Hull as a Longitudinal Girder

Classical approaches to ship structural design treat the hull structure as a beam for purposes of analytical evaluation. [3-1] The validity of this approach is related to the vessel's length to beam and length to depth ratios. Consequently, beam analysis is not the primary analytical approach for small craft. Hull girder methods are usually applied to vessels with length/depth (L/D) ratios of 12 or more, which usually corresponds to vessels greater than 100 feet (30 meters). Very slender hull forms, such as a canoe or catamaran hull, may have an L/D much greater than 12. Nevertheless, it is always instructive to regard hull structure as a beam when considering forces that act on the vessel's overall length. By determining which elements of the hull are primarily in tension, compression or shear, scantling determination can be approached in a more rational manner. This is particularly important when designing with anisotrophic materials, such as composites, where orientation affects the structure's load carrying capabilities to such a great extent.

A variety of different phenomena contribute to the overall longitudinal bending moments experienced by a ship's hull structure. Analyzing these global loading mechanisms statically is not very realistic with smaller craft. Here, dynamic interaction in a seaway will generally produce loadings in excess of what static theory predicts. However, empirical information has led to the development of accepted safety factors that can be applied to the statically derived stress predictions. Force producers are presented here in an order that corresponds to decreasing vessel size, i.e., ship theory first.

Still Water Bending Moment

Before a ship even goes to sea, some stress distribution profile exists within the structure. Figure 3-1 shows how the summation of buoyancy and weight distribution curves leads to the development of load, shear and moment diagrams. Stresses apparent in the still water condition generally become extreme only in cases where concentrated loads are applied to the structure, which can be the case when holds in a commercial vessel are selectively filled. The still water bending moment (SWBM) is an important concept for composites design because fiberglass can be susceptible to creep or fracture when subjected to long term loads. Static fatigue of glass fibers can reduce their load carrying capability by as much as 70 to 80% depending on load duration, temperature, moisture conditions and other factors. [3-2]

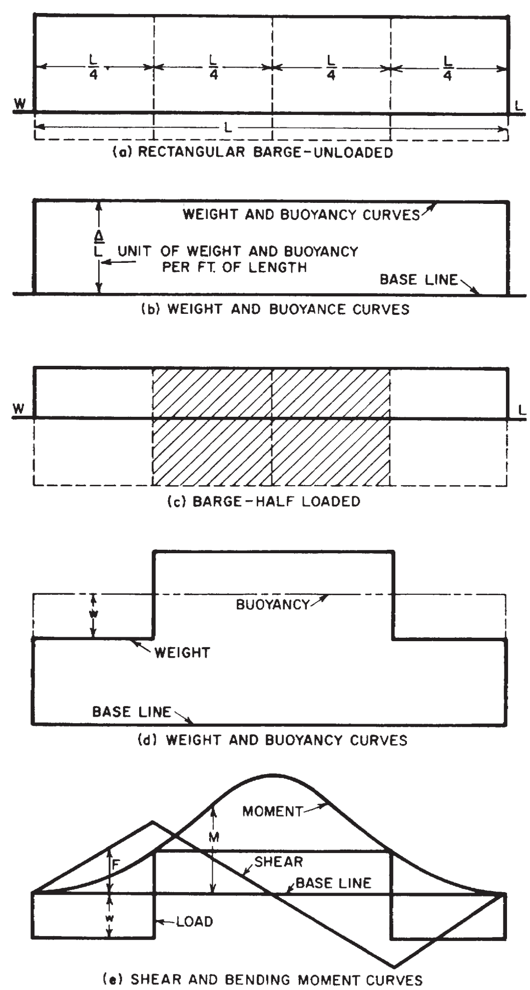

Figure 3-1 Bending Moment Development of Rectangular Barge in Still Water [*Principles of Naval Architecture*]

Wave Bending Moment

A static approach to predicting ship structure stresses in a seaway involves the superposition of a trochoidal wave with a wavelength equal to the vessel's length in a hogging and sagging condition, as shown in Figure 3-2. The trochoidal wave form was originally postulated by Froude as a realistic two-dimensional profile, which was easily defined mathematically. The height of the wave is usually taken as $L/9$ (L < 100 feet or 30 meters), $L/20$ (L > 100 feet or 30 meters) or $1.1L^{1/2}$ (L > 500 feet) or $0.6L^{.6}$ (L > 150 meters). Approximate calculation methods for maximum bending moments and shearing forces have been developed as preliminary design tools for ships over 300 feet (91 meters) long. [3-3] Except for very slender craft, this method will not apply to smaller vessels.

