ROVING

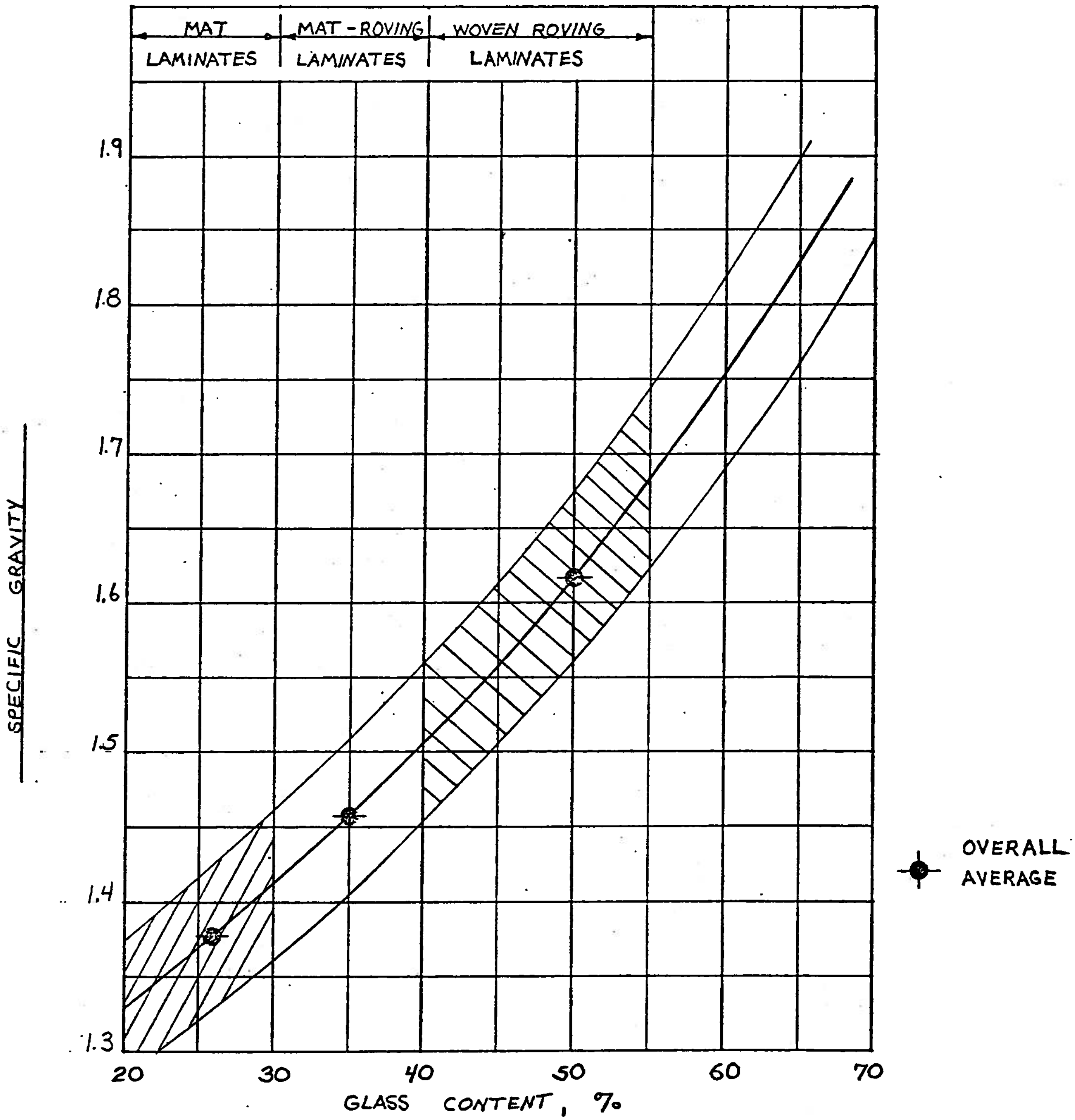


FIGURE 32

SPECIFIC GRAVITY

TABLE 1

NUMBER OF PLIES OR PAIRS VS LAMINATE WEIGHT
POUNDS PER SQUARE FOOT

Laminate	Glass Content (Percent)		Number of Plies or Pairs: 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1½ oz. Mat	20	Low	.439	.878	1.32	1.76	2.20	2.63	3.07	3.51	3.95	4.39	4.83	5.27	5.71	6.15	6.59
		High	.499	.998	1.50	2.00	2.50	2.99	3.49	3.99	4.49	4.99	5.49	5.99	6.49	6.99	7.49
	25	Low	.345	.690	1.04	1.38	1.73	2.07	2.42	2.76	3.11	3.45	3.80	4.14	4.49	4.83	5.18
		High	.405	.810	1.22	1.62	2.03	2.43	2.84	3.24	3.65	4.05	4.46	4.86	5.27	5.67	6.08
	30	Low	.283	.566	.849	1.13	1.42	1.70	1.98	2.26	2.55	2.83	3.11	3.40	3.68	3.96	4.25
		High	.343	.686	1.03	1.37	1.72	2.06	2.40	2.74	3.09	3.43	3.77	4.12	4.46	4.80	5.15
Composite Laminate (Alternate plies of 1½ oz. Mat and 24 oz. WR)	30	Low	.823	1.65	2.47	3.29	4.12	4.94	5.76	6.58	7.41	8.23	9.05	9.88	10.7	11.5	12.3
		High	.913	1.83	2.74	3.65	4.57	5.48	6.39	7.30	8.22	9.13	10.0	11.0	11.9	12.8	13.7
	35	Low	.700	1.40	2.10	2.80	3.50	4.20	4.90	5.60	6.30	7.00	7.70	8.40	9.10	9.80	10.5
		High	.789	1.58	2.37	3.16	3.95	4.73	5.52	6.31	7.10	7.89	8.68	9.47	10.3	11.0	11.8
	40	Low	.606	1.21	1.82	2.42	3.03	3.64	4.24	4.85	5.45	6.06	6.67	7.27	7.88	8.48	9.09
		High	.696	1.39	2.09	2.78	3.48	4.18	4.87	5.57	6.26	6.96	7.66	8.35	9.05	9.74	10.4
24 oz. WR	40	Low	.403	.806	1.21	1.61	2.02	2.42	2.82	3.22	3.63	4.03	4.43	4.84	5.24	5.64	6.05
		High	.430	.860	1.29	1.72	2.15	2.58	3.01	3.44	3.87	4.30	4.73	5.16	5.59	6.02	6.45
	45	Low	.357	.714	1.07	1.43	1.79	2.14	2.50	2.86	3.21	3.57	3.93	4.28	4.64	5.00	5.36
		High	.383	.766	1.15	1.53	1.92	2.30	2.68	3.06	3.45	3.83	4.21	4.60	4.98	5.36	5.75
	50	Low	.320	.640	.960	1.28	1.60	1.92	2.24	2.56	2.88	3.20	3.52	3.84	4.16	4.48	4.80
		High	.347	.694	1.04	1.39	1.74	2.08	2.43	2.78	3.12	3.47	3.82	4.16	4.51	4.86	5.21
	55	Low	.290	.580	.870	1.16	1.45	1.74	2.03	2.32	2.61	2.90	3.19	3.48	3.77	4.06	4.35
		High	.316	.632	.948	1.26	1.58	1.90	2.21	2.53	2.84	3.16	3.48	3.79	4.11	4.42	4.74
	60	Low	.265	.530	.795	1.06	1.33	1.59	1.86	2.12	2.39	2.65	2.92	3.18	3.45	3.71	3.98
		High	.292	.584	.876	1.17	1.46	1.75	2.04	2.34	2.63	2.92	3.21	3.50	3.80	4.09	4.38

TABLE 2

NUMBER OF PLIES OR PAIRS VS LAMINATE THICKNESS IN INCHES

Laminate	Glass Content (Percent)		Number of Plies or Pairs: 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
$1\frac{1}{2}$ oz. Mat	20	Low	.060	.120	.180	.240	.300	.360	.420	.480	.540	.600	.660	.720	.780	.840	.900
		High	.076	.152	.228	.304	.380	.456	.532	.608	.684	.760	.836	.912	.988	1.064	1.140
	25	Low	.045	.090	.135	.180	.225	.270	.315	.360	.405	.450	.495	.540	.585	.630	.675
		High	.061	.122	.183	.244	.305	.366	.427	.488	.549	.610	.671	.732	.793	.854	.915
	30	Low	.035	.070	.105	.140	.175	.210	.245	.280	.315	.350	.385	.420	.455	.490	.525
		High	.050	.100	.150	.200	.250	.300	.350	.400	.450	.500	.550	.600	.650	.700	.750
Composite Laminate (Alternate plies of $1\frac{1}{2}$ oz. Mat and 24 oz. WR)	30	Low	.110	.220	.330	.440	.550	.660	.770	.880	.990	1.100	1.210	1.320	1.43	1.540	1.650
		High	.126	.252	.378	.504	.630	.756	.882	1.008	1.134	1.260	1.386	1.512	1.638	1.764	1.890
	35	Low	.090	.180	.270	.360	.450	.540	.630	.720	.810	.900	.990	1.080	1.170	1.260	1.350
		High	.107	.214	.321	.428	.535	.642	.749	.856	.963	1.070	1.177	1.284	1.391	1.498	1.605
	40	Low	.075	.150	.225	.300	.375	.450	.525	.600	.675	.750	.825	.900	.975	1.050	1.125
		High	.091	.182	.273	.364	.455	.546	.637	.728	.819	.910	1.001	1.092	1.183	1.274	1.365
24 oz. WR	40	Low	.045	.090	.135	.180	.225	.270	.315	.360	.405	.450	.495	.540	.585	.630	.675
		High	.061	.122	.183	.244	.305	.366	.427	.488	.549	.610	.671	.732	.793	.854	.915
	45	Low	.038	.076	.114	.152	.190	.228	.266	.304	.342	.380	.418	.456	.494	.532	.570
		High	.054	.108	.162	.216	.270	.324	.378	.432	.486	.540	.594	.648	.702	.756	.810
	50	Low	.032	.064	.096	.128	.160	.192	.224	.256	.288	.320	.352	.384	.416	.448	.480
		High	.048	.096	.144	.192	.240	.288	.336	.384	.432	.480	.528	.576	.624	.672	.720
	55	Low	.027	.054	.081	.108	.135	.162	.189	.216	.243	.270	.297	.324	.351	.378	.405
		High	.042	.084	.126	.168	.210	.252	.294	.336	.378	.420	.462	.504	.546	.588	.630
	60	Low	.023	.046	.069	.092	.115	.138	.161	.184	.207	.230	.253	.276	.299	.322	.345
		High	.038	.076	.114	.152	.190	.228	.266	.304	.342	.380	.418	.456	.494	.532	.570

The laminate property data was derived from a number of published sources, as well as extensive data provided by the U.S. Navy, U.S. Coast Guard and a number of pleasure boatbuilders. Most of the latter data was taken from hull cutouts, and is thus representative of actual shop practice throughout the industry.

The graphs present the basic engineering properties of mat, mat-woven roving composite and woven roving laminates as a function of glass content. In reviewing the raw data used in preparing these graphs, it was found that the cluster of data from each of the three types of laminates formed a definite band when plotted against glass content. It was also found that the upper and lower ends of the mat-woven roving band overlapped the ends of the mat and woven roving bands to form a single continuous band. Therefore a single, continuous band can be presented for each property, with arbitrary limits on glass content applicable to each of the three types of laminates. It is important to note that this is true only within the limits on resin content selected for each type of laminate. Thus it would not be proper to conclude that the properties of a mat laminate with 40 percent glass content are identical to those of a woven roving laminate with 40 percent glass content.

For each type of laminate, the over-all range of properties is represented by a trapezoid bounded on the sides by the glass content upper and lower limits, and on the top and bottom by the corresponding limits on the property. This format offers the advantages of presenting both an overall average value for general use, and a range of values which allows the user some interpretation based upon the glass content which can reasonably be expected in his layup operation. Laminate glass content is the basic parameter in plotting properties since the relationship between the laminate properties and glass content is clearly established, and glass content data is most easily obtainable in the average shop.

The upper and lower limits on the properties bands in these graphs are not intended to be extreme limits, since much of the raw data falls above or below these limits. However, the band widths are intended to present a suitable design spectrum representative of typical fiberglass structures. Within a given structure, local areas may have properties above or below this band. However, the safety factors normally used in design are considered adequate to account for locally lower values. Also, the loads on a typical boat structure are sufficiently well distributed that a very localized area of low laminate strength will seldom precipitate premature failure.

The designer should keep in mind that basically the total strength of the laminate depends on the fiberglass content, and any slight variation in the resin/glass rates, although affecting the unit stress (PSI) will not have as significant an effect on the total strength of the hull or part. For example, while mechanical properties generally decrease with decreasing glass content, thickness per ply increases, resulting in greater inertia, area and section modulus. Thus these two factors tend to be offsetting. Looking at it a different way, a high-glass content laminate can be thinner than one with low glass content when designed to resist a given bending moment or axial load. Its lower section modulus and area are offset by its higher unit physical properties.

This particular characteristic of FRP laminates provides the designer with the ability to investigate the relationship between the resin-glass ratio and required strength and weight characteristics.

The designer must also bear in mind that the low glass content laminate will weigh slightly more per square foot than an equivalent laminate of higher glass content, but will contain proportionately less glass reinforcement and will require less stringent quality control procedures during fabrication. A typical comparison study of high and a low glass content laminates is shown in Example 1.

EXAMPLE 1 - LAMINATE COMPARISON STUDY

Design single skin mat-woven roving laminates of 30 and 40 percent glass content to satisfy each of the following loading conditions:

(A) Flexure - an ultimate bending moment of 1100 lb.-in. per inch of laminate

(B) Tension - an ultimate axial load of 10,000 pounds per inch of laminate

(C) Compression - an ultimate axial load of 10,000 pounds per inch of laminate

(A) Flexure

	Glass Content	
	30%	40%
Average Flexural Strength - 0° (from Figure 17)	27700 PSI	34200 PSI
Required Section Modulus per inch of Laminate	.03971 $in.^3/in.$	.03216 $in.^3/in.$
Required Laminate Thickness	.488 in.	.439 in.
Specific Gravity (from Figure 32)	1.412	1.505
Total Weight per Square Foot of Laminate	3.58#/Ft^2	3.44#/Ft^2
Weight of Glass per Square Foot of Laminate	1.07#/Ft^2	1.38#/Ft^2
Weight of Resin per Square Foot of Laminate	2.51#/Ft^2	2.06#/Ft^2

EXAMPLE 1 (Cont'd)

(B) Tension

	Glass Content 30%	40%
Average Tensile Strength (from Figure 11)	12400 PSI	19200 PSI
Required Laminate Thickness	.806 In.	.521 In.
Total Weight per Square Foot of Laminate	5.92#/Ft^2	4.08#/Ft^2
Weight of Glass per Square Foot of Laminate	1.78#/Ft^2	1.63#/Ft^2
Weight of Resin per Square Foot of Laminate	4.14#/Ft^2	2.45#/Ft^2

(C) Compression

	30%	40%
Average Compressive Strength (from Figure 23)	21300 PSI	23800 PSI
Required Laminate Thickness	.469 In.	.421 In.
Total Weight per Square Foot of Laminate	3.44#/Ft^2	3.29#/Ft^2
Weight of Glass per Square Foot of Laminate	1.03#/Ft^2	1.32#/Ft^2
Weight of Resin per Square Foot of Laminate	2.41#/Ft^2	1.97#/Ft^2

In the case of flexure and compression, the 30 percent glass content laminate would require one fewer plies of mat and woven roving, though in the tensile case, one additional ply of each would be required.

Since the mechanical properties of the laminates under consideration are primarily a function of glass content, it is possible to approximate the properties of various types of mat-woven roving composite laminates from Figures 11 through 35 on the basis of anticipated glass content. For example, a composite of alternating plies of 1 ounce mat and 40 ounce woven roving will have a higher average glass content than the 35 percent of the 1-1/2 ounce mat - 24 ounce woven roving composite laminate. Conversely, the glass content of a 2 ounce mat - 18 ounce woven roving composite laminate will be lower. The designer can estimate the effects of such variations on glass content by means of Figure 35, and use the graphs of mechanical properties accordingly. In such cases, it is strongly recommended that tests be conducted to verify the actual glass content of the laminate as well as other properties. A sample calculation showing the proper use of Figure 35 is presented in Example 2.

EXAMPLE 2 - COMPOSITE LAMINATE DESIGN

Determine the average glass contents of the following laminates:

(A) A composite of alternate plies of 3/4 ounce mat and 24 ounce woven roving.

(B) A composite of alternate plies of 2 ounce mat and 24 ounce woven roving.

(A) Total Weight of Glass Reinforcement:

Mat	6.75 ounces/sq.yd.
Woven Roving	24.00 ounces/sq.yd.
Total Glass Weight	30.75 ounces/sq.yd.

$$\frac{\text{Weight of WR}}{\text{Total Glass Weight}} = 0.78$$

Entering Figure 35 with a weight of WR to total glass weight ratio of 0.78 gives a glass content of 38.2 percent.

EXAMPLE 2 (Cont'd)

(B) Total Weight of Glass Reinforcement:

Mat	18.0 ounces/sq.yd.
Woven Roving	24.0 ounces/sq.yd.
Total Glass Weight	42.0 ounces/sq.yd.

$$\frac{\text{Weight of WR}}{\text{Total Glass Weight}} = 0.57$$

Entering Figure 35 with a weight of WR to total glass weight ratio of 0.57 gives a glass content of 33.2 percent.

The choice of data for zero, 45 or 90 degrees to the warp direction largely depends upon the application. For most marine structures such as hulls and decks, the basic structural arrangement is such that the direction of principle stresses can be determined with reasonable accuracy. In general, the stresses will be either longitudinal or lateral relative to the axis of the boat, since structural supports such as framing and bulkheads tend to run in a longitudinal or transverse direction. It is also customary to align fiberglass reinforcement either longitudinally or transversely. This means that, except in rare cases, the low strengths at 45 degrees are not critical. The use of the higher properties in the warp direction (zero degrees) is generally acceptable, since design safety factors are sufficient to account for the loss in strength in the fill direction, which will be less than 5 and 10 percent for mat-woven roving composite and all woven roving laminates respectively.

The data in Figures 11 through 35 and Tables 1 and 2 are not applicable to laminates using unidirectional reinforcement or combinations of unidirectional and bidirectional or isotropic reinforcement. For laminates of this type, properties data should be determined from tests, or from manufacturer's literature, since the physical properties are highly variable, depending upon the percent glass present in the laminate. For guidance, Table 3 presents typical values for the warp direction of a high strength laminate utilizing unidirectional rovings. The properties in the fill direction would be far lower.

TABLE 3

AVERAGE[a] PHYSICAL PROPERTIES - UNIDIRECTIONAL FRP LAMINATES

Per Cent Glass by Weight, %	60-65
Specific Gravity	1.9
Flexural Strength, PSI	114,000
Flexural Modulus, PSI	4.1×10^6
Tensile Strength, PSI	110,000
Tensile Modulus, PSI	3.9×10^6
Compressive Strength, PSI	100,000
Compressive Modulus, PSI	3.9×10^6

[a] Average values for Guidance Only, Warp Direction. Strength values for ultimate strengths.

Fatigue

The fatigue strength of typical FRP laminates relative to that for steel is shown in Figure 36 based upon data from Reference (9). These data are based primarily upon mat and cloth laminates. Lack of data on fatigue of unidirectional and composite laminates makes it necessary to use these data for those materials as well. The single curve is considered applicable to tensile, flexural, compressive and shear strength of FRP laminates, for full stress reversal.