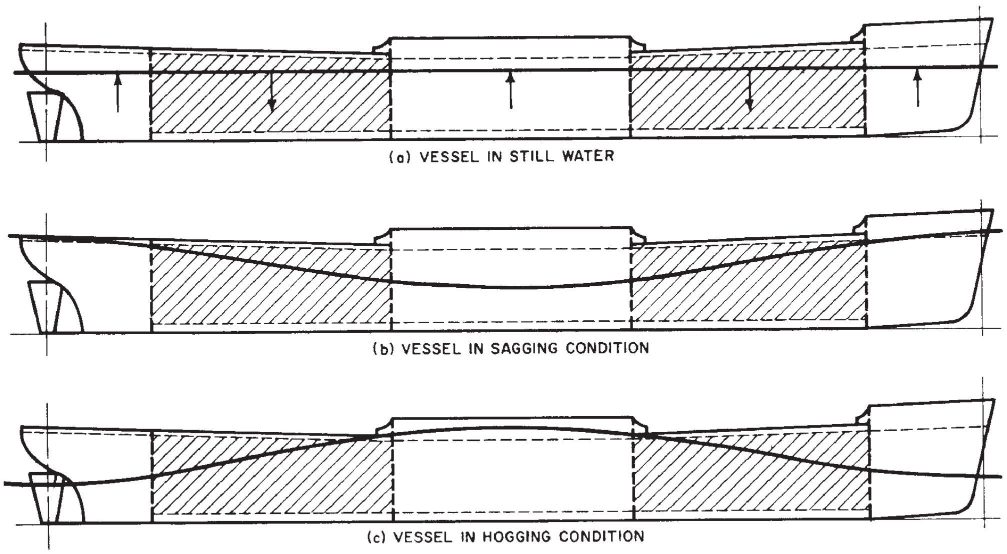

Figure 3-2 Superposition of Static Wave Profile [*Principles of Naval Architecture*]

Ship Oscillation Forces

The dynamic response of a vessel operating in a given sea spectrum is very difficult to predict analytically. Accelerations experienced throughout the vessel vary as a function of vertical, longitudinal and transverse location. These accelerations produce virtual increases of the weight of concentrated masses, hence additional stress. The designer should have a feel for the worst locations and dynamic behavior that can combine to produce extreme load scenarios. Figure 3-3 is presented to define the terms commonly used to describe ship motion. It is generally assumed that combined roll and pitch forces near the deck edge forward represents a "worst case" condition of extreme accelerations for the ship.

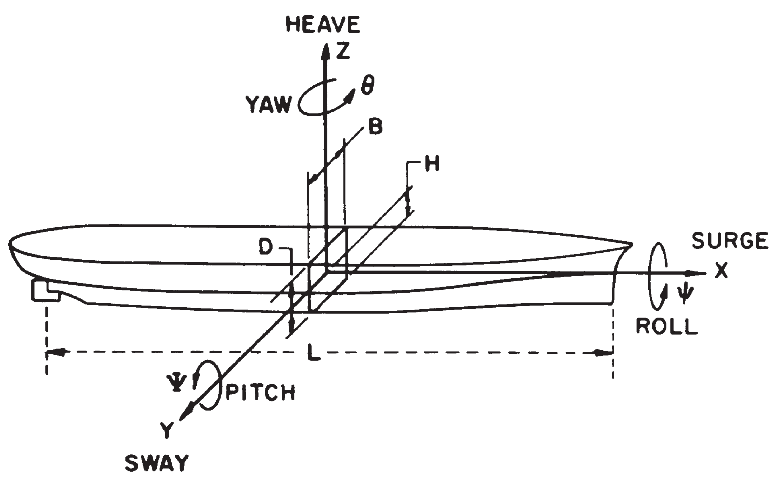

Figure 3-3 Principal Axes and Ship Motion Nomenclature [Evans, *Ship Structural Design Concepts*]

Dynamic Phenomena

Dynamic loading or vibration can be either steady state, as with propulsion system induced phenomena, or transient, such as with slamming through waves. In the former case, load amplitudes are generally within the design limits of hull structural material. However, the fatigue process can lead to premature failures, especially if structural components are in resonance with the forcing frequency. A preliminary vibration analysis of major structural elements (hull girder, engine foundations, deck houses, masts, etc.) is generally prudent to ensure that natural frequencies are not near shaft and blade rate for normal operating speeds. [3-4] Schlick [3-5] proposed the following empirical formula to predict the first-mode (2-node) vertical natural frequency for large ships:

$$N_{2v} = C_1 \sqrt{\frac{I}{\Delta L^3}} \quad (3\text{-}1)$$

where:

L = length between perpendiculars, feet
Δ = displacement, tons
I = midship moment of inertia, $in^2 ft^2$
C_1 = constant according to ship type
= 100,000 for small coastal tankers, 300-350 feet
= 130,000 for large, fully loaded tankers
= 143,000 suggested by Noonan for large tankers
= 156,850 for destroyers

The transient dynamic loading referred to generally describes events that occur at much higher load amplitudes. Slamming in waves is of particular interest when considering the design of high-speed craft. Applying an acceleration factor to the static wave bending analysis outlined above can give some indication of the overall girder stresses produced as a high-speed craft slams into a wave. Other hull girder dynamic phenomena of note include springing and whipping of the hull when wave encounter frequency is coincident with hull natural frequency.

Sailing Vessel Rigging Loads

The major longitudinal load producing element associated with sailing vessels is the mast operating in conjunction with the headstay and backstay. The mast works in compression under the combined action of the aforementioned longitudinal stays and the more heavily loaded athwartship shroud system. Hull deflection is in the sagging mode, which can be additive with wave action response.

Transverse Bending Loads

Transverse loading on a ship's hull is normally of concern only when the hull form is very long and slender. Global forces are the result of beam seas. In the case of sailing vessels, transverse loads can be significant when the vessel is sailing upwind in a heeled condition. Methods for evaluating wave bending moment should be used with a neutral axis that is parallel to the water.

Torsional Loading

Torsional loading of hull structures is often overlooked because there is no convenient analytical approach that has been documented. Quartering seas can produce twisting moments within a hull structure, especially if the hull has considerable beam. In the case of multihulls, this loading phenomena often determines the configuration of cross members. Vessels with large deck openings are particularly susceptible to applied torsional loads. New reinforcement materials are oriented with fibers in the bias direction (±45°), which makes them extremely well suited for resisting torsional loading.

Slamming

The loads on ship structures are reasonably well established (e.g. ***Principles of Naval Architecture***, etc.), while the loads on small craft structures have received much less attention in the literature. There are some generalizations which can be made concerning these loads, however. The dominant loads on ships are global in-plane loads (loads affecting the entire structure and parallel to the hull plating), while the dominant loads on small craft are local out of plane loads (loads normal to the hull surface over local portions of the hull surface). As a result, structural analysis of ships is traditionally approached by approximating the entire ship as a box beam, while the structural analysis of small craft is approached using local panel analysis. The analysis of large boats (or small ships) must include both global and local loads, as either may be the dominant factor. Since out-of-plane loads are dominant for small craft, the discussion of these loads will center on small craft. However, much of the discussion could be applied to ships or other large marine structures. The American Bureau of Shipping provides empirical expressions for the derivation of design heads for sail and power vessels. [3-6, 3-7]

Out-of-plane loads can be divided into two categories: distributed loads (such as hydrostatic and hydrodynamic loads) and point loads (such as hauling or keel, rig, and rudder loads on sail boats, or strut, rudder or engine mounts for power boats). The hydrostatic loads on a boat at rest are relatively simple and can be determined from first principles. Hydrodynamic loads are very complex, however, and have not been studied extensively, thus they are usually treated in an extremely simplified manner. The most common approach is to increase the static pressure load by a fixed proportion, called the dynamic load factor. [3-8] The sources of point loads vary widely, but most can be estimated from first principles by making a few basic assumptions.

Hydrodynamic Loads

There are several approaches to estimating the hydrodynamic loads for planing power boats. However, most are based on the first comprehensive work in this area, performed by Heller and Jasper. The method is based on relating the strain in a structure from a static load to the strain in a structure from a dynamic load of the same magnitude. The ratio of the dynamic strain to the static strain is called the “response factor,” and the maximum response factor is called the “dynamic load factor.” This approach is summarized here with an example of this type of calculation. Heller and Jasper instrumented and obtained data on an aluminum hull torpedo boat (YP 110) and then used this data as a basis for the empirical aspects of their load calculation. An example of the pressure data is presented in Figure 3-4. The dynamic load factor is a function of the impact pressure rise time, t_o, over the natural period of the structure, T, and is presented in Figure 3-5, where c/c_c is the fraction of critical damping. The theoretical development of the load prediction leads to the following equations:

Maximum Impact Force Per Unit Length:

$$P_0 = \frac{3W}{2L} \times \left(1 + \frac{y_{CG}}{g}\right) \qquad (3\text{-}2)$$

where:

p_0 = maximum impact force per unit length

W = hull weight

L = waterline length

y_{CG} = vertical acceleration of the CG

g = gravitational acceleration

Maximum Effective Pressure at the Keel

$$P_{01} = \frac{3 p_0}{G} \qquad (3\text{-}3)$$

where:

p_{01} = maximum effective pressure at the keel

G = half girth

Maximum Effective Pressure

$$\overline{P} = p_{01} \times DLF \qquad (3\text{-}4)$$

where:

$\overline{P}$ = the maximum effective pressure for design

DLF = the Dynamic Load Factor from Figure 3-5 (based on known or measured critical damping)

An example of the pressure calculation for the YP110 is also presented by Heller and Jasper:

Maximum Force Per Unit Length:

$$p_0 = \frac{3 \times 109{,}000}{2 \times 900}\left(1 + 4.7\right) = 1{,}036 \text{ lbs/in}$$

Maximum Effective Pressure at the Keel:

$$p_{01} = \frac{1036 \times 3}{96} = 32.4 \text{ psi}$$

Maximum Effective Pressure:

$$\overline{P} = 32.4 \times 1.1 = 35.64 \text{ psi}$$

This work is the foundation for most prediction methods. Other presentations of load calculation, measurement, or design can be found in the classification society publications cited in the reference section.

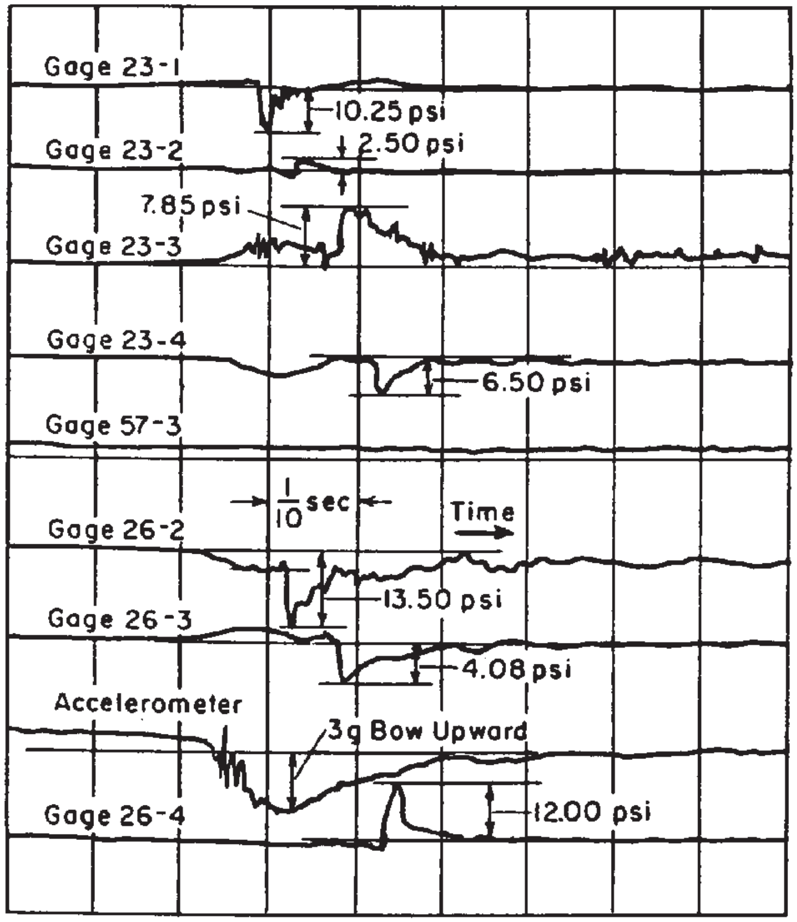

Figure 3-4 Pressures Recorded in Five and Six Foot Waves at a Speed of 28 Knots [Heller and Jasper, *On the Structural Design of Planing Craft*]