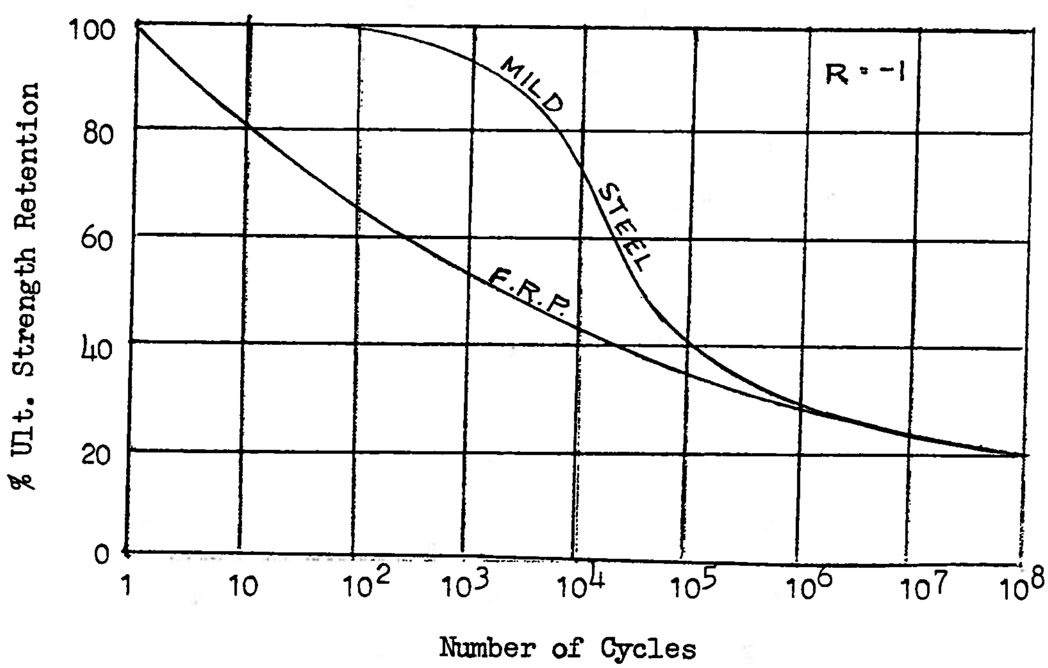


FIGURE 36

S-N CURVES OF STEEL AND FRP LAMINATES

Reference (9) indicates that the fatigue strength of notched specimens is about 15 percent less than that of an unnotched specimen in the range of from 10^2 to 10^4 cycles, though this difference reduces to zero at the extremities of the curve, i.e. the ultimate strength retention of notched specimens of 10^8 cycles is about 20 percent.

The fatigue strength of FRP laminates exposed to elevated temperatures and extreme weathering conditions or immersed in water will be less than that shown in Figure 36, though the data available to date are too limited to present quantitative information on these effects.

Creep

Reference (9) presents data which indicate that creep, or deformation under constant stress, is negligible for FRP laminates at room temperature if stress levels are kept to 20 to 30 percent of the ultimate strength. For higher continual stress levels or higher temperatures, however, creep can be significant and must be carefully considered.

The heat distortion temperature of the thermoplastic PVC foam is relatively low, resulting in possible creep of PVC-cored deck surfaces subjected to direct sunlight or internal heat. This characteristics is not necessarily a disadvantage, but one which must be recognized in designing structures with this material.

Impact Strength

Data in Reference (9) indicate that the impact strength of FRP laminates incorporating cloth or woven roving reinforcement is about twice that of mat laminates of equal thickness or weight. It is not possible to equate these quantitative impact strength data on FRP laminates to those for steel or aluminum due to differences in test methods. However, general observations of FRP boat hulls over extended periods indicate that the impact strength of FRP is quite satisfactory for the normal range impact loads such as slamming, where the structure responds elastically. This is primarily due to the highly resilient nature of the material. Under extreme conditions of impact, FRP panels suffer from their inability to respond plastically. Thus, whereas a steel or aluminum panel would dish, FRP laminates will craze around the edges and in way of the load. If the load is sufficiently severe, rupture of the panel will occur. As noted previously, there are no data available to indicate whether a FRP panel will craze or rupture under impact enough to lose watertightness at a lower energy level than an equivalent steel or aluminum panel. However it would appear that metals would be somewhat superior to FRP in this regard, due primarily to their ability to deform plastically.

Buckling Strength

The tendency of FRP structures to buckle is considerably more pronounced than with metals due to the much lower modulus of elasticity of FRP. This places increased importance on checking FRP plate panels and columns to determine their ability to resist buckling loads. In general, it is satisfactory to analyze FRP panels and columns using conventional theoretical techniques, treating the material as isotropic, and considering compressive moduli and ultimate strengths.

Buckling must also be carefully considered in selecting the dimensions of stiffening members, both to prevent local buckling of the webs and over-all instability of the member. These considerations suggest the use of curvature in laminate panels wherever possible and lateral supports for exceptionally deep framing members.

Secondary Bonds

A secondary bond is defined as any bond between two FRP structures which is made after one or both of the individual structures has effectively cured. In this case, the bonding resin is essentially "gluing" itself to the pre-cured part, and proper surface preparation is essential in producing a good mechanical bond, particularly when non-air inhibited resins are used which produce wax film. The alternative to secondary bonding is primary bonding, in which both parts are uncured when the bond is made. In this case the bond strength is based upon a chemical linkage as a result of continuous cure of the resin. Primary bonds exhibit higher strength than secondary bonds, and are recommended wherever possible. Secondary bonding is discussed in detail later.

Temperature Effect

FRP laminate strength is adversely affected by high temperatures. For a typical laminate incorporating polyester resin the percent strength retention at 200 degrees F, 300 degrees F and 400 degrees F are 90, 50 and 10 percent respectively of the strength at room temperature. Thus it is concluded that FRP structures can withstand continuous exposure to temperatures of about 150 degrees F - 200 degrees F and intermittent exposures to higher temperature. Since polyester resin is a thermosetting resin, it is unlikely that the laminate would regain strength after removal of the heat source.

The properties of FRP in a cold or supercooled environment are higher than at room temperature. Thus operation of an FRP vessel in cold climates will not degrade its strength.

CORE MATERIAL PROPERTIES

Typical design properties of the more commonly used core materials are shown in Tables 4 and 5. Table 4 is based upon typical material suppliers' data, while Table 5 was derived from Reference (22). The properties of foamed plastics such as PVC or polyurethane vary nearly linearly with density, so that properties at densities other than those listed in Table 4 can be approximated by multiplying by density ratios. However, it is suggested that these estimates be confirmed by consultation with the manufacturer.

TABLE 4

AVERAGE PHYSICAL PROPERTIES - CORE MATERIALS

	MATERIAL			
Property	PVC (Thermosetting)	PVC (Thermoplastic)	Polyurthane	End Grain Balsa
Density, Lb./Cu.Ft.	6	5	6	6
Ult. Tensile Strength, PSI	-	-	200	1375 parallel to grain 112 perp. to grain
Ult. Compressive Strength, PSI	250 at 10% compr.	60	200	500 parallel to grain 84 perp. to grain
Ult. Flexural Strength, PSI	-	160	300	825 parallel to grain
Ult. Shear Strength, PSI	170	240	100	170

TABLE 5

PLYWOOD PANEL (DOUGLAS FIR) DESIGN PROPERTIES (1)

Description	3-Ply face & back plies, .030"; core, .040"	3-Ply face & back plies, .047"; core, .095"	5-Ply face & back plies, .047"; cross bands, .060"; core, .040"	7-Ply all plies .080"	9-ply all plies .080"	11-Ply all plies .095"
Weight, PSF(2)	.308	.560	.770	1.66	2.14	3.09
Static Bend Mod of Elast, 1000 PSI						
Parallel	1392	1305	1141	1082	1018	977
Perpendicular	189	276	440	499	562	603
Static Bend Moment for Mod of Rupture, in-lb/in.width						
Parallel	15	47	74	329	513	1040
Perpendicular	4.5	20	43	206	361	789
Compression Mod of Elast, 1000 PSI						
Parallel	1021	865	911	978	954	938
Perpendicular	718	873	828	761	785	800
Ult. Strength in Tension PSI						
Parallel	6540	5420	5750	6230	6060	5950
Perpendicular	4360	5480	5150	4670	4840	4950
Ult. Strength in Shear, PSI						
Parallel	1630	1130	1410	1150	1170	1080
Tension at 45°	2310	2620	2550	2420	2470	2500
Compression at 45°	2730	2620	2670	2730	2720	2710

NOTES: (1) Parallel and perpendicular refer to the relation between the grain direction at the face plies and the direction of the span.

(2) Allows a moisture content of 15% and a weight of .012 lb. per sq.ft. of glue line

WEIGHT ESTIMATING

Estimating the weight of FRP hull structures is somewhat more difficult than with other materials, because of the use of the number of constituents which make up a given structural element: gel coats, resin, reinforcement, core materials, fasteners, etc. In addition, it is necessary to consider the overlaps which occur when individual plies of reinforcement are overlapped in making up a continuous laminate, and resin soakage, particularly into the porous structure of end grain balsa.

Estimating the weight of laminates can be accomplished by using the data in Table 1 and adding a margin of 0.10 to 0.20 pounds per square foot for gel coat. Since this data is based on general purpose resins, the use of fire-retardant resins requires special consideration. The specific gravity of fire-retardant polyester is about 1.33, versus 1.15 for general purpose resins. Thus, if a laminate is assumed to have 35 percent glass content, 65 percent of the laminate weight from the Table should be increased by the ratio of 1.33/1.15 or 1.16. The FRP minesweeper studies, Reference (7), indicates that the use of fire-retardant resins adds about 6 percent to the lightship weight of a large hull.

As an alternative to the above, it is possible to obtain an approximate laminate weight by multiplying its volume by 62.4 times the specific gravity from Figure 32. However, this is not as accurate, since the variation in thickness enters.

For laminates other than mat, woven roving or a composite, it is possible to estimate laminate weight by dividing the dry weight of the reinforcement by the assumed glass content. For example, a laminate consisting of 10 plies of

16 ounce unidirectional reinforcement with an assumed glass content of 65 percent would contain 10 x 16 or 160 ounces of glass (including weight of binder or sizing as applicable) per square yard, equivalent to 1.11 pounds per square foot. Thus the total laminate weight is 1.11/.65 or 1.70 pounds per square foot, leaving a balance of 0.59 pounds of resin per square foot.

This method can also be used with mat and woven roving laminates as well, but requires more computational effort.

All estimates of laminate weight should include a 5 percent margin for overlaps of reinforcement. This is based on an assumed 2 inch overlap with 40 inch wide reinforcement. If wider material is used, this margin can be reduced.

The soakage of resin into the porous cellular structure of end grain balsa can add as much as 0.3 pounds per square foot of surface area (0.6 pounds both sides). The equivalent soakage into foam or wood cores can generally be neglected.

Weight Comparison

The weight of FRP boat structure can be as little as 50 to 60 percent of the equivalent structure of wood, ferro-cement or steel, though this is highly variable, depending on the size and type of boat and the relative percentage of FRP and other heavier materials, such as wood bulkheads or steel foundations. An aluminum hull will generally be equal to or slightly lighter in weight than an FRP hull. For large flat FRP surfaces such as decks and bulkheads, sandwich construction with lightweight cores will generally be lighter than single skin construction.

Consideration of vessel size is very important in evaluating the above generalities. For small boats, the weight savings over steel are more pronounced, due to the effects of corrosion allowances on the thickness of steel plates. On the other hand, the weights of small wood and FRP boats are often fairly close. However, as wood boats get larger, their weight generally increases at a greater rate than FRP, since thicker planking is required to maintain overall hull rigidity and tightness.

As an example of relative weights of larger hulls, Reference (6) estimates the hull structural weights of 110 foot trawlers of wood, steel and FRP to be 120, 130 and 75 tons respectively. This corresponds to a savings with FRP of 30 to 35 percent. The actual life-cycle savings over wood is even greater, since the wood hull can be expected to soak up about 5-10 tons of water. Reference (7) indicates between 32 and 37 percent weight savings in the hull structure of FRP minesweepers 112 to 189 feet long, relative to wood.

Recent U.S.-built FRP shrimp trawler hulls in the 70-75 foot range are only 20 to 25 percent lighter than steel hulls (Reference (2)), since the FRP hulls incorporate large steel fuel tanks and plywood-cored decks, bulkheads and bottom structure.

DESIGN LOADS AND SAFETY FACTORS

Design Loads

The loads which must be considered in designing small boats include the following:

Hull Bottom:	Impact pressure for high speed planing hulls, including fatigue considerations Slamming loads forward Hydrostatic loads when operating in heavy seas Docking or trailering loads Lifting loads, if slings are used Loads from inboard engines and other equipment and appendages attached to hull Abrasion from grounding Mast and keel loads (sailboats)
Hull Sides:	Impact against docks Slamming loads in flared areas forward Hydrostatic loads Wind loads Rigging loads (sailboats)
Transom:	Hydrostatic loads Loads from inboard/outboard or outboard engines Loads from rudders (if fitted on transom)
Weather Decks:	Hydrostatic loads Static loads from equipment and cargo, if applicable Footprint loads Snow and ice loads Impact against docks at edges Impact of cargo or gear (workboats) Abrasion
Interior Decks:	Static loads from equipment and cargo, if applicable Footprint loads Flooding loads (if watertight) Hydrostatic loads for tank boundaries Impact from cargo or gear (workboats) Abrasion
Bulkheads:	Flooding loads Loads transferred from decks supported
Superstructures:	Wave slap (house fronts) Loads from equipment Footprint loads Snow and ice loads Wind loads Hydrostatic loads (lower level of sides)
Foundations:	Loads from equipment supported, including acceleration and fatigue effects

The magnitude of these loads is highly variable, depending upon the type and size of boat, intended service and so forth, and are essentially identical to the design loads which would be used for equivalent boats of other materials. These loads are discussed in detail in References (9) and (24).

Safety Factors

The safety factors used in designing FRP small boats are based upon the ultimate strength of the laminate or the core material, and are generally somewhat higher than for steel or aluminum to account for loss of strength in the wet condition, fatigue, creep and the variability in laminate thickness and properties discussed previously. For conventional FRP boat design, the following safety factors are recommended:

Hydrostatic and equipment loads on the hull and weather deck	4.0
Rigging and foundation loads	4.0
Impact loads on hull and weather deck	1.5
Static and equipment loads on interior decks	3.0
Loads on superstructures	3.0
Flooding loads on bulkheads and tight decks	2.0

For columns, a safety factor of 2.0 on the buckling strength is recommended, as is a safety factor of 1.5 on the buckling strength of flat panels in edge compression. Data on column and panel buckling strengths of FRP structures can be obtained from References (8) and (10).

High performance military and commercial power boats such as crew boats can be expected to operate at high speed in heavy waves for far greater periods during their lives than equivalent pleasure boats. For craft of this type, it is suggested that bottom scantlings be designed for a safety factor of 1.5 on the laminate strength of 10^6 cycles, using average rather than peak slamming pressures.

Fatigue should also be considered in establishing safety factors for design of foundations supporting cyclically-loaded equipment. Examples include gasoline or diesel engines, trawl winches for fishing vessels and shaft struts.

FRP structure supporting rigging loads should be designed for a minimum safety factor of 1.5 on the laminate strength with the rigging stressed to its breaking point.

DEFLECTION LIMITATIONS

The low modulus of elasticity of fiberglass laminates can result in excessive deflections which are objectionable for several reasons. As noted previously, most boat owners object to "soft" decks, and equate noticeable hull side or bottom panel deflections with structural weakness. Excessive panel deflections are objectionable, since the rotation between the panel edge and the stiffener can weaken the bonded joint, and excessive stiffener deflection can cause misalignment of shafting.

As a general guideline, the deflection of panels and stiffeners subjected to the loads discussed previously should not exceed the following, where L is defined as the length of a stiffener between supports or the minimum unsupported span of a panel:

Decks - uniform or equipment loads	L/200
Decks - footprint loads	L/100
Shells - impact or hydrostatic loads	L/100
Bulkheads - flooding loads	L/50
Superstructures - all loads	L/100

VIBRATIONS

The inherent flexibility of fiberglass structures requires careful consideration of vibrations, particularly in the following areas:

Foundations for engines, generators and other rotating machinery

Shaft strut supports

Shell panels in the immediate area of the propellers

In addition, the overall rigidity of large unsupported panels, such as cabin tops, and the racking rigidity of superstructures should be considered.

It is usually sufficient to calculate the lowest (fundamental) frequency of the structural members using conventional isotropic plate or beam theory, and to ensure that these frequencies are not in resonance with forcing frequencies:

RPM of rotating equipment at operating speed

Shaft RPM at operating speed

Blade frequency, which is the shaft RPM multiplied by the number of blades

Hull pounding frequency at high speed

In some cases, it is possible to obtain a fundamental structural frequency which is above the forcing frequencies. In small FRP boats, however, this is often not possible because of the inherent flexibility of the structure and the high forcing frequencies. In such cases, it is desirable to have resonance between the forcing function and the structure occur at a low RPM, as the equipment is being brought up to its operating range of RPMs, since the forcing energy is low.

For a more detailed discussion of small boat vibrations, including examples, Reference (25) is suggested. Although this book is directed toward aluminum construction, the basic principles are applicable to FRP designs.

DESIGN PRINCIPLES

The design of fiberglass small boat structural elements can generally be accomplished with relatively uncomplicated engineering formulations and design principles if a laminate such as mat, cloth, woven roving or a combination of these materials is used, since the effects of orthotropicity can be ignored or easily taken into account. However, this is not necessarily true for laminates of unidirectional material, as noted previously. In such cases, the more complex formulations of References (8) and (10) are recommended. The simplified design approach may also be invalid for the design of very high performance craft, such as hydrofoils and air cushion vehicles, where requirements for light weight force the designer to reduce safety factors to the minimum, and to fully optimize his design. Therefore the balance of this discussion is restricted to conventional small boat structures.

Single Skin Panels

Single skin panels can generally be considered as uniformly loaded, fixed-edges plates for which the bending stress and deflection can be determined from any standard structural text. It is conventional to consider the span as the distance between the toes of stiffeners, as shown in Figure 36. For panels with aspect ratios (panel length divided by width) greater than 2.0, a one-inch wide strip of plate can be isolated and analyzed as a fixed-ended beam. If the deflections exceed one-half the panel thickness, membrane stresses will develop, which should be considered.

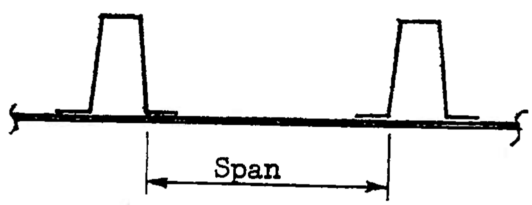


FIGURE 36

DESIGN SPAN FOR PLATE PANELS

Curved panels are inherently stronger and stiffer than flat panels, which makes the above approach conservative. If the hull has significant curvature, as in the case of many sailboats, a reasonably simple computer analysis is possible, by isolating a one-inch strip of laminate and analyzing it as a continuous curved beam over several supports. The use of a finite element computer program is also possible, but its added complexity is seldom justified in small boat design unless it is necessary to consider panel curvature in two directions.

Some hull panels are not truly fixed at all edges, such as the panels adjacent to chines, which can rotate at their outboard edges as shown in Figure 37. However, it is generally satisfactory to neglect this effect.