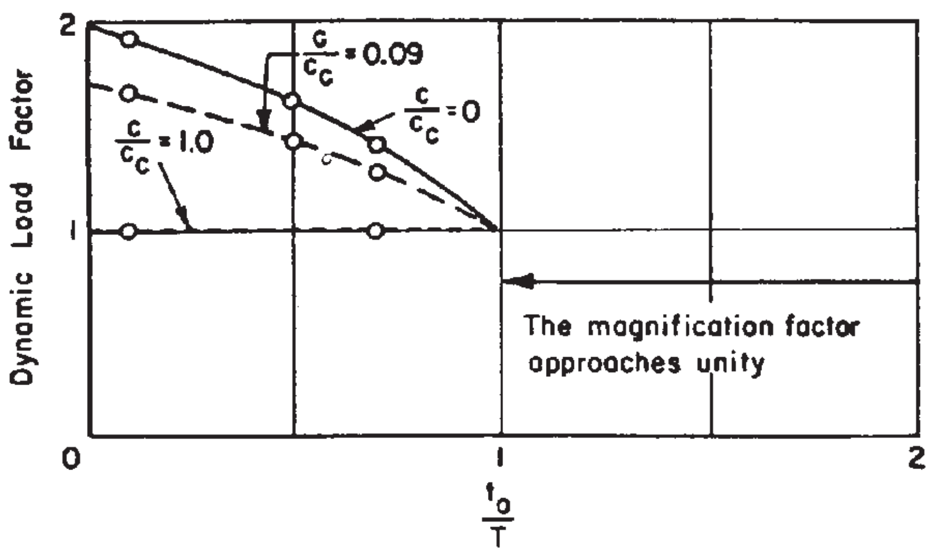

Figure 3-5 Dynamic Load factors for Typical Time Varying Impact Loads [Heller and Jasper, *On the Structural Design of Planing Craft*]

Load Distribution as a Function of Length

Classification society rules, such as the ABS Guide for High-Speed Craft (Oct, 1996 Draft) recognize that slamming loads vary as a function of distance along the waterline. Figures 3-6 and 3-7 show vertical acceleration factors used to calculate dynamic bottom pressures based on hull form and service factors, respectively. The general relationship given by the rules is as follows:

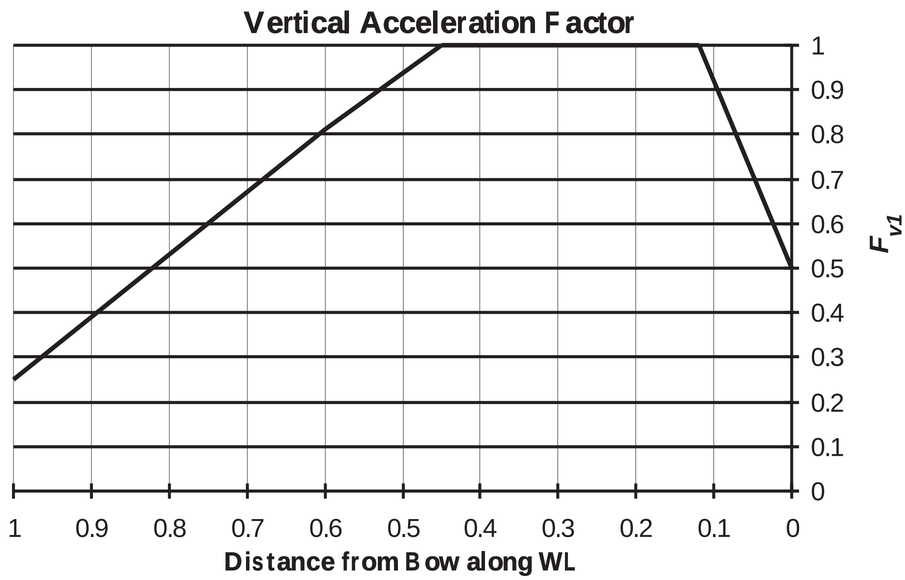

Figure 3-6 Vertical Acceleration Factor as a Function of Distance from Bow, F_{v1}, Used in ABS Calculations

$$Pressure_b \approx \frac{\Delta}{L_{wl}\ B} F_{v1} \quad (3\text{-}5)$$

and

$$Pressure_i \approx N\ d\, F_{v2} \quad (3\text{-}6)$$

where:

Δ = displacement

L_{wl} = waterline length

B = beam

N = service factor

d = draft

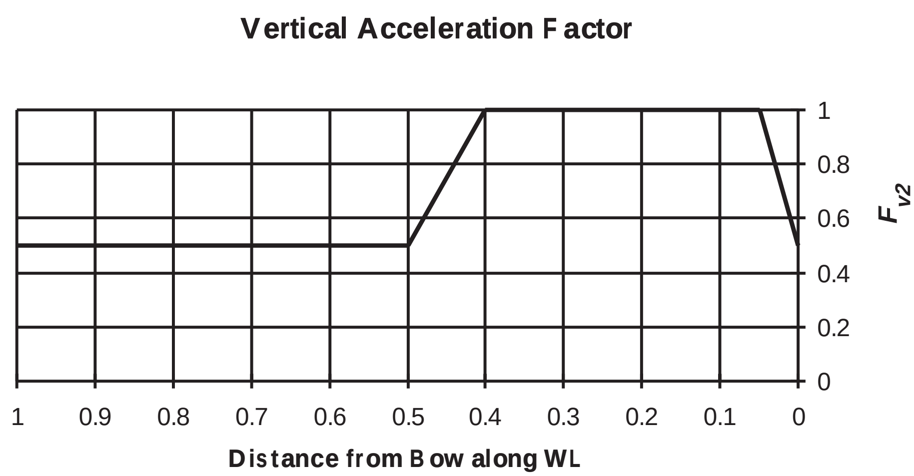

Figure 3-7 Vertical Acceleration Factor as a Function of Distance from Bow, F_{v2}, Used in ABS Calculations

The rules require that the higher pressure calculated be used as the design pressure for planing and semi-planing craft. The reader is instructed to consult the published rules to get the exact equations with additional factors to fit hull geometry and engineering units used.

Slamming Area Design Method

NAVSEA's *High Performance Marine Craft Design Manual Hull Structures* [3-9] prescribes a method for calculating longitudinal shear force and bending moments based on assigning a slamming pressure area extending from the keel to the turn of the bilge and centered at the longitudinal center of gravity (LCG). This area is calculated as follows:

$$A_R = \frac{25\,\Delta}{T} \quad (\text{ft}^2) \qquad (3\text{-}7a)$$

$$A_R = \frac{0.7\,\Delta}{T} \quad (\text{m}^2) \qquad (3\text{-}7b)$$

The slamming force is given as:

$$F_{sl} = \Delta\, a_v \qquad (3\text{-}8)$$

where:

Δ = Full load displacement in tons or tonnes

T = Molded draft in feet or meters

a_v = $\frac{1}{10}$ highest vertical acceleration at the LCG of the vessel

The vertical acceleration, a_v, is calculated for any position along the length of a monohull craft by the following expression:

$$a_v = \frac{k_v\ g_0\ v^{1.5}\left[\frac{H_s}{L}\right]}{1.697\,[1.0 + 0.04L]}\left[1 - \frac{\sqrt{L}}{2.6\,V}\right] \quad (\text{ft/sec}^2) \qquad (3\text{-}9a)$$

$$a_v = \frac{k_v\ g_0\ v^{1.5}\left[\frac{H_s}{L}\right]}{1.697\,[1.0 + 0.012L]}\left[1 - \frac{\sqrt{L}}{4.71\,V}\right] \quad (\text{m/sec}^2) \qquad (3\text{-}9b)$$

where:

H_s = Significant wave height (ft or m)

L = Vessel length (ft or m)

g_0 = Acceleration due to gravity

k_v = Longitudinal impact coefficient from Figure 3-8

V = Maximum vessel speed in knots in a sea state with significant wave height, H_s

The maximum bottom pressure, P_m, is given by:

$$P_m = 0.135\ T\, a_v \quad (\text{psi}) \qquad (3\text{-}10a)$$

$$P_m = 10\ T\, a_v \quad (\text{Mpa}) \qquad (3\text{-}10b)$$

The design pressure, P_d, for determining bottom panel scantling requirements is given by the expression:

$$P_d = F_a \times F_l \times P_m \qquad (3\text{-}11)$$

with F_a given in Figure 3-9 and F_l given in Figure 3-10. When using P_d to calculate loads on structural members, the following design areas should be used:

Structural Member	Design Area
Shell Plating	plate area (a × b)
Longitudinal Stiffener	unsupported stiffener length × stringer spacing
Transverse Stiffener	unsupported stiffener length × stiffener spacing
Structural Grillage	unsupported stringer length × unsupported stiffener length

Nonstandard Hull Forms

Hydrofoils, air-cushion vehicles and surface effect ships should be evaluated up on foils or on-cushion, as well as for hullborne operational states. Vertical accelerations for hydrofoils up on foils should not be less than 1.5 g_0.

Transverse bending moments for multihulls and SWATH vessels are the product of displacement, vertical acceleration and beam and often dictate major hull scantlings. Transverse vertical shear forces are the product of displacement and vertical acceleration only.

Model tests are often required to verify primary forces and moments for nonstandard hull forms. [3-9, 3-10]

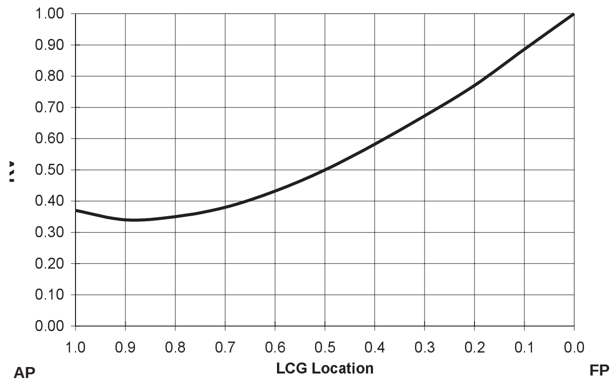

Figure 3-8 Longitudinal Impact Coefficient as a Function of Distance from Bow, k_V, Used in Vertical Acceleration Calculations [NAVSEA *High Performance Craft Design Manual*]

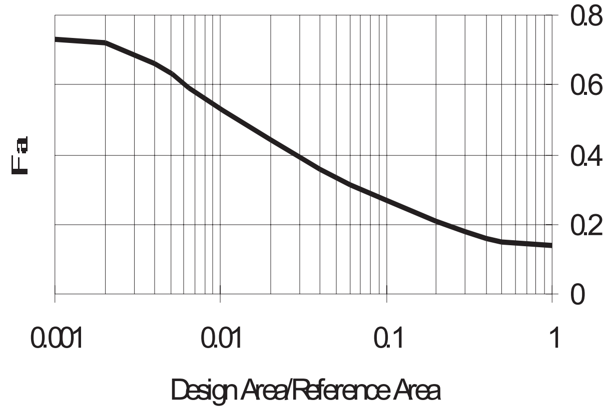

Figure 3-9 Design Area Coefficient Used in Design Pressure Calculations [NAVSEA *High Performance Craft Design Manual*]

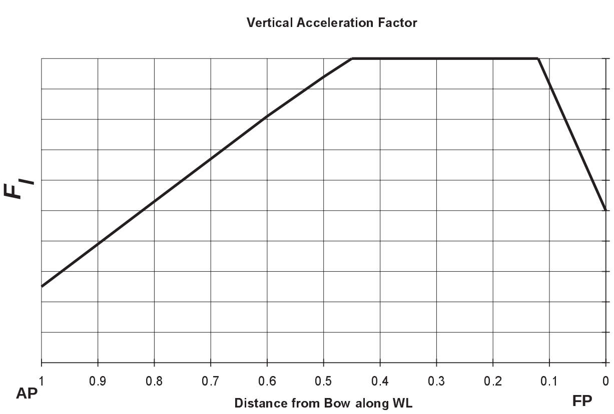

Figure 3-10 Longitudinal Pressure Distribution Used in Design Pressure Calculations [NAVSEA *High Performance Craft Design Manual*]

Hull Girder Stress Distribution

When the primary load forces act upon the hull structure as a long, slender beam, stress distribution patterns look like Figure 3-11 for the hogging condition with tension and compression interchanged for the sagging case. The magnitude of stress increases with distance from the neutral axis. On the other hand, shear stress is maximum at the neutral axis. Figure 3-12 shows the longitudinal distribution of principal stresses for a long, slender ship.

The relationship between bending moment and hull stress can be estimated from simple beam theory for the purposes of preliminary design. The basic relationship is stated as follows:

$$\sigma = \frac{M}{SM} = \frac{Mc}{I} \qquad (3\text{-}12)$$

where:

- σ = unit stress
- M = bending moment
- SM = section modulus
- c = distance to neutral axis
- I = moment of inertia

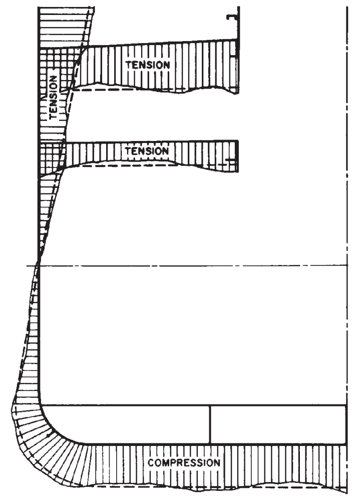

Figure 3-11 Theoretical and Measured Stress Distribution for a Cargo Vessel Midship Section [*Principles of Naval Architecture*]

The neutral axis is at the centroid of all longitudinal strength members, which for composite construction must take into account specific material properties along the ship's longitudinal axis. The actual neutral axis rarely coincides with the geometric center of the vessel's midship section. Hence, values for σ and c will be different for extreme fibers at the deck and hull bottom.