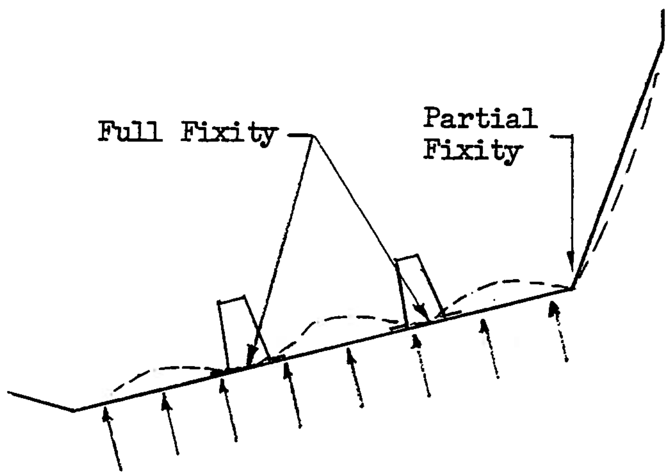


FIGURE 37

PANEL FIXITY

Single skin panels loaded with a concentrated load from a footprint or piece of equipment can also be analyzed with conventional formulae, such as those in Reference (26).

The shear stresses and deflections in plate panels are generally small enough relative to those caused by bending that they can be neglected.

The analysis of single skin panels should be based upon the flexural properties of the laminate.

Sandwich Panels

The classical analysis of sandwich panels is quite complex, because of the difference in moduli of the core and skins. References (8), (10) and (11) go into this matter in extensive detail, and should be consulted where a precise analysis of the panel's behavior is required. Fortunately, there are several simplifications which can be used in most cases, based upon converting the sandwich panel to an equivalent single skin panel, and analyzing the stresses and deflections with the procedures applicable to single skin.

There are two distinct cases which must be considered: cores which are essentially ineffective in resisting bending, such as foam and balsa, and cores which are effective, such as plywood. In the former case, the core can be neglected in calculating stresses or deflections due to bending or axial loads, while the skins are neglected in considering shear. In this case, the following design procedure is recommended:

(1) Isolate a one inch wide strip of sandwich panel, and calculate the inertia and section modulus of this strip.

(2) Calculate the thicknesses of a one inch wide strip of single skin laminate with identical inertia and section modulus.

(3) Using normal plate theory, calculate the stresses and deflection of the single skin panel, which are identical to those of the equivalent sandwich. In the case of sandwich panels, the stresses should be compared to the tensile or compressive ultimate strength of the laminate, since the faces are in pure tension or compression. The average of the tensile and compressive moduli should be used for calculating deflections.

(4) The core should be checked for its ability to carry the shear load on the panel, neglecting the skins. If the skins are thick relative to the core, their contribution in carrying the shear load should be investigated.

(5) If the skin thicknesses are unequal, the foregoing procedure should be modified slightly to account for the unequal stresses in the two skins. This can be done by converting

the stress on the equivalent single skin strip to a bending moment by multiplying by its section modulus, then applying this moment to the strip of sandwich panel, dividing it by the section modulus to the thin and thick faces.

In the case where an effective core such as plywood is used, it is often possible to neglect the effects of thin FRP skins, since their modulus of elasticity is quite similar to that of the wood. If the skins are thick, or the moduli differ significantly, composite beam theory should be used to determine the actual stress at the interface between the wood and FRP. This is illustrated in Figure 38.

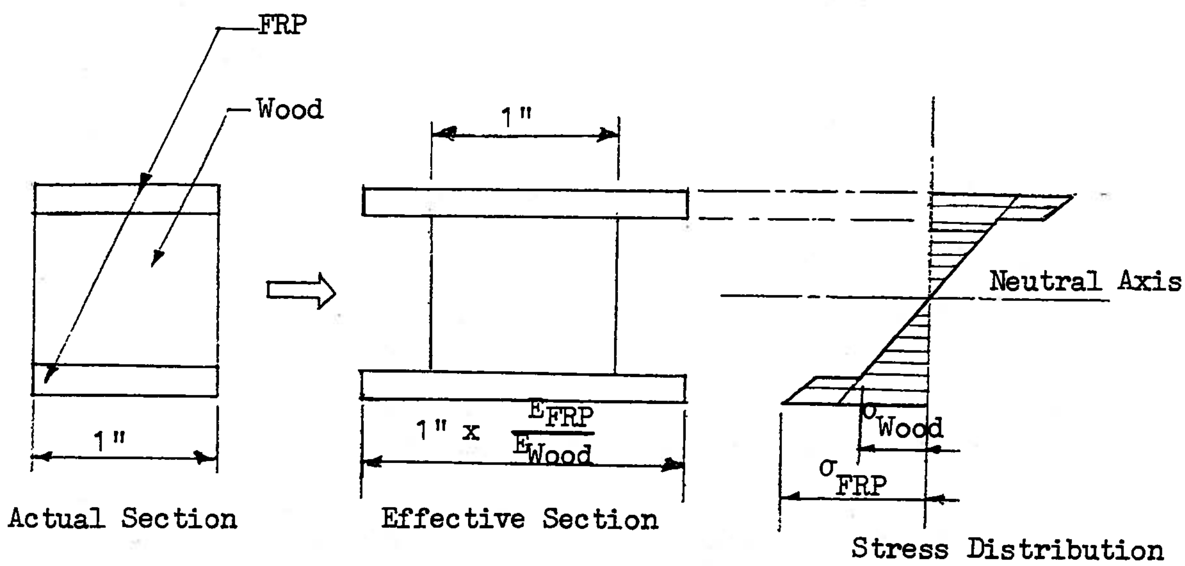


FIGURE 38

ANALYSIS OF WOOD - FRP PANEL

If the core is of plywood, consideration must be given to the difference in effectiveness between the plies whose grain is oriented with the load, and the cross plies.

Beams

The analysis of FRP beams can be carried out using conventional beam theory, with stress calculations based upon either the tensile or compressive moduli. This convention has been adopted since the flange and effective plate, which are the main contributors to the section modulus and inertia, are in pure tension or compression, similar to a sandwich panel.

Although shear are often neglected in calculating beam deflections, the contribution of shear is generally significant, particularly with short, deep beams.

The effective width of laminate to be used in calculating the properties of a beam is shown in Figure 39, based upon recommendations in Reference (10). This width should not exceed the frame spacing. For beams bonded to sandwich panels, the effective width should be based upon 15 times an equivalent single skin panel with inertia identical to that of the sandwich panel.

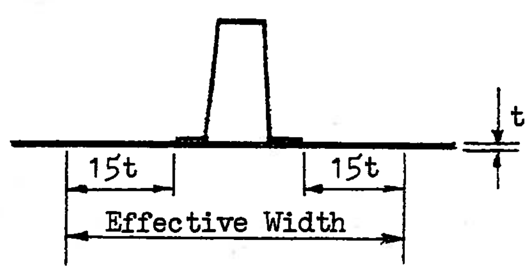


FIGURE 39

EFFECTIVE WIDTH OF FRP PANEL

VII. CONSTRUCTION OF FIBERGLASS BOATS

The following discussion of fiberglass boat construction is a brief overview, since the subject is covered in considerable detail in References (8), (14), (27) and numerous other sources. We will only cover the so-called "contact pressure molded" or "hand layup" process used for most small boats, though brief mention will be made of other molding methods.

BASIC MOLDING PROCEDURES

There are five basic procedures which are applicable to the construction of FRP boats and components: contact pressure, vacuum bag, matched metal die, autoclave molding, and filament winding.

Contact Pressure

This is by far the most common method utilized, in which the combination of uncured resin and reinforcement are layed into a mold, and allowed to cure without external heat or pressure. As discussed previously, the catalyst added to the resin, in combination with an accelerator, generates sufficient heat to affect cure at room temperature.

Vacuum Bag

This procedure is used primarily to fabricate high-performance sandwich panels, but is seldom used in commercial boat production. The purpose of vacuum bagging is to force all air and excess resin from the layup to achieve a high glass content, and to ensure a uniform, strong bond between the skins and core. This is accomplished by laying up the panel in a mold and covering it with a thin plastic bag, which is then evacuated by a vacuum pump. The result is a uniform pressure of as high as 13 or 14 PSI over the surface of the layup. Excess resin is worked to the edge of the part and drawn off.

Autoclave Molding

This type of molding is essentially the opposite of vacuum bagging. The mold, layup and thin plastic covering bag are put into an airtight chamber where external pressure and heat are applied. Neither vacuum or autoclave molding are used to any extent in small boat production, since the higher quality of the resultant product is not sufficient to offset the greater time and cost required for these processes.

Matched Metal Die Molding

This type of molding utilizes two matched metal dies of the required shape, and with a gap between them equal to the desired laminate thickness. A preform of uncured resin and reinforcement is draped into one half of the mold, and the two halves of the mold are clamped together and heated to produce cure. This process rapidly produces a smooth, uniform part, but the high cost of the tooling cannot generally be justified for boat production, where hull shapes are changed fairly often.

Filament Winding

Filament winding consists of spiral winding continuous impregnated glass filaments onto a mandril of the desired shape. The wrap angle can be varied to provide very close control of laminate properties. The filament winding process has found wide applicability in producing rocket fuel tanks and other aerospace applications, but the relatively high cost of the process has limited its use in the marine industry to masts and other relatively simple bodies of revolution.

TOOLING

The basic tool used in FRP boat production is a mold, either female or male, as shown in Figure 40. For most layups, the female mold is preferred, since it results in a smooth outer surface for the part, whereas the male mold produces a smooth inner surface.

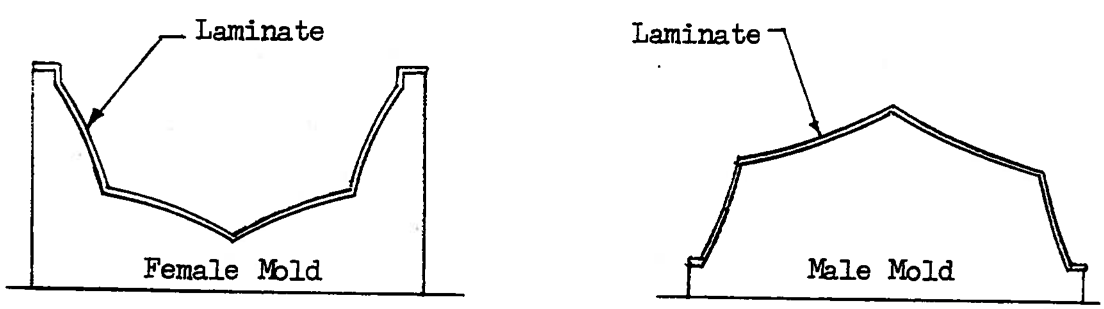


FIGURE 40

FEMALE AND MALE MOLDS

The first step in preparing a mold is to prepare a wood "plug" of exactly the shape desired for the final product. This plug is carefully surfaced with a smooth, non-porous material, either paint or fiberglass, and is them waxed or coated with a thin parting film. An FRP mold is then layed up on the plug, generally using sandwich construction to achieve the desired rigidity and long life. Prior to removing the mold from the plug, it is reinforced with a framework of wood or pipes, so that the entire assembly can easily be moved around the shop as required.

Molds can either be one piece or split along the centerline. The one piece mold is simpler to construct and maintain, but requires that the hull be lifted clear of the mold after completion. For small boats, this is no problem, but for larger hulls, heavy chain falls or other lifting apparatus is required, and the height of the molding area must be at least twice that of the part, unless the mold is placed in a pit. The split mold avoids this problem, since the two halves can be moved outward and the completed hull moved longitudinally without lifting. The disadvantages of the split mold are the necessity of bolting the two halves together for layup, and the greater amount of floor space required to permit moving the mold halves.

Split molds are sometimes hinged along the centerline, so that the two halves can be layed flat as shown in Figure 41. This provides the advantage of being able to lay up the laminate in a downhand position, thus minimizing the problem of resin drainage from vertical surfaces. The basic disadvantage is that a heavy bridging laminate must be layed up along the centerline to join the two halves of the hull.

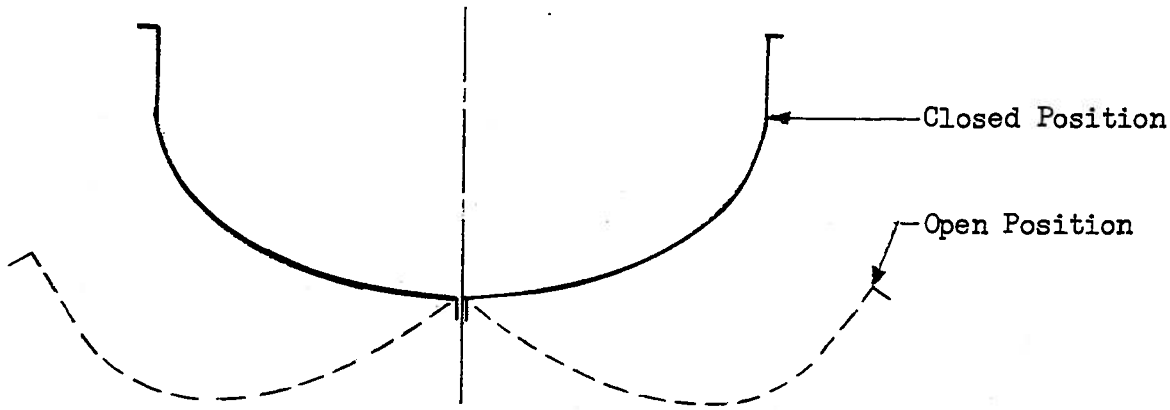


FIGURE 41

HINGED SPLIT MOLD

Molds should not have sharp corners, since the reinforcement will tend to "bridge" or develop a radius, leading to air entrapment. They should incorporate a draft of about 3 degrees minimum on vertical surfaces, to facilitate removal of the part, and should avoid deep, narrow cavities such as skegs or sailboat keels, since layup in such cavities is difficult.

The conventional female molds discussed previously are relatively expensive, and can only be justified for relatively high-volume production. For production of a single or limited number of FRP hulls, there are several types of inexpensive molding procedures available:

Planked Wood Mold

This type of female mold consists of an inexpensive planked form layed up over a wood framework, which is then sanded smooth, surfaced with fiberglass and finished to the desired surface finish. In a sense, this type of mold is a conventional wood boat built inside-out. As an alternative, a male form can be built, similar to a wood boat built upside down. This precludes the requirement for carefully finishing the surface of the mold, since it would be the inner surface of the hull, but it requires that the outer non-mold surface of the hull be sanded, and also requires turning the hull over. Another alternative is to use plywood in lieu of planking to surface the form in relatively flat areas. The fundamental advantage of this type of mold is elimination of the plug, though it lacks the dimensional stability and long life of a conventional mold.

Integral or "Lost" Mold

This technique can be used for laying up hulls of sandwich construction. An inexpensive open wood framework is "planked" with strips of polyurethane foam or PVC foam, which are nailed lightly to the framework. The foam is then covered with fiberglass, which is allowed to cure. The assembly is inverted, the framework removed and the inner skin of fiberglass is layed up. This technique requires that the outer surface of the hull be sanded or ground to achieve the desired surface finish.

GEL COATS

The first step in laying up a fiberglass part in a mold is to carefully wax the mold surface or to apply a parting agent which permits easy removal of the part after cure. The waxed or coated mold surface is then sprayed with a thin (10 to 30 mils) layer of gel coat resin, which is generally allowed to cure so that subsequent layups will not produce thin spots or ripples. The gel coat can then be reinforced with a fiberglass backup, which precedes the layup of the structural laminate. This backup, which generally consists of layers of cloth or mat serves both to stabilize and strengthen the gel coat, and to prevent "print-through" of the coarse pattern of woven roving.

Gel coat resins are generally sprayed on the mold surface in order to achieve a rapid, smooth, uniform distribution. For small parts, the gel coat resin may be applied by brush to avoid the wastage caused by overspray.

HAND LAYUP

The hand layup process is used in small boat production to deposit and combine resin and reinforcement in the mold. The resin is generally sprayed on using a two-part system which mixes separate supplies of catalyzed and accelerated resins with a gun much like that used for paint spraying. Since neither type of resin can cure by itself without being added to the other, this system minimizes the chances of premature cure of the resin while it is still in the drum or the sprayup equipment. This system provides uniformity of cure as well as good control of the quantity and dispersion of the resin on the part.

Some shops dispense resin to their laminators in buckets, to which catalyst is added just prior to use. There are several disadvantages to this system, however. The quantity of catalyst required to cure a given amount of resin is very small, and requires thorough mixing to achieve a uniform distribution. This is often not achieved in the shop, resulting in uneven cure. Since the cure process is irreversible, and cannot easily be slowed down, the laminator must use up the bucket of resin before it begins to cure and becomes unworkable. If the resin begins to "kick over" before it has been used up, the laminator will find it necessary to work in a faster, sloppier manner, which results in a laminate of poor quality.

The catalyzation process is highly sensitive to temperature variations, and requires a temperature range of from about 60 to 85 degrees F. Thus fabrication of FRP boats should be accomplished in an enclosed, temperature-controlled environment.

The plies of fiberglass reinforcement are generally pre-cut to the desired shape in a special cutting room, and packaged in kits which contain all of the pieces necessary for a given molded part. After a thin layer of resin has been spread over the surface of the mold, one or two layers of dry reinforcement are placed on the surface, and the resin is forced up through the reinforcement by rolling on the surface with mohair or grooved metal rollers, or by squeegying. This process completely saturates the reinforcement with resin, distributes the resin properly, and removes any air trapped behind the reinforcement. This process is repeated as often as necessary to achieve the desired laminate thickness. A layer of reinforcement may consist of a number of individual pieces, which should be overlapped a minimum of 2 inches to maintain full strength.

Upon completion of the skin layup, framing and other supporting structures are added. It is recommended that all hull framing and bulkheads be installed prior to removing the hull from the mold, since the laminates will not fully cure for several weeks, and an unstiffened hull may develop sags after removal from the mold. Since production considerations dictate rapid turnover of parts from the mold, it is common to transfer the hull from the mold to a rolling framework which supports the hull during subsequent outfitting and equipment installation.

LAYUP OF SANDWICH PANELS

Commercial boatbuilders seldom use vacuum or autoclave pressure to affect a good bond between the skin and core. More commonly, the core is coated with resin and is manually bedded on the uncured mold skin. If the core is rigid, such as plywood or board foam, sandbags or other weights may be placed on the core during cure. If a flexible core is used, such as small blocks of end grain balsa or oven-softened PVC foam, the core is pressed into the uncured skin laminate with rollers. In either case, the interfacing surface of the mold skin should consist of a thick, resin-rich layer of mat which will act as a spongy cushion to fill irregularities between the skin and core, thus achieving a better bond.

After cure of the core to the mold skin, the weights are removed and the upper, or non-mold skin is layed up directly on the core. Here again, a layer of mat is suggested against the core.

The surface preparation of core materials is quite important in achieving a good skin-to-core bond. Plywood should be rough sanded to open up the grain or kerfed lightly with a circular saw. End grain balsa should be thoroughly resin-coated on both sides prior to layup, so that excessive amounts of resin will not be drawn from the skins into the core cells by capillary action, creating dry laminates. If the balsa is being layed down in small blocks, it is desirable that the gap between blocks be resin-filled to prevent migration of water through the core if the hull is punctured.

SPRAY-UP OF CHOPPED STRANDS

A special gun is used by many fabricators to deposit a mixture of resin and chopped strands of fiberglass filaments on the mold surface, producing a laminate very similar to mat. The gun, called a "chopper", draws continuous strands of fiberglass from a spool which are fed through a series of whirling blades which chop it into strands about 2 inches long. These chopped strands are blown into the path of two streams of atomized liquid resin, one accelerated and one catalyzed, and the resin-strand mixture is sprayed onto the mold surface. The chopper gun produces mat-type laminates easily and rapidly, and provides close control of resin-glass ratios. The fundamental disadvantage of the chopper gun is lack of control of laminate thickness and possible wet-out problems if the sizing on the glass filaments produces a "stiff" strand. At present, control of thickness is generally provided by a colored tracer which is fed through the gun with the rovings. The gun operator judges the thickness of the laminate by the relative intensity of the colored strands on the layup.

SECONDARY BONDING

The problem of secondary bonding, discussed previously, has resulted in a number of studies to optimize the production methods used in achieving them.

One of the most extensive investigations of secondary bond strength was undertaken in connection with the U.S. Navy's FRP minesweeper program. Reference (23) summarizes the results of the test program and provides considerable quantitative data on static and impact bond strength. In reviewing these results, the following conclusions were reached:

> Preferable secondary bonding procedures are as follows:
>
> > Bond resin: either general purpose or fire-retardant, resilient.
> >
> > Surface treatment: roughened with a pneumatic saw tooth hammer, peel ply, or continuous cure of rib to panel; one ply of mat in way of bond.
> >
> > Stiffener faying flange thickness: minimum consistent with rib strength requirement.
> >
> > Bolts or other mechanical fasteners are recommended in areas of high stress.
>
> Acceptable procedures are as follows:
>
> > Bond resin: general purpose or fire-retardant, rigid air inhibited.
> >
> > Surface treatment: rough sanding.
>
> Undesirable procedures are as follows:
>
> > Excessive stiffener faying flange thicknesses.
> >
> > No surface treatment in way of bond.

The "peel ply" referred to above consists of laying down, but not wetting out, a strip of dry cloth on the uncured laminate in way of the anticipated secondary bond. After cure, the strip is peeled away, leaving a rough bonding surface with raised glass fibers.

The U.S. Navy and Coast Guard currently require sanding of laminates in way of secondary bonds, where a secondary bond is defined as one which occurs after either twice the gel time or the gel time plus 2 hours, whichever is greater.

Fabricators of pleasure boats do not generally use sanding, because of the problems with shop cleanliness, skin irritation and equipment maintenance. Either a dry, wipe or an acetone wipe will usually be used to remove dust from the area, after which the secondary bond is made. Sanding is considered necessary only for laminating resins with high wax content or for cosmetic purposes.

One might question the difference between commercial and Navy or Coast Guard practice, particularly when the majority of pleasureboat builders report very few problems with secondary bond failures. There are several justifications for the more stringent requirements of the Navy and Coast Guard, including their use of fire-retardant resins, which do not bond as well as general purpose resins, and the more rugged nature of the service life.

WORKABILITY

Fiberglass laminates can be drilled, sawed, ground, and otherwise worked much the same as a soft metal, although such metalworking techniques as bending, flanging, heat fairing, punching and chipping are not possible. Metalworking tools should be used for fiberglass, because the abrasiveness of the glass will rapidly dull woodworking drill bits or saw blades.

Fasteners commonly used for fiberglass construction include bolts, self-tapping screws and pop rivets. Bolts, backed with large washers or backing plates, are preferred wherever possible, particularly for attaching highly loaded foundations and fittings. Lock washers are recommended for attaching vibrating machinery.

Where bolts cannot be installed because of inaccessibility, screws may be used. The hardness and incompressibility of FRP precludes the use of conventional wood screws, but straight-shanked self-tapping screws will produce a satisfactory attachment for lightly-loaded connections. The soundness of such an attachment is dependent upon proper size of the lead hole and suitable laminate thickness, which should not be less than 3/16 inch for tapping.

Pop rivets are used extensively for making blind joints in small boat hulls, such as attachment of paneling, trim, hull to deck and lightly-loaded hardware.

When fasteners such as those just described are used with sandwich panels, special precautions are required. Core materials often do not have sufficient compressive strength to resist bolt loads, necessitating high-strength core inserts or large backing plates. Sandwich panel skins may be too thin to provide good attachment of self-tapping screws. These considerations, and further details on the use of fasteners with FRP, are available in References (8) and (27).

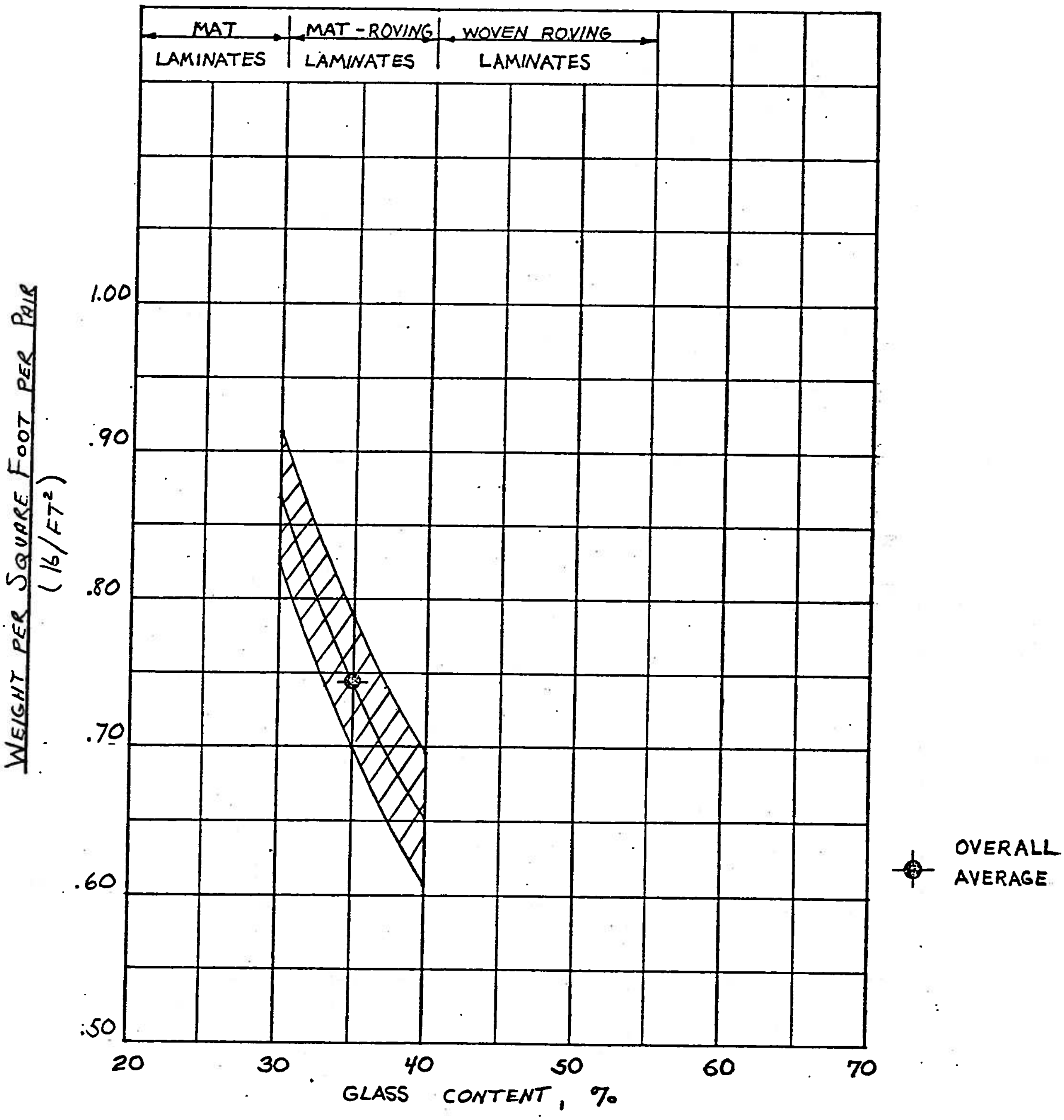


FIGURE 33

WEIGHT PER SQUARE FOOT PER PAIR - ALTERNATING PLIES OF 1-1/2 OZ. MAT AND 24 OZ. WOVEN ROVING

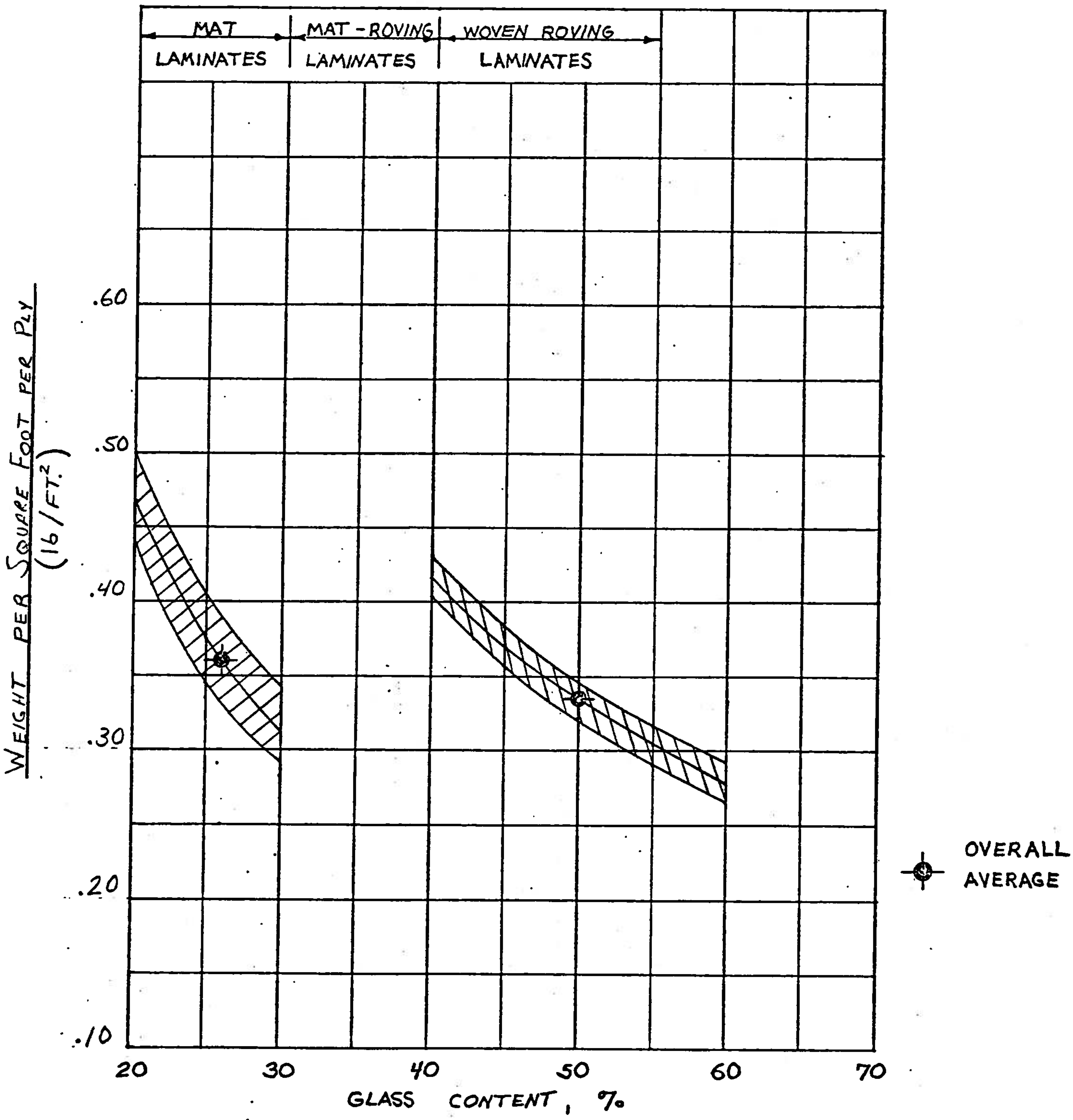


FIGURE 34

WEIGHT PER SQUARE FOOT PER PLY
1-1/2 OZ. MAT OR 24 OZ. WOVEN ROVING

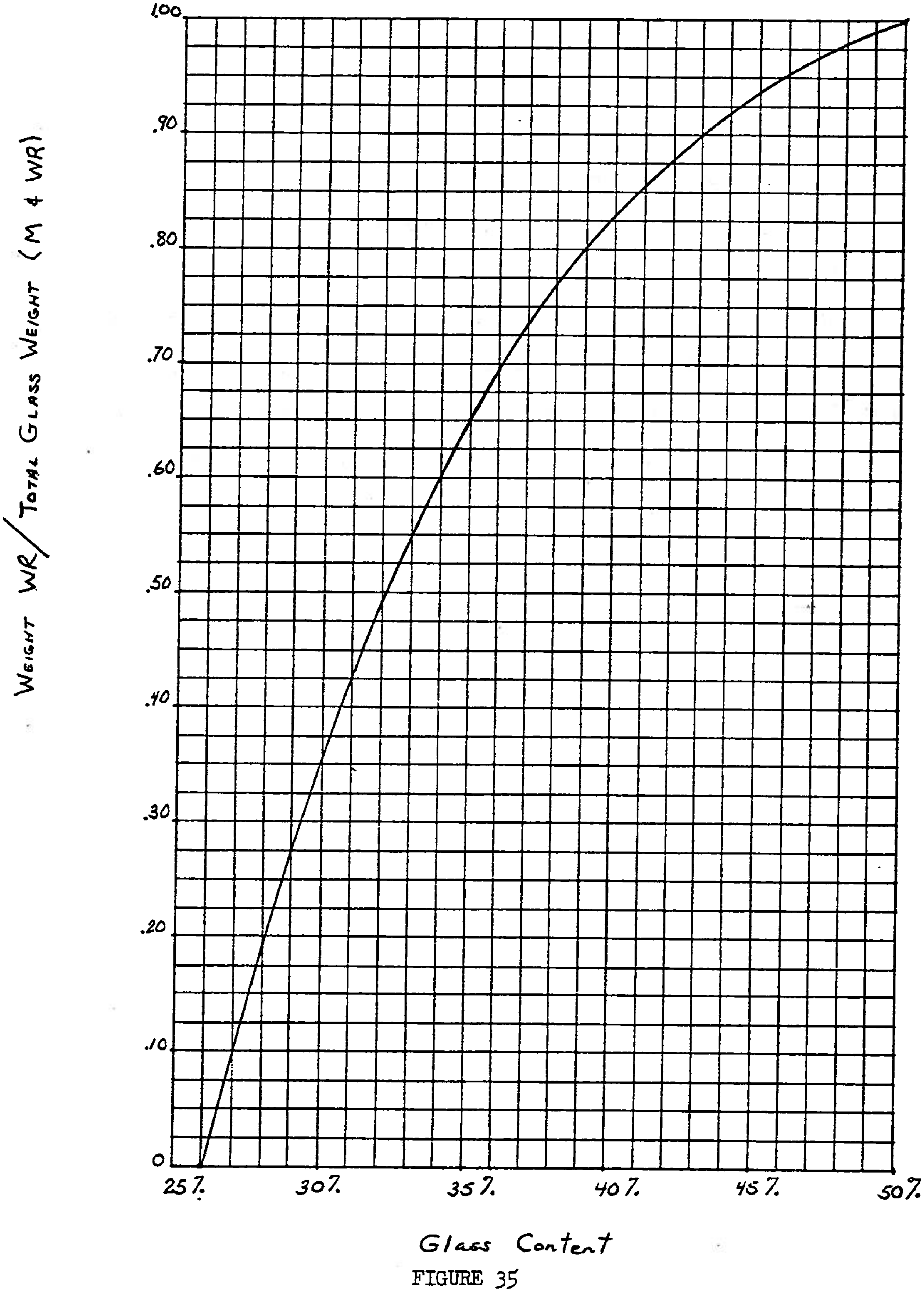


FIGURE 35

RATIO:WEIGHT OF WOVEN ROVING/TOTAL GLASS WEIGHT VS GLASS CONTENT

Columns

FRP compressive members can be designed with the column theory for isotropic members, using Euler's equations with the appropriate compressive modulus of elasticity.

In summary, it is again noted that the foregoing simplified design procedures are based upon the use of a laminate with properties in the warp and fill direction which are relatively similar. In special cases, the lower strength at 45 degrees to the warp should be considered, but for most boat designs, such instances are rare.

QUALITY CONTROL AND INSPECTION

The quality control and inspection (QC and I) requirements for FRP construction must be more extensive and demanding than for other materials, since the basic properties of the hull structure are determined during the fabrication process. In this section, we will consider those areas in which QC and I requirements for FRP are unique.

The level of QC and I is dependent upon many factors, including the design margins which can be incorporated in the design. For high performance craft, where weight is critical and service requirements are severe, the QC and I requirements must be very high. For designs in less demanding service, higher safety factors can relieve the QC and I requirements to some degree.

Another factor which must be considered in establishing QC and I is the competitive nature of the business. Both the Navy and Coast Guard insist on relatively stringent QC and I requirements, not only because of the rugged service seen by their boats, but to ensure that they have adequate control over the quality of the product turned out by the builders. Most Government FRP boat contracts are let out for competitive bids, with award going to the low bidder, so that the need for some controls is obvious. In the pleasure and commercial end of the business, the level of QC and I is generally developed over the years to achieve an optimum balance between the cost of in-plant QC and I and the cost of correcting unfound deficiencies in the field after sale of the boat.

A final, and most important factor is the ability and conscientiousness of the laminators and on-line leadmen. An inexperienced or apathetic crew naturally requires closer control than one with enthusiasm and experience. Unfortunately, rapid turnover in shop personnel and low incentive is far too common, particularly among laminators.

The Navy and Coast Guard QC and I requirements include the following which are applicable to FRP construction, with References (28) through (33) among the more important applicable documents:

> All materials must be covered by a Certificate of Compliance certifying that they meet MIL-Spec. requirements.
>
> The fabricator must prepare and follow a Process Description describing materials, material storage, resin mixing methods, gel time controls, type of layup, assembly sequence, etc.
>
> Visual inspection of laminates for waviness, air bubbles, foreign matter, incomplete wetout, blisters, crazing, delamination, or surface cracks, and repairs to same. Navy and Coast Guard boats are layed up with unpigmented resin to facilitate this inspection.
>
> Laminate physical properties tests to compare to Specification minimums: tensile strength, flexural strength, void content, hardness, resin content. Test procedures generally comply with Reference (28).
>
> Core bond strength tests on sandwich panels.
>
> Physical properties tests on buoyancy foam: density, compressive strength (load to compress 1/10 inch), water absorption, humid aging (change in volume due to exposure to humid, hot environment), compression set (change in thickness under compressive load in 24 hours at high temperature) and oil resistance.
>
> Weighing major components for consistency with the weight of the prototype part.
>
> Close monitoring of resin gel times, and control of temperature within the laminating area.
>
> Monitoring all fabrication processes to ensure compliance with specification requirements.

Most builders of small pleasure or commercial boats seldom employ QC and I procedures as stringent as those required for military craft. In addition to the conventional on-line inspection and check lists used for other materials, the following procedures applicable to FRP are often employed:

> Laminate testing for the prototype boat, similar to Navy tests, with monitoring of resin content in subsequent hulls. These tests are generally conducted on hull cutouts.
>
> Monitoring the quantities of glass and resin going into major parts. This effort assists in evaluating sources of wastage.
>
> Checking the degree of cure of a part prior to removing it from the mold. This is done with a "Barcol" hardness tester, which measures the penetration of a calibrated needle point into the laminate.
>
> Visual inspection of laminate surfaces for flaws. Since pigmented resins are generally used for commercial or pleasure FRP boats, internal laminate flaws cannot be detected unless they are very obvious, such as blisters.
>
> Checking materials prior to use against in-house requirements. This would include viscosity, uniformity and shelf life of resins, additives in resins, quality of reinforcements (uniformity of weave, width, thickness and weight; cleanliness; dryness; stiffness; wetability) and density and apparent structural quality of core materials.
>
> Checking gel times, including close control of variations in catalyst concentrations with daily fluctuations in shop temperature, if required.

The quality control and inspection procedures used by FRP pleasure and commercial boatbuilders vary considerably from plant to plant, depending upon the general quality of the personnel and the desired quality of the product. In a sense, the competitive nature of the business tends to produce a relative stability in this area, with builders of questionable quality having difficulty surviving the cyclic small boat market. Those who weather these economic crises find it necessary to produce boats of reasonable quality, since buyers are becoming more sensitive to boatbuilding quality and builders cannot afford the risk of solving numerous expensive guarantee problems. Unfortunately, we still have a long way to go in establishing guidelines for small boat structures, particularly for FRP, though this matter is being given increasing attention.

STRUCTURAL DETAILS

The details used in laying up and assembling FRP small boats are of extreme importance, since these are the usual source of problems, rather than the basic laminates. The types of details to be considered here include the attachment of the hull to deck, bonding in bulkheads and flats, attachment of fittings and engine foundations. References (2), (8), (15), (16) and (27) are suggested for further guidance.

Prior to reviewing typical details, there are some general guidelines applicable to structural details which should be considered:

> Mechanical fasteners should be used in lieu of, or in conjunction with, secondary bonding of highly loaded joints and attachments.
>
> Surfaces of FRP must be properly prepared in way of secondary bonds, as discussed previously, if the bond strength is to be relied upon.
>
> Bolts should be used in lieu of self-tapping screws wherever possible, and fasteners must be properly backed up to spread the loads over a large area.
>
> Core inserts should be provided in sandwich panels where the basic core material has inadequate strength to resist the fastener loads.
>
> Metal fittings attached to FRP should be bedded in a resin putty to assure uniform bearing, unless the surface is smooth.
>
> Subassemblies of FRP should fit tightly together, and the gap should be filled with resin putty.

The midship sections shown in Figures 4 through 9 illustrate many typical details used in constructing FRP boats, and additional details are shown in Figure 42. One of the details found in nearly all FRP boats is the so-called "bonding angle" used to bond bulkheads to hulls and decks and other similar applications, Figure 42(a). The bonding angle consists of layers of glass tape overlapped equally onto both precured parts. The first layer of reinforcement in the bonding angle should be mat, to achieve higher bond strength, followed by subsequent layers of mat or woven roving or both as required. The scantlings of bonding angles are determined somewhat arbitrarily, but for general guidance the minimum overlap should be about 2 inches in very small boats, up to as much as 6 inches for large trawlers. Three to 4 inch laps are most commonly used. The total thickness of the bonding angle (both sides) should be about equal to that of the thinner of the parts being joined.

A number of experiments have been conducted to determine the value of fillets at the corners of bonding angles, Figure 42(b). Although somewhat inconclusive, there appears to be some benefit to this type of construction, particularly in resisting lateral or bending type loads.

The bulkhead bedding procedure shown in Figures 42(a) and (b) vary widely throughout the industry, though most builders favor a small gap between the bottom of the bulkhead and the hull, sometimes filled with foam or a resilient bedding material, to minimize the hardspot caused by the bulkhead.

The flat-to-hull connections shown in Figures 42(c) and (d) illustrate how FRP shelves or lips can be molded into the hull, and how FRP sandwich panels should be brought back to single skin in way of attachments.

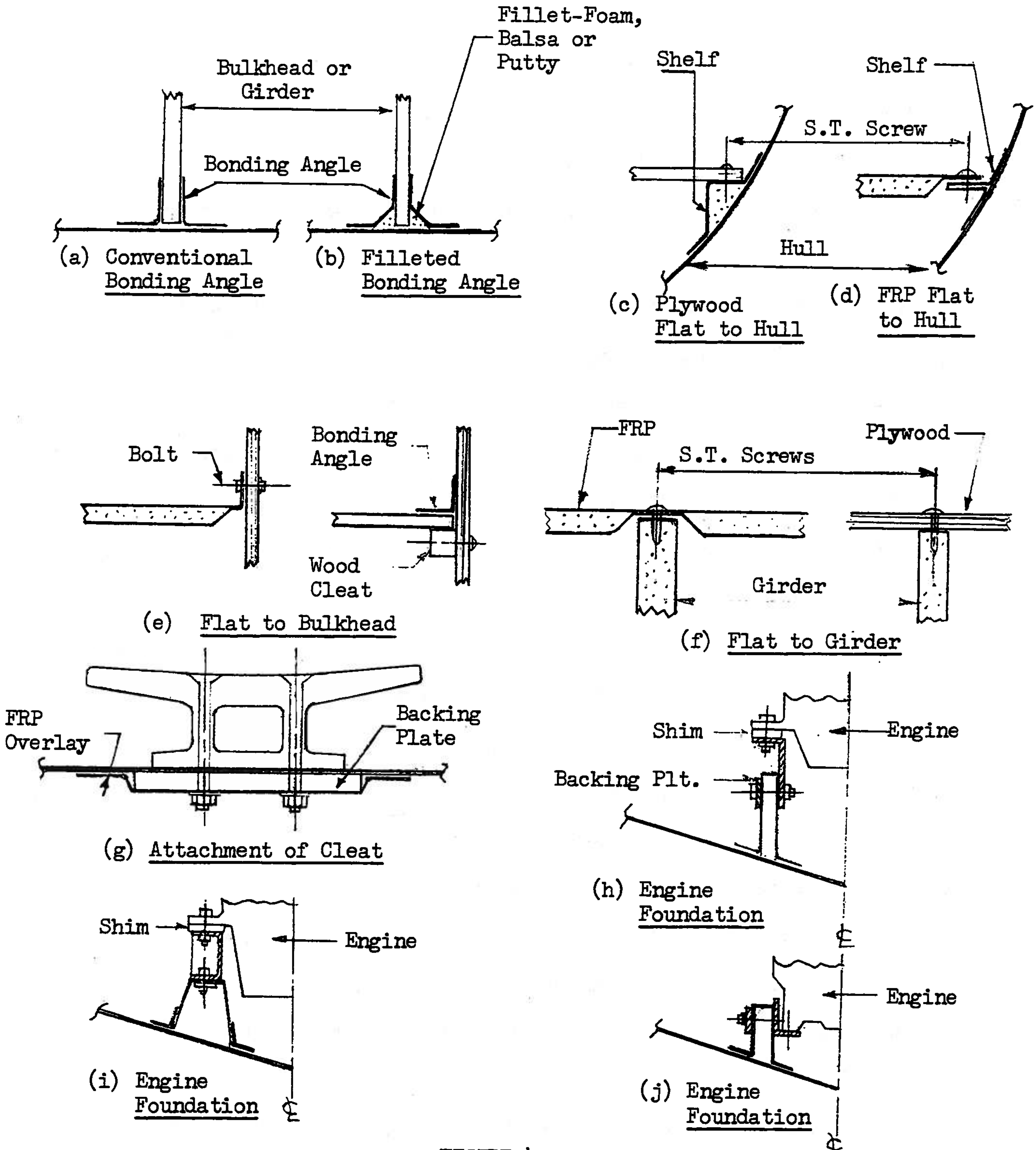


FIGURE 42

TYPICAL STRUCTURAL DETAILS

The engine foundations shown in Figures 42(h) through (j) illustrate the use of a metal subbase ruggedly attached to the FRP hull structure, with high strength core inserts and backing plates as required. The metal subbase should extend for the entire length of the engine, and foundations for heavier engines should have metal bearing caps, Figure 42(i), so that the bolts are not loaded in shear.

Hull-to-Deck Connections

Figures 5 through 9 illustrate typical details used for this very important connection. The horizontal lap joint in Figure 5 is common in smaller boats. The faying surface should be coated with resin-impregnated mat or resin putty prior to installing the aluminum and vinyl extrusion and pop rivets. The vertical lap joint in Figure 6 is also very popular, but requires careful control of hull and deck dimensions to provide a snug fit without binding at corners. The detail in Figure 7 utilizes a special aluminum extrusion to join four separate FRP moldings. For larger boats, it is desirable to back up the overlapped and bolted connection with an internal FRP bonding angle, as shown in Figures 8 and 9. The deckedge detail in Figure 9 is quite interesting, in that the inner face of the bulwark is molded with the deck and the outer face with the shell. The two are lapped at the top of the bulwark, and a heavy FRP bonding channel is layed up at the deck level to bridge the gap between the deck and shell.

VIII. ECONOMICS

The economics of building FRP boats are somewhat difficult to analyze, since the price paid by the buyer reflects the economic structures of many groups or individuals other than those directly associated with the boat's fabrication. These include dealers, shippers, central distributors, the parent organizations that own many small boatbuilders, etc. This picture is further clouded by the wide range of options, financing arrangements, and service contracts available to the buyer. Therefore, we will concentrate only on those factors relating directly to the manufacturer's cost of constructing the basic hull structure of FRP boats.

MATERIALS

The price of the materials that go into constructing an FRP boat vary widely, depending on the quality of materials, quantities purchased, location of plant, bargaining power, the general health of the industry and so forth. For general guidance, Table 6 presents average 1970 prices for large-quantity purchases of commercial-quality materials.

Materials meeting Navy or Coast Guard MIL-Specification requirements are generally more expensive, particularly resins. A MIL-Specification general purpose polyester resin would cost about \$0.25 per pound, and fire-retardant resins about \$0.40 per pound.

When estimating material costs, a margin of about 10 percent should be included for wastage.

TABLE 6

FRP MATERIAL COST

Item	Cost per Pound ($ US, 1970)
Mat (1-1/2 Oz.)	0.48
Mat (1 Oz.)	0.51
Woven Roving (24 Oz.)	0.50
Cloth	1.00
Unidirectional Reinforcement	0.62
Gel Coat Resin	0.70
General Purpose Polyester Resin	0.18
Fire-Retardant Polyester Resin	0.31
Polyurethane Foam - Prefoamed Board	1.50
Polyurethane Foam - Ingredients	0.65
End Grain Balsa	1.50
PVC Foam Board	3.00

LABOR

Labor rates for laminators vary widely throughout the country, from as low as $2.00 to as much as $3.00 per hour. For general estimating, an average of $2.50 is suggested.

Productivity of labor is highly dependent upon experience, the complexity of the part being fabricated, the efficiency of the plant, degree of automation in materials handling and fabrication, number of different boat models being produced, and required level of quality, among other factors. For general guidance, the layup rate of a production of 10 or more identical parts can be assumed as follows:

Single skin with frames	- pleasure boats	=	20 lbs/MH
Single skin with frames	- Military boats	=	12 lbs/MH
Sandwich construction	- pleasure boats	=	10 lbs/MH
Sandwich construction	- Military boats	=	6 lbs/MH

The sandwich panel layup rates are applicable to foam or balsa cores, but not to plywood cores, due to the higher weight of plywood.

The above rates include not only laminating but margins for other related activities such as sweeping and cleaning, material handling, mold preparation, moving subassemblies - in short, all of the labor demands (other than supervision) required to lay up and assemble the hull structure.

The manhour requirements for constructing one, two and five identical boats can be estimated by increasing the foregoing values by 30, 15 and 5 percent respectively.

If possible, it is highly desirable to obtain a more detailed breakdown of labor requirements and to assign appropriate manhours and wage rates rather than rely upon the foregoing, which must be regarded as only approximations. Unfortunately, data of this type is difficult to obtain, and is generally applicable only to the source from which it was obtained.

OVERHEAD

The overhead, figured as a percentage of direct labor, will also vary widely, depending upon the level of on-line supervision, fringe benefits, advertising, size of the "overhead staff" (executive, administrative, financial, engineering, quality control, protection, service, etc.), size and cost of facilities and method of amortization, capital investment, and so forth. Another factor which must be considered is the possible relationship between the boatbuilder and a parent organization. In many cases, one of the penalties associated with being a part of a conglomerate is the need to absorb part of the overhead of the parent company. This is offset by the financial assistance available in hard times, as well as the greater leverage available in obtaining financing for expansion and capital improvement.

The range of overhead for builders of small FRP boats will generally run from 125 to 200 percent, with both higher and lower values not being unexpected. Again, these numbers must be used with discretion, since it is often difficult to determine just what is included in "overhead", and requires a knowledge of financing which is beyond the scope of this study.

The overhead figures cited above are higher than those usually associated with wood or metal construction. This results partially because much of the overhead cost of a small boatbuilding operation is insensitive to the wages of the baseline work category, in this case the laminator. Since FRP laminators earn less than equivalent metal or woodworkers, the overhead, expressed as a percentage of their wage, would be higher. Also, the enclosed environment required for fabricating with polyester resin results in higher fixed operating and initial plant costs.

TOOLING

The cost of tooling up to produce a line of fiberglass boats is relatively insignificant for a long production run. A well-built mold can produce hundreds of parts, and the cost of such molds can be easily amortized. For limited production, however, the cost of tooling can be a significant factor.

The cost of conventional tooling, including both plugs and molds, will vary from perhaps three to five times the cost of the part being produced from it, though low-cost tooling methods can reduce this cost for limited-production runs.

PROFIT

For general estimating, a 10 percent profit should be added to the cost of material, labor and overhead.

START-UP COSTS

The cost of a prototype boat can be several times that of production boats, due primarily to high labor and associated overhead costs. It is impossible to generalize on this subject, but it must be considered in doing an overall economic analysis of a proposed FRP boatbuilding project. Much of the difficulty is that there is no consistent method of accounting for start-up costs in establishing the selling price of a boat, though such costs must obviously be passed on to the consumer. For preliminary estimating purposes, it is recommended that a 10 percent margin be added to the total of material, labor and overhead for this and other contingencies.

Examples

The following examples apply the foregoing cost data to a typical design problem.

Example 1

Given: A commercial (pleasure) powerboat hull, weighing 1000 pounds (structure only) built of alternate plies of 1 ounce mat and 24 ounce woven roving, with 35 percent glass content, using commercial general purpose resin.

Find: The cost of building each of 50 hulls (structure only) without profit. Neglect gel coat cost.

Materials: Glass = 0.35 x 1000 = 350 lbs.

$$\text{Mat} = \frac{350 \times 16 \ \text{Oz/Yd}^2}{(16 + 24) \ \text{Oz/Yd}^2} = 140 \text{ lbs.}$$

Woven Roving = 350 - 140 = 210 lbs.

Resin = 0.65 x 1000 = 650 Lbs.

$$\text{Cost} = 1.1 \left[(140 \times .51) + (210 \times .50) + (650 \times .18) \right] =$$

$347 ($.35/lb.)

Labor: For 20 lbs/MH, $2.50/hour

$$\text{Cost} = \frac{1000 \times 2.5}{20} = \$\ 125$$

Overhead at 150 percent = 1.5 x 125 = $ 188

Material, Labor and Overhead = $ 660

Contingencies and Margin at 10 percent = $ 66

Total = $ 726 ($.73/lb.)

Tooling: Assume 4 x 726 = $2900

$$\text{Cost of 50 boats} = 726 + \frac{2900}{50} = \$784 \text{ each } (\$.79/\text{lb.})$$

The selling price (no dealer mark-up) would be 10 percent higher.

Example 2

Given: A Navy boat hull, also weighing 1000 pounds (structure only) of all-woven roving construction, with 50 percent glass content, and fire-retardant resins, meeting Navy MIL-Specification requirements.

Find: The cost of building 5 hulls (structure only) without profit. Neglect gel coat cost.

Materials: Glass = 0.50 x 1000 = 500 lbs.

Resin = 0.50 x 1000 = 500 lbs.

$$\text{Cost (with wastage)} = 1.1 \left[500 \times .50 + 500 \times .40\right] =$$

$495 ($.50/lb.)

Labor: Assume 12 lbs/hr basic, 5 percent increase for only 5 hulls, and a labor rate of $2.50/hour.

$$\text{Cost} = 1.05 \left[\frac{1000 \times 2.50}{12}\right] = \$220$$

Overhead at 150 percent = $330

Material, Labor and Overhead = $1045

Contingencies and Margin at 10% = $105

Total = $1150 ($1.15/lb.)

Tooling: Assume $2900, similar to the previous example, since the mold could be constructed of commercial materials with a commercial level of quality control.

$$\text{Cost of 5 boats} = 1150 + \frac{2900}{5} = \$1730 \text{ each } (\$1.73/\text{lb.})$$

The selling price would be 10 percent higher (dealer mark-up not applicable).

COMPARISON WITH OTHER MATERIALS

There is no simple answer to the question of cost comparisons between FRP and competitive materials, since there are so many factors to be considered, and the entire picture is affected by preferences in materials based upon maintenance and repair and other life cycle cost considerations. However, the following comments are offered:

> FRP is at a cost disadvantage in smaller, simple hulls such as prams, rowboats, etc. where plywood offers a less expensive solution to the design of relatively flat surfaces where deflection becomes a constraint. Sheet aluminum construction appears to be less expensive than FRP for canoes and rowboats though this differential diminishes with thicker aluminum, which requires more expensive forming and joining techniques.

The scarcity of high quality wood for boat construction and qualified woodworkers places this material at a disadvantage for larger hulls.

Aluminum and FRP construction are roughly competitive for a production run of larger hulls, though aluminum still dominates the one-off or limited production market due to the high cost of FRP tooling.

Experience with large fishing trawlers (70-80 feet long) indicates that wood construction is least expensive, followed by steel, then FRP and aluminum, which are about equal in price. There is no comparative data on ferrocement. The workmanship in wood trawler hulls is not up to the standards of pleasure boat construction, however, so that large wood yachts would probably be as expensive, or more expensive than either FRP or metal construction. This is hard to determine, since the cost of a large yacht's hull is a relatively small percentage of the overall price.

In summary, then, it appears that FRP can be competitive, or nearly competitive, with aluminum construction on a final cost basis except for very small boats and limited production of larger hulls. Steel does not become a serious contender until lengths of perhaps 40 or 50 feet, and steel construction will usually be less expensive. FRP should be less expensive than wood for all except very small boats with flat or developable surfaces or very limited production of larger boats. Limited information indicates ferrocement to be less expensive in lengths of 30 feet and over, though much of the data is based upon limited production by amateur boatbuilders, and is thus not a valid basis for comparison.

It should be noted that the limited or one-off production of FRP boats can be achieved quite economically with the recent developments in inexpensive tooling discussed previously, but it appears unlikely that such techniques will produce a decided cost advantage for FRP over other materials.

IX. MAINTENANCE AND REPAIR

One of the fundamental advantages of FRP as a boatbuilding material is its low maintenance requirements and ease of repair. These factors are generally sufficient to offset any higher first cost of FRP boats. The subject of FRP maintenance and repair has been documented extensively including References (27), (34) through (39), and will not be covered here in detail. However, a few comments are in order.

MAINTENANCE

Fiberglass substantially reduces the arduous maintenance normally required for small boat hulls, though an understanding of the material is suggested for undertaking what little maintenance is required.

The hull maintenance normally involves taking care of, or anticipating, the following gel coat problems:

Fouling

As noted previously, FRP is as susceptible to marine growth as any material, though it is not degraded structurally by marine borers or similar organisms. Thus, a good antifouling bottom paint system is required for salt water service to prevent accumulation of growth. Excellent AF paint systems are available, but it is vital to follow directions closely.

Fading

After 3 to 5 years, gel coats will begin to fade, particularly in climates with very intense sun. Dark colors are more susceptible to fading than light colors.

Chalking or Erosion

The gel coat may gradually loose thickness, due to a slow but steady erosion, until glass fibers begin to show.

Scratches and Gouges

Minor surface abrasion due to walking, sliding anchors, etc. will eventually take its toll.

Staining

In heavily polluted waters, the boot top area may develop oil or chemical stains which defy the best cleaners.

These problems point out that the gel coat of an FRP boat is quite similar to a car finish, and similar maintenance is required: washing seasonally or more often with detergent; seasonal waxing and buffing above the antifouling area; use of scouring pads or special FRP cleaners on stubborn spots. After between 3 and 5 years, the deterioration of the surface may require painting. A system of alkyd, epoxy or urethane paint may last 2-3 years, if the surface is well sanded and cleaned and directions are carefully followed.

Winter storage requirements for FRP boats are similar to or easier than for other materials. These include washdown to remove dirt and fouling, proper support of the keel and bilge and covering decks to protect the gel coat.

Periodic inspection of the hull interior and exterior, particularly critical details, is also suggested. Cored hulls should be carefully checked for possible leakage into the core, particularly below the waterline.

REPAIRS

The repair of FRP small boats is widely credited with being easier than with any other material, since unskilled personnel can affect the repair with readily available materials and ordinary hand tools, without torches or other high-heat producers. However, reasonable care must be exercised if a sound repair is to be achieved. This includes assuring that the repair area is heated to at least 65-70 degrees F, using infra-red lights if necessary, maintaining surface cleanliness in the repair area, and following directions.

Surface Repairs

Repairs to gouges, blisters or crazing of the gel coat are accomplished by gouging or routing out the damaged area and filling the resultant depression with an epoxy surfacing compound.

Single Skin Repairs

Figure 43 illustrates the principles involved in single skin repairs. The damaged laminate is cut away, and the edge beveled to a slope of 12 to 1. A temporary backup of metal, wood or even cardboard is attached to the back of the panel, and patches of repair glass of progressively larger size are installed, filling up the hole. This is followed by several plies which overlap the sound laminate by several inches, unless prohibited by aesthetic considerations. The repair laminate should preferably be layed up with cloth or, for thick laminates, woven roving using epoxy resin if possible. However, polyester will do.

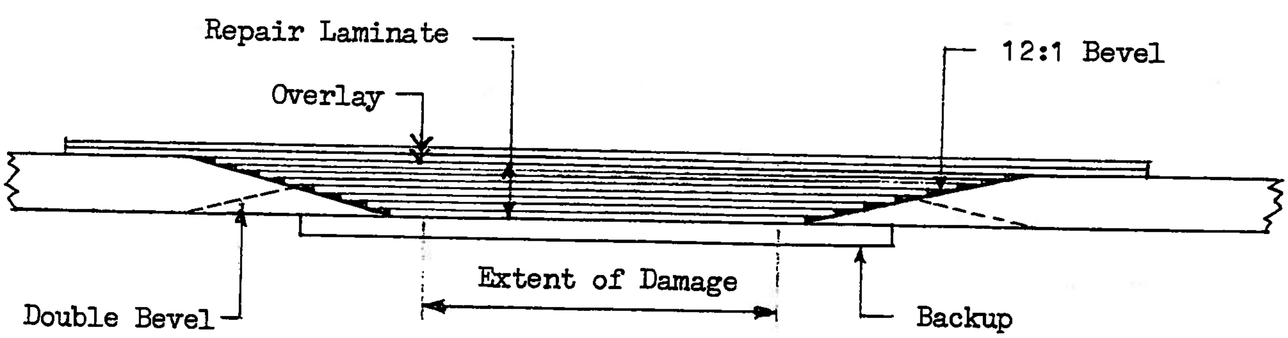


FIGURE 43

SINGLE SKIN REPAIR

A preferred patch consists of a double bevel, which is layed up from both sides of the panel. This type should be used wherever access permits.

This method has been used for making very extensive repairs. Reference (27) cites several interesting examples. Perhaps the most striking examples of this type of extensive repair occurred in Viet Nam, where entire bows and bottoms were replaced on damaged PBR's. With extensive damage of this nature, it is usually necessary to cast a temporary mold or backup from the original hull tooling or a similar boat in order to duplicate the original shape.

Sandwich Panel Repairs

The repair of sandwich panels is similar to that described above for single skin repairs, except that the core is first returned to strength with an insert of similar or stronger material, and then used as a backup for the skin repair.

Delamination of the skin from the core can often be repaired by drilling a series of small holes through the laminate and injecting resin into the interface with a large hypodermic needle. If the core is saturated or moist, this procedure will not work, and the delaminated area must be removed, the core dried or replaced and repairs made as above.

Secondary Bond Repairs

When a secondarily bonded angle or overlap separates from the basic laminate, resin injection into the gap may not work, because the accumulation of water, dirt, etc. in the gap cannot be removed. The first solution would be the use of mechanical fasteners to draw the surfaces together. Where this is impractical, the bonding angle must be cut away, the area cleaned and sanded, and a new angle of equivalent strength installed.

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ALUMINUM SMALL BOAT DESIGN

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Product Development Division
REYNOLDS METALS COMPANY
Richmond, Virginia

September 24, 1971

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Preface

The purpose of this paper is to serve as a technical reference to designers, builders and boat enthusiasts regarding small boats.

Small boats have been the forerunner of the use of aluminum in the marine field and the aluminum industry has accrued more marine aluminum experience with small boats than with any other type of hull.

History of aluminum boats takes us back to 1891 when the Swiss built a 17-foot launch in Zurich for use on the lakes nearby. In 1895 the French built a torpedo boat of aluminum which increased the speed of the vessel by over three knots, primarily due to reduced deadweight.

In 1931 the 55-foot motor yacht Diana II was built by the British of a magnesium-and-manganese containing aluminum alloy. The vessel is still in excellent condition.

The 72-foot Morag Mhor, also built in England, was one of the first all welded hulls. Today yachts, utility boats, houseboats, sailboats, fishing boats, gunboats, hydrofoils, crewboats, supply boats and air cushion and surface effect vehicles made of marine aluminum travel the inland and sea coasts of all five (5) continents.

The Aluminum Association reports show that in 1968 the use of marine aluminum reached the 50 million lb. figure and in 1969 about 60 percent of all pleasure craft produced in the United States, 331,000 boats, were aluminum. At the same time marine motor manufacturers used about 60 million pounds of aluminum.

It is to be expected, therefore, that a short course in small boats would include a presentation on the design and manufacturing aspects of marine aluminum.

I. From the Ore to the Finished Alloy

The principal ore of aluminum is bauxite ($(Al_2O_3).2H_2O$) which is scattered throughout the world since aluminum is the most plentiful of the metals. Rich bauxite deposits closest to the U. S. mainland are in Jamaica and Guyana. Ocean going ore carriers transport the bauxite to U. S. plants where first alumina (aluminum oxide) Al_2O_3 is produced by the Bayer process and secondly alumina is reduced to pure aluminum by the Hall process.

The Bayer method involves a series of chemical treatments (the ore is first crushed, and then washed to remove the clay content) the result of which is the fine white alumina precipitate.

The Hall process is the electrolytic smelting of alumina in the presence of a catalyst (molten cryolite). Pure aluminum in the liquid state is then collected and casted into ingots.

Ingots are then melted, alloyed and hot or cold worked so that the desired temper and thickness can be achieved.

Extrusions are produced by forcing alloy billets through dies whose openings are patterned to suit the desired shape. Uniformity of metal flow is in direct relation to the feeding speed, pressures and temperature. It is very important to note that the design of an extrusion, such as let us say a special extrusion for the chine, must be such that the possibility of nonuniform flow of the metal is minimized.

In general, four pounds of bauxite are required to produce one pound of pure aluminum.

Finally it is worth noting that in laying out plate sizes from the economic standpoint, one must consider factors such as availability of plate, length and width desired, welding equipment, handling capabilities of the yard, fit up, inspection, etc.

II. Why Aluminum Craft

Naval architects, owners and boatbuilders have been for many years trying to improve the efficiency of the hulls they design, own or construct and aluminum offers exactly what is needed to achieve this.

1. Light Weight:

   The light weight of aluminum (one third as heavy as steel) offers the best opportunity for a high horsepower to weight ratio, an increase in speed or a reduction in power requirements, reduction in draft, improved stability, better maneuverability, and most of all, presents the opportunity to alter the basic hull dimensions (add more beam or increase the length) for better over all performance.

2. Corrosion Resistance:

   Marine aluminum hulls need not be painted because of the inherent corrosion resistance of marine aluminum alloys which is attributed to the ever present aluminum oxide film. Small boats are most often painted for aesthetic or decorative purposes or for antifouling protection against barnacles and other organisms. Thinning of scantlings due to corrosion is practically eliminated by using marine aluminum which, of course, adds to the maintenance and repair savings for the owner.

3. Durability and Impact Resistance:

   Marine aluminum alloys possess high tensile strengths and stiffness which add to the integrity of the hull and provide a long-lasting boat. The low modulus of elasticity of aluminum, on the other hand, ($10X10^6$ for aluminum compared to $30X10^6$ fir steel) offers large deflections which in turn allow the aluminum hull to absorb more impact energy than boat hulls made of other materials.

4. <u>Non-Sparking and Non-Magnetic</u>:

Marine aluminum alloys will not affect electronic and navigational equipment (depth finders, radio-telephones, compasses, etc.) and since they do not create sparks, they are prime candidates for the construction of hulls for the transportation of inflammable liquids, as well as for the transportation of various chemicals that are harmful to other shipbuilding materials.

In general, marine aluminum boats have inherent advantages over steel or other hull materials and it depends upon the designer, the owner and the builder as to how well the advantages of marine aluminum can be utilized.

III. Recommended Marine Aluminum Alloys

The 5,000 series alloys are the only alloys recommended for marine use due to their excellent corrosion-resistant characteristics and welded properties. 6061 aluminum alloy has been superseded by the 5,000 series alloys for nearly all structural installations except for small riveted boat hulls because, although it provides excellent corrosion resistance, it loses most of its strength when welded.

The following is a table of specification properties of aluminum alloys as they appear in the "Guide for the Selection and Use of Aluminum Alloys for Structure of Ships of the U. S. Navy" dated November, 1967.

Specification Properties of Aluminum Alloys

Alloy	Ultimate Strength	Tensile Strength Yield	Allowable Working Stress[1]	
			Shear	Tension & Compression
Plate:				
5052-H34	34,000	26,000	10,000	16,000
5086-H32	40,000	28,000	11,000	18,000
5454-H34	39,000	29,000	8,000	14,000
5456-H321	46,000	33,000	13,000	21,000
Shapes:				
5083-H111	40,000	24,000	10,000	16,000
5086-H111	36,000	21,000	8,000	14,000
5454-H111	33,000	19,000	8,000	14,000
5456-H111	42,000	26,000	10,000	17,000
Tubing:				
5086-H32	40,000	28,000	11,000	18,000
5086-0	35,000	14,000	8,000	13,000

[1]These values should be checked against Section 9110-0-a of the General Specifications for Ships of the U. S. Navy or the detail specifications. These values are not to be used for compressive loads when stability controls.

NOTE: Modulus of elasticity (Young's modulus) 10,300,000 p.s.i.

The three major aluminum alloys being used in the marine field today are 5086, 5456 and 5083. Reynolds Metals Company recommends 5086 alloy in its new temper for plate H116 and for extrusions H111, primarily because of its higher elongation than both 5456 and 5083 as well as because in the welded condition the area under the stress-strain diagram indicating toughness favors 5086 by a considerable margin. Alloy 5086, due to its low magnesium content, is also less susceptible to exfoliation than alloy 5456. Exfoliation problems did arise with some small navy boats in Vietnam built of 5456 hull plate. The table below (Ref. 5) shows a comparison between the minimum welded properties of the marine alloys.

MINIMUM MECHANICAL PROPERTIES FOR WELDED ALUMINUM ALLOYS
(Gas Tungsten Arc or Gas Metal Arc Welding With No Postweld Heat Treatment)

Alloy and Temper	Product and Thickness Range in.	TENSION Ftuw ksi	TENSION Ftyw* ksi	COMPRESSION Fcyw* ksi	SHEAR Fsuw ksi	SHEAR Fsyw ksi	BEARING Fbuw ksi	BEARING Fbyw ksi
5083-H111	Extrusions	39	21	20	23	12	78	32
-H321	Sheet & Plate 0.188-1.500	40	24	24	24	14	80	36
-H321	Plate 1.501-3.000	39	23	23	24	13	78	34
-H323, H343	Sheet	40	24	24	24	14	80	36
5456-H111	Extrusions	41	24	22	24	14	82	38
-H112	Extrusions	41	19	19	24	11	82	38
-H321	Sheet & Plate 0.188-1.500	42	26	24	25	15	84	38
-H321	Plate 1.501-3.000	41	24	23	25	14	82	36
-H323, H343	Sheet	42	26	26	25	15	84	38
5086-H111	Extrusions	38	18	17	21	10	70	28
-H112	Plate 0.250-0.499	35	17	17	21	9.5	70	28
-H112	Plate 0.500-1.000	35	16	16	21	9	70	28
-H112	Plate 1.001-2.000	35	14	14	21	8	70	28
-H32, H34	Sheet & Plate	35	19	19	21	11	70	28

* 0.2 percent offset in 10 in. gage length across a butt weld.

The metallurgy of each of the above alloys has been carefully studied, especially as it relates to the magnesium content of the alloy, the service temperature, the magnitude of the locked in stresses and the salt water (marine) atmosphere. The 5086 alloy is within the "safe" limits of magnesium content, although such limits are not accurately defined in the metallurgists' mind. In any case 5086 has a 3 1/2% to 4 1/2% magnesium content, whereas the other two alloys have higher magnesium percentages.

The important metallurgical aspect to be aware of is the continuity of the precipitate at the grain boundaries. It must be pointed out that if one has a continuous grain boundary network, then the material <u>can be</u> susceptible to intergranular corrosion, stress corrosion, and even exfoliation in the case where elongated grain structure is present. Nevertheless, the mere presence of continuous networks does not always result in corrosion failure.

In general, I would like to suggest that users of aluminum refer to specifications QQA-00250/19 and 20 as well as a metallographic examination where questions arise as to the suitability of aluminum magnesium alloys for a given application.

IV. Aluminum Design

When it comes to designing an all aluminum boat the naval architect has indeed found utopia, the reason being that, if the architect begins his aluminum design "from scratch" without a "comparable" steel or wood design, he has a wide choice of avenues to take with regard to the basic hull characteristics, powering, light ship weight, stability, trim, etc.

The unfortunate part, however, is that in most cases there is a design on the shelf for steel or wood and the architect feels compelled to be guided by it to the last inch with the net result that the advantages of aluminum are not fully utilized. For instance, unlike steel, the indiscriminate increase in member size to "play it safe" or to consolidate sections results in a severe cost penalty for an aluminum craft.

Let us discuss the major factors in an aluminum design:

1. Deflection.

The basic expression for deflection is usually expressed as:

$$\delta = \frac{W \ell^3}{E\ I} \times K$$

where:

W = the weight of the craft

ℓ = the length

I = moment of inertia

E = modulus of elasticity

K = a coefficient

It is easily seen that, other parameters being the same, the aluminum design will result in a deflection three (3) times as much as the steel design due to the difference in the modulus of elasticity between the two materials. Of course, there may well be a case where three times as much deflection is either desirable or tolerable, but in most cases, equal deflection is required, in which case the moment of inertia of the aluminum member must be equal to three times that of steel. The designer has indeed four decisions to make concerning the increase in the moment of inertia. He can increase the depth of the aluminum member under question or he can increase the flange area, or do both, or as the last resort he can bring into the picture the spacing of the member(s).

Usually headroom is one of the main design considerations for small boats, especially sail boats, and as such the maximum depth of a beam or girder, for example, has already been fixed.

2. Strength.

The section modulus of an aluminum member must be increased by some ratio of mechanical strength properties between aluminum and steel. This ratio has been, to date, the focal point of discussions between naval architects, regulatory agencies, shipbuilders, etc. For example, when Reynolds Metals Company discussed with A.B.S., the U. S. Coast Guard and the owners the design criteria for the all aluminum trailership, "Sacal Borincano", the following relations were developed:

Plating:

$$T_{al.} = T_{st.} \times .80 \times \frac{60{,}000}{\text{ultimate strength of alum. (unwelded)}}$$

Extrusions:

$$SMA = SMS \times .80 \times \frac{60{,}000}{\text{ultimate strength of alum. (unwelded)}}$$

Hull Girder:

$$SMA = 0.9 \times 2.0 \times SMS$$

Lloyd's Register of Shipping has expressed the opinion that the following criteria (which in the author's opinion are very conservative) should prevail when considering aluminum hulls:

a) Plating:

Plate thicknesses are increased by the square root of the ratio of material ultimate tensile strengths (29 tons/in^2 for steel).

b) Extrusions:

Section moduli increased by the ratio of the ultimate tensile strengths to steel.

c) Hull Girder:

Section Modulus is increased as for extrusions.

The F.D.L. deckhouses designed by Gibbs and Cox were based on the following design criteria:

a) Plating - designed for lateral loading from wave slap, deckload, etc:

$$tal = 0.9 \times t_{st} \times \left(\frac{UTSS}{UTSA}\right)^{1/2}$$

b) Plating - designed for edge loading induced by longitudinal bending or axial loads:

$$tal = 0.9 \times t_{st} \times \left(\frac{UTSS}{UTSA}\right)$$

c) Extrusions

$$SMA = SMS \times \left(\frac{UTSS}{UTSA}\right)$$

where:

UTSS is the ultimate tensile strength of steel

UTSA is the ultimate tensile strength of the aluminum in the unwelded condition

SMS is the required Section Modulus in steel

SMA is the required Section Modulus in aluminum

All of the above offered criteria should serve as design reference only and it is strongly suggested that each individual case for conversion to aluminum scantlings be looked upon carefully, primarily in the light of the intended service of the boat.

The following pages present typical scantlings for small aluminum hulls based on discussions with designers and aluminum fabricators throughout the United States. Let me again bring to your attention that these are typical scantlings and no guarantee is given as to the structural integrity of a boat built on the basis of these scantlings.

Length Range Ft.	24-30	30-40	45-55	60-70
Plating				
Bottom forward 0.8	.140-.160	.190	1/4"	5/16"
Bottom aft 0.2	.140-.160	.190	5/16"	3/8"
Side	.130-.160	.160	3/16"	1/4"
Deck	.125	.125	3/16"	3/16"
Transom	.130-.160	.160	1/4"	5/16"
Cabin*	.125	.125	.125	.125
Keel	1/2" x 3"	3/8" x 5"	3/8" x 6"	1/2" x 7"
Stem	1/2" x 3"	3/8" x 5"	3/8" x 6"	1/2" x 7"
Chine**	1/2" ϕ bar	5/8" ϕ bar	3/4" ϕ bar	1" ϕ bar
Bulkhead	.125	3/16"	3/16"-1/4"	3/4"-1/4"
Framing - All Sections are angles unless noted				
Transverse Side	3" x 1/4"	3" x 5/16"	4" x 3/8"	6"x2"x1/4"
Transverse bottom	5" x 1/4"	5" x 5/16"	6" x 3/8"	6"x2"x1/4"
Transverse deck	1-1/2" x 1/4"	2" x 1/4"	3" x 1/4"	3" x 1/4"
Transverse floors	1/4" Plate	1/4" Plate	1/4"x2" flg.	1/4"x2" flg.
Longitudinal side	2"x1/4"-1/8"	3" x 1/4"	4" x 1/4"	3"x1"x1/4"
Longitudinal bottom	2" x 1/4"	3" x 1/4"	4" x 1/4"	3"x1"x1/4"
Engine Fdn Vertical	1/4" Plate	1/4" Plate	1/4" Plate	3/8"
Engine Fdn Horizontal	1/4" Plate	1/4" Plate	3/8"	5/8"
Bulkhead stiffners	2" x 3/16"	3" x 3/16"	3"x1/4" FB	3"x1"x1/4"
Transom Vertical	2" x 1/4"	3" x 1/4"	4" x 1/4"	3"x1"x1/4"
Transom Horizontal	5" x 1/4"	5" x 5/16"	6" x 3/8"	6"x3"x1/4"

Length Range Ft.

Frame Spacing	24-30	30-40	45-55	60-70
Bottom transverse	30"	36"	4'	2.5'-4
Side transverse	30"	36"	4'	2.5'-4
Deck transverse	12"	12"	12"	12"
Bottom longitudinal	12"	10"-12"	12"-18"	9"-12"
Side longitudinal	12"	10"-12"	12"-18"	9"-12"
Bulkhead vertical	12"	12"	12"	12"
Transom vertical	12"	12"	12"	12"
Transom horizontal	24"	24"	30"	30"
Fenders 1/2 pipe***	2	3"	4"	5"
Anodes, 3"x3"x1/4"	10"	12	15	18
Approximate wt. of alum.	5,000#	10,000#	20,000#	26,000#

*Interlocking extrusions can be substituted here.
**Special extrusions would be recommended if production warranted.
***Extrusions or formed plate may be more desirable.

Each design must be analyzed carefully and important structural members must be checked for lateral stability. The author recommends the Aluminum "Construction Manual," published by the Aluminum Association as a design guide for determining allowable stresses.

3. Impact and Vibration Considerations

It is a well accepted fact that in small boats the elastic behavior of the hull under dynamic loading is of the utmost importance since small boats are subjected to dynamic loads (impact and vibration) at high frequencies. In other words, the small boat structure, while maintaining its allowable stress, transmits a certain amount of kinetic energy under dynamic loads. The expression for the strain energy per unit weight is:

$$\frac{f^2}{2E\alpha}$$

Thus the ratio of weights between aluminum and steel required to absorb a given amount of kinetic energy by tension is (bearing in mind that the total weight of material required to transmit an amount of kinetic energy while maintaining the design allowable stress is inversely proportional to the strain energy stored in the structure):

$$\frac{W_a}{W_s} = \frac{\left(\frac{2E\alpha}{f^2}\right)_{al}}{\left(\frac{2E\alpha}{f^2}\right)_{st}} = 0.108$$

Hence, the ability of aluminum to absorb impact and other dynamic loadings in the elastic range is almost ten times greater than that of structural steel.

On the other hand, when identical steel and aluminum beams are subjected to an impact load causing stresses up to the yield point in both the steel and the aluminum, the aluminum beam can absorb 2.9 times more impact energy than the steel beam provided both materials have the same yield properties.

In addition, when identical steel and aluminum beams are subjected to the same impact load the stress in the steel beam is about 70% more than the stress in the aluminum, where the deflection of the aluminum beam is approximately 70% more than the deflection of the steel beam.

A point in case here is the experience the U.S. Navy had with the all-aluminum Landing Craft Utility (LCU). Results of beaching tests showed that the loss in plate thickness due to the beachings was less for aluminum than for steel for the same number of landings (LCU aluminum hulls weighed 60.5 tons vs. 120 for steel).

The author strongly suggests that the designer refer to the "Influence of Structural Characteristics on Slamming Impact Pressures" by F. Jellars (Ref. 17).

4. Thermal Stresses

With regard to temperature stresses in an aluminum structure analysis shows that these stresses will be about 70% as high as the stresses in the same steel structure. The magnitude of temperature stresses is:

$$f = \Delta t \quad (\alpha t E)$$

where Δt = a temperature differential

αt = coefficient of thermal expansion

E = modulus of elasticity

The stress is proportional to αtE for constant Δt's and although αt for aluminum is almost twice as high as αt for steel, we have that:

$$(\alpha t E)\ al = 135.7$$

$$(\alpha t E)\ st = 194.3$$

V. Welding Aluminum Hulls

Welding of marine structures requires either the MIG (Metal Inert Gas) or the TIG (Tungsten Inert Gas) process. TIG welding is ideal for piping and minor repairs whereas MIG welding is recommended for all structural work.

In general the strength of an aluminum weld is lower than the parent metal properties. Mr. C. H. Holtyn mentions in one of his papers (Ref. 2) that:

> "Several years ago SNAME's HS-6-1 task group undertook a program to develop data on the strength of welded aluminum alloy joints produced by representative shipyards in the country. The results of this program were published in January of 1965, as the Technical and Research Bulletin No. 2-13.
>
> A total of 684 welded and 51 parent plate specimens were prepared. Alloys 5086, -H32, -H34, and -H112 and 5456, -H321 and -H24 were selected in 1/4, 1/2, 3/4 and 1-inch thicknesses. Metal was supplied by Alcoa, Kaiser, and Reynolds in order to eliminate any alloy variable. Weld samples were prepared in accordance to specifications by Newport News Shipbuilding and Drydock Company, Bath Iron Works, Bethlehem Steel Company, and the Todd Shipyards Corporation. Samples were tested by ABS.
>
> The results of the test program showed the statistical averages for welded tensile and yield strengths to be slightly below published industry minimum. The program was so broad and had so many variables, however, that it is impossible to generalize on the results without giving misleading information. It is suggested that this report be read by those interested in this field."

Nevertheless, it is still a fact that a good strong weld is the result of good equipment, proper filler metal, proper gas proportions, proper joint preparation, precleaning and well trained personnel.

1. Filler Metal

a) All bare electrodes shall conform to the requirements as spelled out in the latest edition of (AWS A5.10) "Specification for Aluminum and Aluminum Alloy Welding Rods and Bare Electrodes", as well as Military Specification E-16053L and radiograph 437A.

For the sake of an example, 1/16" diameter filler wire is recommended for manual welding of 1/4" plate in the flat position with 3/64" and 1/16" for vertical and overhead welding.

b) For TIG welding tungsten electrodes must conform to the requirements of the latest edition of specifications for TIG welding electrodes ASTM B297 (AWS A5.12).

It must be emphasized that filler wire must be stored in such a manner that it remains dry and free of other contaminants prior to its usage.

2. Shielding Gas

Shielding gas for MIG and TIG (with AC current) must be argon and for TIG (with DC current) must be helium or a mixture of argon and helium (such as 75% helium and 25% argon or such a percentage as is suited for the thickness of the material, the welding position, the joint design, etc.). Pure argon is very economical and liquid argon is recommended for mass produced hulls. The hose to be used for shielding gas should not be of natural rubber (synthetic rubber is acceptable) and must not have been previously used for other gasses or water.

3. Joint Geometry and Preparation

Joint designs should usually comply with some military specification or with the practice of the yard based on previous experience with aluminum hulls.

Square butt welding aluminum, thusly eliminating joint preparation costs and reducing filler wire and shielding gas requirements in thicknesses up to 3/16 inch, is not really objectionable, although it must be mentioned that square butts welded manually usually result in questionable penetration. If square butt welding is performed automatically then marine aluminum up to 1/2 inch could be so welded.

Plates and structural members can be cut and their edges prepared for welding by mechanical (sawing, machining, chipping or sheaving) and/or plasma metal cutting processes. Metal surfaces must be cleaned of grease, oil, dirt, machining or forging lubricants with a suitable solvent (such as trichlorethylene or its equivalent) or by vapor decreasing. They must also be free of tears, burrs and everything else that would have an adverse affect on the quality of the weld.

4. Oxide Removal

Clean stainless steel power driven wire brushes, 6" in diameter with .012 to .016" bristles, are to be used, or a chemical cleaner may be used. The chemical cleaner must then be removed by steam-spraying the aluminum member and then it must be allowed to dry thoroughly. Vertical welding shall be from the bottom to the top although flat welding is the most desirable position.

Many detail structural deficiencies begin as crater cracks that slowly propagate into the weld or even the parent metal. To avoid this it is absolutely essential that all craters be filled to the full cross section of the welds by reversing direction of travel before terminating the arc. Preheating (oxygen acetylene heating torch only) shall be done only to remove moisture prior to welding and the metal temperature should not exceed 150°F.

This brings forth a very controversial question indeed. Should continuous or intermittent welding be used? Many hours have been spent in discussing the pros and cons of these two welding specifications. Generally speaking, continuous welding should be specified for areas subjected to high stress concentrations or vibrations (especially aft end of power boats) since it minimizes the possibility of crater cracks. The writer has had on occasion the opportunity to inspect large aluminum power yacht hulls where bottom longitudinals immediately forward of the rudder stock had become loose because they had not been welded continuously, and they had been evidently in resonance with the engine or propeller vibrations. Higher welding speed and more uniform metal deposition are some of the good characteristics of continuous welding as well as prevention of crevice corrosion in areas such as ballast tanks, fuel oil tanks, etc. or other areas where entrapment of liquid can occur. There are areas of the boat, however, where intermittent welding can be used quite effectively (continuous welding adds more to the weight of the hull than intermittent welds) and should be so specified. Specifications for intermittent welding must specify the length of the fillet weld (at least 6 inches) and they should specify that both fore and aft, port and starboard or supper and lower ends of the structural member be welded continuously for a certain percentage of the length of the member. Also it is important to note that limber holes snipes and ends of brackets must show continuous weld bends around them.

Fillet sizes for double continuous welds should not exceed the thickness of the thinner member being welded. The U.S. Navy, however, has been calling for fillet sizes or double continuous welds of almost twice the size of the thinnest member being of the joint. It is felt that such specification adds to the distortion of a structure (incorrect weld sequence and slow speed are also prime causes of welding distortion).

VI. Finishing - Painting and Dissimilar Metal Protection of Aluminum Hulls

1. Finishing and Painting

Aluminum boats and oceangoing hulls do not require painting because of the corrosion resistance of the marine alloys. Nevertheless, owners specify painting for aesthetic and/or decorative reasons or in order to provide antifouling protection below the waterline.

Preparations for painting of the hull differ based on the craft size, the expected service conditions, etc. Let us examine the question of painting the hull of boats with antifouling paint:

a. Small Pleasure Craft

(1) Precleaning (Factory Painting)

Precleaning is performed by using solvents and processing through a multistage of non-etch cleaning, rinsing, deoxidizing and light etching, rinsing and drying.

Precleaning in the Field

Remove any loose oxide prior to the application of the acid solution described below. Apply to the ambient temperature hull (after washing the surface) by spraying or brushing an alcoholic phosphoric acid solution which can be made by the owner himself consisting of (by volume):

35% butyl alcohol (concentrated)
25% isoprophyl alcohol (concentrated)
22% water
18% phosphoric acid (85% by weight)

Rinse this solution thoroughly after five or ten minutes.

(2) Priming

A work primer conforming to MIL P-15328C should be sprayed on the hull to about 0.2 to 0.5 mils dry film thickness. Drying time to be specified by supplier.

(3) Top Coat Painting

Usually on small craft a single coat of epoxy paint to 1.5-2.0 mils (dry film thickness) can be used, the alternative being multiple coats of other resin based paints.

Antifouling paint suppliers recommend number and film thickness for top coat painting, and their recommendations should be adhered to.

(4) Antifouling Paint

Apply two or three coats of TBTO (tri butyl tin oxide), TBTA (tri butyl tin acetate) or TBTF (tri butyl tin fluoride) to a total dry film of 3.5 mils in thickness.

b. Craft Between 25-100 ft. L.O.A.

These recommendations apply to yachts, tugs, barges, workboats, crewboats, supply hulls, as well as to navy vessels within the L.O.A. stated above.

(1) Precleaning

Sandwash or use aluminum oxide utilizing a nozzle pressure of 25-30 psi and an angle of blasting to produce an anchor pattern not more than 1-1/2 mils.

(2) Priming

Same as for the requirements for small hulls with particular attention to the fact that primer must be applied before soiling or extensive oxidation of the surface to be coated occurs.

(3) Top Coat Painting

Usually coats should be applied in multiples to a total dry film thickness of between 3-8 mils. One or more coats of zinc or zinc chromate inhibited paints could be applied in order to provide galvanic protection to the aluminum hull.

(4) Antifouling Paint

Normally at least two coats are applied in order to arrive at a dry film thickness of 3-12 mils.

c. Superstructures

The precleaning and painting of the superstructures of these boats should be performed in the same manner as indicated on Item 1a (1).

Top coats applied depend on the gloss retention, and general weathering performance.

d. Bilges

These are potential corrosion areas of the hull due to accumulation of stagnant water (seawater, fresh or brackish), and particular care must be taken in cleaning the bilges thoroughly. If the bilge structure is complex to the point where thorough rinsing of the area is not possible (especially after using acid liquid cleaners for precleaning), then mechanical roughening is preferred.

Zinc or zinc chromate inhibited top coats are recommended together with coal tar epoxy formulations for the final coat. The total dry film mil thickness of the intermediate coats and the final coat is around 10-25.

e. Deck Painting

Inasmuch as there is a wide variety of paint requirements depending on the owner specifications and craft involved, deck paintings range from single paint coatings (2-5 mils with or without non-skid characteristics) to intricate systems with intermediate non-skid coats (5-8 mils).

More detailed information regarding the above as well as maintenance painting, maintenance of natural aluminum trim, reconditioning of unmaintained bare aluminum, maintenance of anodized trim, as well as a listing -- not endorsement -- of paint material suppliers is found in the soon to be released paper on "Finishing and Maintenance of Aluminum Hulls" by S. B. Wyman, Reynolds Metals Company, Engineering and Technical Services.

f. Painting of the Sacal Borincano

The all-aluminum trailership "Sacal Borincano" was very recently drydocked at Levingston Shipyard in Orange, Texas and the following painting operation took place in order to "freshen up" the antifouling paint applied to the underwater portion of the hull three years ago.

The entire paint operation was supervised by Mr. P. H. Hawner, Reynolds Metals Company, Research and Development Division, and it is outlined in this paper as additional information concerning antifouling hull protection of aluminum vessels.

The paint was supplied by International Paint Company of New Orleans.

(1) Primer

A partial coat of Latenac hi-build chlorinated rubber was applied on the flats and over the bare areas at a film thickness of 8-9 mils wet yielding a 3-3.5 mils dry. Application was made with an airless spray gun using hydraulic pressure rather than air to accomplish atomization of the coating material.

(2) Antifouling Paint

After drying overnight the first coat of Wide Spectrum Mark I 3200 was applied from keel to waterline over the entire underwater surface of the hull. This Wide Spectrum is a vinyl base paint containing TBTF as antifouling agent.

This was followed with a second coat of Wide Spectrum Red for a total thickness of approximately 4-5 mils dry.

A test patch, on starboard side extending aft from the end of the bilge keel to the next weld and up from the turn of the keel to the waterline received one coat of antifouling only. This test patch may demonstrate the sufficient protection given by one coat of antifouling TBTF only resulting in considerable cost savings during the next paint operation.

The steel rudders were sandblasted and received the following coating:

- 1 coat Intergard Epoxy Red
- 2 coats Intergard Epoxy Mastic Black
- 1 coat #200 Primer
- 2 coats Wide Spectrum 3200 Red

Draft marks were painted with TBTO #40 Surf White

2. <u>Dissimilar Metal Protection of Aluminum Hulls</u>

As stated elsewhere marine aluminum alloys have excellent corrosion resistant characteristics.

One area, however, where special care must be exercised is the area of dissimilar metals. It is almost inevitable that some portion of a powerboat or some deck fitting will not be of aluminum. In this case proper insulation details and materials must be used in order to eliminate the possibility of corrosion. For example, many times one comes across a boat whose hull is of steel and her deckhouse of aluminum. The appropriate recommended detail for such a joint has been very well depicted and described by Mr. C. H. Holtyn in many of his papers.

Lately, however, such deckhouse to deck connections or machinery foundations to deck or deck plating to hull have been designed and/or built using explosion-bonded-aluminum-to-steel welding transition joints made by Dupont.

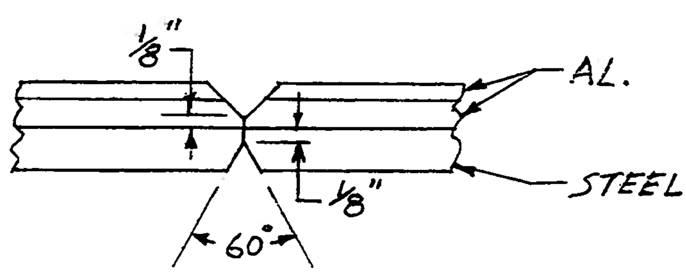
The largest tuna boat, for instance, the Apollo, built by Tacoma boat, has her aluminum deckhouse welded to the steel deck by using Detacouple (trade name for explosion-bonded-aluminum-to-steel).

Detacouple is purchased in strips which are obtained by sectioning large clad plates. Corrosion tests on unpainted samples showed that when the aluminum begins to corrode at the interface between steel and aluminum, a slight penetration forms. This area quickly fills with hydrated aluminum oxide sealing off the aluminum-steel interface from the corrosion environment and therefore reduces corrosion to an almost negligible rate.

Salt spray - accelerated tests demonstrated that corrosion at the unpainted bond zone becomes negligible after the initial barrier is built up.

Many other tests concerning impact resistance of the aluminum-steel interface, shear and fatigue, have been performed and the results obtained compare favorably to any other mechanically jointed sample.

The best Detacouple butt design arrived at to date is the following:



It is of interest to know that A.B.S. and the U.S. Coast Guard Commercial have given approval for use of explosion-bonded transition joints aboard ships. In the writer's opinion Detacouple is the answer to today's question of joining aluminum to steel, and it is strongly suggested that the reader refer to the article by Messrs. C. R. McKenney and J. G. Banker in the Marine Technology, July, 1971, pp. 285-292 for further details.

VII. Aluminum Hull Outfitting

Outfitting an aluminum hull is certainly no more difficult than outfitting a steel one, and little detailed information will be given about it in this paper. The writer strongly recommends that the applicable referenced publications be studied for more specific information on outfitting with aluminum as well as for sources of procurement.

Here are answers to some of the most frequent questions concerning hull outfitting:

1. Pipe

Aluminum pipe can be used for fresh and salt water lines, scupper lines, fuel oil lines, etc. The recommended alloy is 6061 and it is readily available.

2. Pumps

An aluminum hull can utilize aluminum (preferred) and/or stainless steel (more expensive) pumps.

3. Stuffing Boxes

The stuffing box packing should be compatible with aluminum and therefore graphite inhibited packings or boxes requiring salt water lubrication in conjunction with an absorbent packing are not recommended.

4. Tread Plate

Aluminum tread plate (raised pattern of diamonds on one side only) is a hot rolled product usually of 6061 alloy and is being widely used in today's marine market.

5. Ladders

Aluminum ladders can be fabricated by the shipyard or purchased through an aluminum fabricator, and they must be completely insulated from steel mounting brackets (they should not be installed directly to the steel, especially when the ladder comes in contact with salt water).

6. Hatches

Aluminum covers can be fabricated by the shipyard or purchased from an aluminum fabricator. The designer must specify compatible alloy such as 18-8 stainless steel, type 304 or 317 for hinge pins and dogs in lieu of brass or bronze attachments which should be avoided.

7. Gratings

Aluminum gratings for walkways, catwalks, platforms, engine room walkings should be carefully selected as to their required load carrying ability, maximum deflection, vibration and fatigue loads, case of assembly and they must also be properly isolated from steel (if they come in contact with steel) by neoprene, micarta, polysulfide or some other appropriate insulating material.

8. Deck Fittings

Aluminum deck fittings can be welded to aluminum decks or bolted to steel or wood decks (the base must be properly insulated and plastic ferrules should be used with the bolts). Large aluminum deck fittings must be specially cast and the alloy checked for strength.

9. Anodes

The alloy composition for aluminum anodes is formulated to offer long life and maximum protection. Aluminum and/or zinc anodes can be used to protect aluminum and steel hulls. Aluminum anodes are welded directly to the aluminum hull, thusly eliminating installation costs. The latest Reynolds Metals Company anode compositions are RX-722 (indium-magnesium alloy) and 7-12. Both are currently available.

10. Bearings

When cutlass bearings are used, aluminum or plastic housing is recommended in place of the normal bronze housing. Otherwise, care must be taken to isolate the bronze from the aluminum shaft strut housing. Entrance of seawater can be prevented by sealing the annular crevice with a polysulfide or urethane.

11. Lifeboats

Aluminum lifeboats (offer among others reduction in topside weight) are readily available in today's marine market.

12. Cabinets and Furniture

Light aluminum cabinets (without brass hardware) and furniture are used extensively aboard naval vessels. Commercial vessels and private yachts also utilize aluminum furniture because of its corrosion resistance, good appearance and lightweight characteristics.

VIII. Aluminum Fishing Boats

The latest development in the Reynolds Metals Company aluminum fishing boat program is the construction of 78-ft. shrimp hulls by the Lantana Boatyard Company in Lantana, Florida.

Three vessels have already been constructed and two more are in the planning stage.

The boats (which can operate as deep water shrimpers or even switch to lobstering) fashion a raised foredeck, and aluminum "A" frame, outriggers and boom thusly eliminating the high maintenance cost when these parts are made of steel. The design of the aluminum outriggers is indeed innovative since it uses box beams of plate rather than conventional "pipe and lacings." Lantana reports that the performance of the three boats and their outriggers has been excellent. The completely refrigerated and air conditioned vessels have the following characteristics:

78 Ft. Lantana Shrimper

Length	78 ft.
Beam (amidships)	22 ft.
Depth (aft)	13 ft. 9 in. deck to bottom of keel
(forward)	17 ft. 3 in. forward of house to bottom of keel
Draft, loaded	9 ft. 5 in.
Displacement	165 tons
Speed	10 knots
Cruising Range	70 days
Crew	6 crew + captain
Hull Plating	3/8 in. bottom - 5/16 in. sides 5086 H116
Hull Framing	4 in.x 3 in.x1/4 in. Angle 5086 H111
Deck Plating	5/16 in. 5086 H116
Deck Framing	4 in.x 3 in.x1/4 in.Angle
Deckhouse Plating	1/4 in. 5086 H116
Deckhouse Framing	2 in.x2 in.x3/16 in. 6061-T6
Total Aluminum	65,000 pounds

CAPACITIES:

Fish Hold	600 boxes
Fuel Oil	23,000 gal.
Fresh Water	5,000 gal.
Lube Oil	200 gal.

MACHINERY AND DECK GEAR:

Main Engine	CAT D343 365 HP
Reduction Gear	6:1
Auxiliary	2 cylinder SR 2 Lister
Alternator	60 amp Leece Neville
Bilge Pump	Itt Jabsco
Water Pump	Itt Jabsco
Shaft	4 in. stainless steel
Bearings	Rubber Cutless
Propeller	4 bladed bronze 66 in.-46 in.
Winches	McElroy 505 Double Drum
	McElroy Try-Net 401

ELECTRONICS AND NAVIGATION EQUIPMENT:

Loran	2
Radio	3
Fathometer	2 Recording Simrad
Electrical System	DC

REFRIGERATION AND CLIMATE CONTROL:

Refrigeration Unit	Carpenter System-Turbo Marine Corp.
Hold Insulation	8 in. Urethane Foam
Air Conditioning	Carpenter System-Turbo Marine Corp.

The 50-ft. shrimper Demonstrator built by HBL Shops, a division of Houston Barge Line (total aluminum weight 20,000 lbs.) and the many 32-ft. gillnetters for Alaskan Salmon are some of the many aluminum fishing hulls in existance today. It is expected that the utilization of marine aluminum alloys in the fishing industry (such as the all-aluminum deckhouse on the 225 ft. class Tacoma boat tuna seiner) will show tremendous growth due to the desperate need to modernize the U.S. fishing fleet and prevent the buildup of bacteria in fish holds (aluminum fish holds are easy to clean thoroughly whereas wood, for instance, tends to sour and absorb fish slime.)

IX. Fire Insulation of Aluminum Hulls

Aluminum being a noncombustible material has definite advantages over most boat building materials such as wood, for instance. In order for an aluminum hull to meet U.S. Coast Guard required fire ratings, insulation is necessary. To date there are no U.S. Coast Guard standards for aluminum A-0, A-30 and A-60 bulkheads and decks although it is expected that such standards are forthcoming in view of the fire testing of aluminum bulkhead and deck assemblies at the Bureau of Standards under the auspices of the Fire Test Ad Hoc Subgroup of Task Group HS-6-1 of the Society of Naval Architects and Marine Engineers.

X. Future of Aluminum Boats

Today's increasing interest in fast, dependable and economic modes of transportation guarantees the evergrowing demand for marine aluminum.

Surface effect ships, amphibious air cushion vehicles, fishing boats, landing craft, hydrofoils, fast destroyer escorts, commuter ferries and other types of craft will utilize the weight/strength advantages of marine aluminum.

It is indeed felt that, although aluminum is being used extensively in the small boat field today, we have just begun our road to success.

XI. Aluminum Manufacturers

The following are two not-all-inclusive lists of U. S. manufacturers of aluminum hulls.

List 1 includes some large yards with oceangoing ship construction facilities by state.

List 2 includes primarily boat manufacturers in alphabetical order.

Some manufacturers appear on both lists.

U. S. BOATYARDS WITH ALUMINUM CONSTRUCTION EXPERIENCE

ALABAMA

Bender Shipbuilding Co., Inc.
P. O. Box 42
Mobile, Ala. 33601

ARKANSAS

Johnson Shipyard
P. O. Box 615
Helena, Ark.

Monark Boat Co.
P. O. Box 210
Monticello, Ark. 71655

CALIFORNIA

Atlantic Research Corp.
3333 Harbor Boulevard
Costa Mesa, Calif. 92626

California Shipbuilding
& Drydock Co.
1601 Water Street
Long Beach, Calif. 90802

Colberg Marine
Stockton and W. Lindsay
Stockton, Calif. 95201

Pacific Coast Engineering
2235 Clement Avenue
Alameda, Calif. 94501

Rohr Corp.
Foot of "H" Street
Chula Vista, Calif. 92012

San Diego Marine Construction Co.
P. O. Box 751
San Diego, Calif. 92112

Stephens Marine, Inc.
345 N. Yosemite Street
Stockton, Calif. 95201

TATCO Shipbuilding Co.
1860 Bay Front Street
San Diego, Calif.

Whiteman Yacht Co.
980 "F" Street
Chula Vista, Calif. 92010

FLORIDA

Argosy Marine Corp.
1300 Southeast 26th Street
Fort Lauderdale, Fla. 33316

Robert E. Derecktor
P. O. Box 22629
Fort Lauderdale, Fla. 33315

Hydro-Ski International
P. O. Box 13007
Fort Everglades Station
Fort Lauderdale, Fla. 33316

Lantana Shipyard
808 North Dixie Highway
Lantana, Fla. 33460

Sermonds Boat Yard
Tarpon Springs, Fla. 33589

ILLINOIS

Grafton Boat Co., Inc.
Foot of Oak Street
Grafton, Ill. 62037

Grebe Boat Company
3250 N. Washington Ave.
Chicago, Ill.

LOUISIANA

American Marine Corp.
Box 8126
New Orleans, La. 70122

Avondale Shipyards, Inc.
P. O. Box 50280
New Orleans, La. 70150

Breaux's Bay Craft, Inc.
P. O. Box 296
Loreauville, La. 70552

Cajun Craft
Jeanerrete, La.

Camcraft
P. O. Box 69
Marrero, La. 70072

Equitable Equipment Co., Inc.
410 Camp Street
New Orleans, La. 70130

Gulf Craft
Patterson, La.

Lafco, Inc.
P. O. Box 3863
Lafayette, La. 70501

Halter Marine Service, Inc.
Route 6
Box 287-H
New Orleans, La. 70129

McDermott Shipyard
Div. of J. Ray McDermott
& Co., Inc.
Box 188
Berwick, La. 70380

Sewart Seacraft
Div. of Teledyne, Inc.
P. O. Box 108
Berwick, La. 70342

Southern Shipbuilding Corp.
P. O. Box 1089
Slidell, La. 70458

Swiftships, Inc.
P. O. Box 1908
Morgan City, La. 70380

MAINE

Paul Luke
East Boothbay, Maine

MARYLAND

Bethlehem - Key Highway Yard
Bethlehem Steel Corp.
Baltimore, Md. 21230

Maryland Shipbuilding
& Drydock Co.
P. O. Box 537
Baltimore, Md. 21203

Wye River Enterprises, Inc.
Queenstown, Md. 21658

MICHIGAN

T. D. Vinette Co.
2201 Sixth Avenue
North Excanaba, Mich. 49829

MISSISSIPPI

Graham Boat Co.
Pascagoula, Miss. 39567

Ingalls Shipbuilding Corp.
P. O. Box 149
Pascagoula, Miss. 39567

NEW JERSEY

Marine Safety Equipment Corp.
Foot of Paynter's Road
Farmingdale, N. J. 07727

NEW YORK

Robert E. Derecktor, Inc.
311 E. Post Road
Mamaroneck, N. Y.

Jakobson Shipyard, Inc.
Oyster Bay, N. Y. 11771

NORTH CAROLINA

Barbour Boat Works, Inc.
South Front Street
New Bern, N. C.

Elizabeth City Iron Works
& Supply Co.
722 Riverside Avenue
Elizabeth City, N. C. 27909

New Bern Shipyards, Inc.
P. O. Box 1389
New Bern, N. C. 28560

OHIO

Tucker Marine, Inc.
4603 Kellogg Avenue
Cincinnati, Ohio 45226

OREGON

Gunderson Brothers
Engineering Corp.
4700 N. W. Front Avenue
Portland, Ore.

Jansen Marine Corp.
Box 19-A
Troutdale, Ore. 97060

Nichols Boat Works Co.
1820 "B" Street
Hood River, Ore. 97031

Onetta Boat Works
4538 S. W. Macadam Avenue
Portland, Ore. 97201

PENNSYLVANIA

Paasch Marine Service
18 W. Front Street
Erie, Pa. 16507

RHODE ISLAND

Blount Marine Corp.
459 Water Street
Warren, R. I.

TEXAS

Brauer Engineering Co.
P. O. Box 727
Ingleside, Texas

Coastal Iron Works
P. O. Box 806
Corpus Christi, Texas 78403

HBL Shops Division
Houston Barge Lines
Houston, Texas

Levingston Shipbuilding Co.
Front & Mill Streets
Orange, Texas 77630

VIRGINIA

Humphreys Railways, Inc.
Weems, Va. 22576

Richmond Engineering Co.,
Inc.
7th & Hospital Streets
Richmond, Va.

WASHINGTON

Alfab, Inc.
Edmonds, Wash. 98020

Duwamish Shipyard, Inc.
5658 W. Marginal Way, S. W.
Seattle, Wash. 98106

WASHINGTON (Continued)

Marine Construction & Design,
Inc.
2300 W. Commodore Way
Seattle, Wash. 98199

Martinac Shipbuilding Corp.
401 E. 15th Street
Tacoma, Wash. 98421

Martinolich Shipbuilding Corp.
1112 Alexander Avenue
Tacoma, Wash. 98421

Peterson Boat Building Co.
223 E. "F" Street
Tacoma, Wash. 98421

Tacoma Boat Building Co.
132 Sitcum Waterway
Tacoma, Wash. 98421

Unimet, Incorporated
P. O. Box 7127
Tacoma, Wash. 98407

Western Boat Building Corp.
Shipbuilding & Repair Div.
2556 E. 11th Street
Tacoma, Wash. 98421

WISCONSIN

Burger Boat Co., Inc.
P. O. Box 7
Manitowoc, Wisc. 54220

Marinette Marine Corp.
Ely Street
Marinette, Wisc. 54143

Palmer Johnson Boats, Inc.
51 Michigan Avenue
Sturgeon Bay, Wisc. 54235

Peterson Builders, Inc.
334 S. First Avenue
Sturgeon Bay, Wisc. 54235

Schwarz Marine Company, Inc.
Two Rivers, Wisc. 54241

BOAT MANUFACTURERS

Alfab Mfg. Co.
Edmonds, Wash.

Aluma Craft Boat
1515 Central Ave., N.E.
Minneapolis, Minn. 55413

Aluminum Cruisers, Inc.
Standiford Field
Louisville, Ky.

Andrews Products
Middlebury, Ind. 46540

Appleby Mfg. Co.
1025 N. Jefferson
Lebanon, Mo. 65536

Aqua-Patio Pontoon Boat Co.
P. O. Box 8
Sturgis, Mich. 49091

Arkansas Boat Co.
P. O. Box 153
Hope, Ark. 71801

Asbestos Roofing Co.
1100 E. Main St.
Eldorado, Ark.

Barracuda Marine Co.
311 Ashland Ave.
Aurora, Ill.

Barrentine Mfg. Co.
P. O. Box 697
Greenwood, Miss. 38931

Bluewater Boat Co.
510 Pope Lick Road
Middletown, Ky. 40043

Boatel Co.
999 East Maple
Mora, Minn.

Breaux's Bay Craft, Inc.
P. O. Box 296
Loreauville, La.

Brown-Hutchinson, Inc.
1831 Clay Street
Detroit, Mich.

Burger Boat Co., Inc.
P. O. Box 27
Manitowoc, Wisc. 54221

Cargile, Inc.
999 Polk Avenue
Nashville, Tenn.

Cari Craft
328 Ripon Road
Berlin, Wisc.

Chrysler Marine Products
P. O. Box 2641
Detroit, Mich. 48321

Crestliner, Inc.
609 13th Ave., N.E.
Little Falls, Minn. 56345

Delcraft Boat Co.
P. O. Box 7
Delhi, La.

Robert E. Derecktor, Inc.
311 E. Post Road
Mamaroneck, N. Y.

DeSoto Mfg. & Supply Co.
P. O. Box 2461
Memphis, Tenn. 38102

Dixie Craft Boat Co.
P. O. Box 324
Allendale, S. C.

Duo Marine, Inc.
P. O. Box 85
Decatur, Ind.

DuraCraft Boats, Inc.
241 East Gaines
Monticello, Ark.

Duranautic Mfg.
1 East Main St.
Beacon, N. Y.

Duratech Div.
(Penn Yan Boats)
Penn Yan, N. Y.

Eldo Craft Boats, Inc.
Smackover, Ark.

Feather Craft, Inc.
450 Bishop Street
Atlanta, Ga.

Fisher Marine, Inc.
P. O. Box 557
West Point, Miss.

Flotel
1 Main St.
Richmond, Inc.

Freeland Sons Co.
Wenzel Ave.
Sturgis, Mich.

General Marine Ind.
Arkadelphia, Ark.

Godfrey Conveyor Co.
Box 357
Elkhart, Ind.

Grafton Boat Co.
Foot of Oak St.
Grafton, Ill.

Gregor Boat Co.
355 "M" Street
Fresno, Calif.

Grumman Boats Div.
Marathon, N. Y.

Harris Mfg. Corp.
2801 State St.
Ft. Wayne, Ind.

Harwill, Inc.
900 Chesaning St.
St. Charles, Mich.

Heating Assurance Co.
124 E. Augusta
P. O. Box 5161
Spokane, Wash. 99205

Hewes Marine Co.
Municipal Airport
Colville, Wash.

Jakobson Shipyard, Inc.
Oyster Bay, N. Y.

Jansen Machine Works
Troutdale, Ore.

Jett Boat Co.
Friendship, Ark.

Kayot, Inc.
Box 818
Mankato, Minn.

Kan David Co.
1700 5th Street
Sandusky, Ohio

Kingscraft
P. O. Box 126
Prospect, Ky. 40059

Lantana Yachts
808 N. Dixie Hwy.
Lantana, Fla. 33460

Lazy Days Mfg. Co.
Holiday Road
Buford, Ga.

Lowell Ind.
5708 Market St.
Spokane, Wash.

Lund Metal Craft, Inc.
P. O. Box 10
New York Mills, Minn.

Maritime Products Corp.
1255 S. Mahoning Ave.
Alliance, Ohio

Maurell Products Co.
Owosso, Mich.

McKenzie Boat Mfg. Co.
McKenzie, Tenn.

Meyers Industries
Tecumseh, Mich. 49286

Mirro Alum. Co.
1512 Washington St.
Manitowoc, Wisc.

Monark Boat Co.
P. O. Box 210
Monticello, Ark.

Muncie Metal Spinning, Inc.
1012 E. 20th St.
Muncie, Ind. 47302

Naden Ind.
505 Fair Ave.
Webster City, Iowa

Norcom, Inc.
510 S. Lansing
Box 1736
Tulsa, Okla.

Onetta Boat Works, Inc.
4538 S.W. Macadam Ave.
Portland, Ore.

Orlando Boat Co.
521 Elwell St.
Orlando, Fla.

Ouachita Marine &
Industrial Corp.
Arkadelphis, Ark.

Paasch Marine Service
18 W. Front St.
Erie, Pa.

Palmer-Johnson Boats, Inc.
Sturgeon Bay, Wisc.

Peterson Builders
Sturgeon Bay, Wisc.

Pioneer Mfg. Co.
193 Perry St.
Middlebury, Ind.

Plucks Craft Mfg. Co.
Rose Island Road
Prospect, Ky.

Polar Kraft Mfg. Co.
1237 N. Watkins
Memphis, Tenn.

Red Cross Mfg. Co.
124 S. Oak St.
Bluffton, Ind.

Richland Mfg. Co.
P. O. Box 653
Richland, Mo.

Roamer Div.
Chris-Craft Corp.
Holland, Mich.

Sea Nymph Mfg. Co.
P. O. Box 298
Syracuse, Ind. 46567

Sea Sprite Boat Co., Inc.
625 S. 1st St.
Monmouth, Ill. 61462

Seth Smith Boat Works, Inc.
201 E. Washington St.
Phoenix, Ariz. 85034

Sewart Seacraft, Inc.
Box 108
Berwick, La. 70342

Smoker Lumber Co.
P. O. Box 215
New Paris, Ind.

Starcraft Boat Co.
Goshen, Ind.

Stephens Marine, Inc.
345 N. Yosemite St.
Stockton, Calif. 95203

Tacoma Boat Building Co., Inc.
132 Sitcum Waterway
Tacoma, Wash. 98421

Terra-Marina Mfg. Co., Inc.
9999 Hempstead Hwy.
Houston, Texas 77018

Texas Boat Mfg. Co., Inc.
1120 Texas St.
Lewisville, Texas 75067

Trailerboat Co.
151 Market St.
San Rafael, Calif. 94901

Valco Boats
5733 E. Shields Ave.
Fresno, Calif. 93727

Viking Boat Co.
Highway 13 North
Middlebury, Ind. 46540

Waco Mfg. Co.
North Little Rock, Ark.

Western Boat Building Co.
2556 E. 11th St.
Tacoma, Wash. 98421

Cripe Equipment Co.
Walcottville, Ind.

Striker Boats, Inc.
3100 State Road 84
Fort Lauderdale, Fla. 33312

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