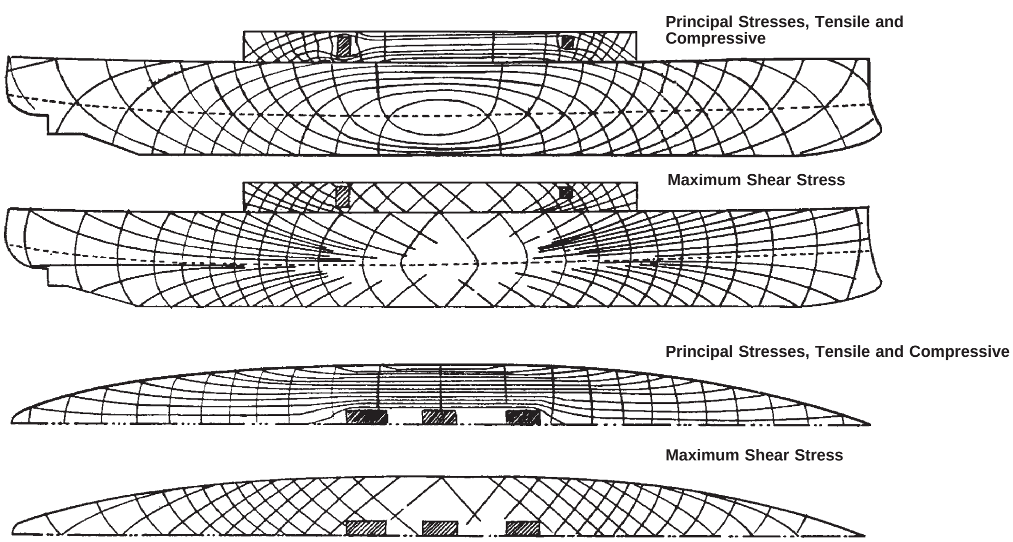

Figure 3-12 Longitudinal Distribution of Stresses in a Combatant [Hovgaard, *Structural Design of Warships*]

Lu & Jin have reported on an extensive design and test program that took place in China during the 1970's that involved a commercial hull form built using frame-stiffened, single-skin construction. Figure 3-13 shows the distribution of longitudinal strains and the arrangement of bending test strain gages used to verify the predicted hogging and sagging displacements of the 126 feet (38.5 meter) GRP hull studied. This study provided excellent insight into how a moderately-sized composite ship responds to hull girder loadings.

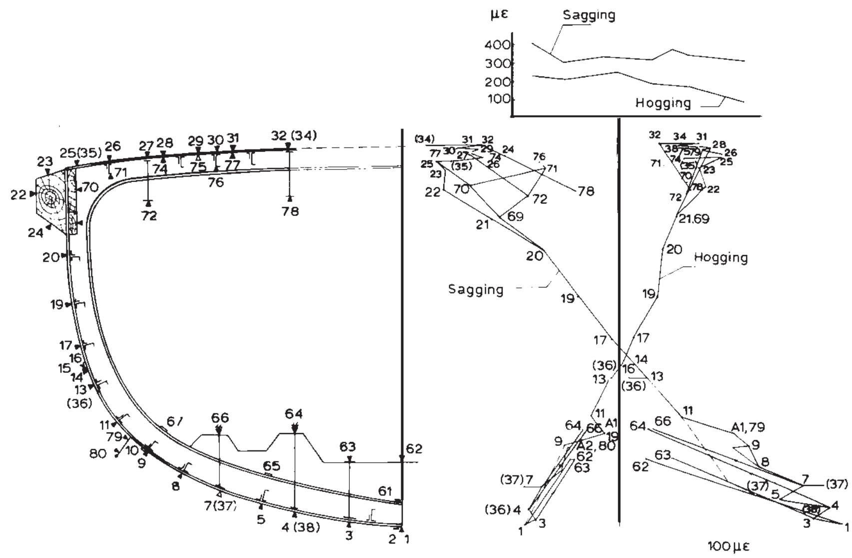

Figure 3-13 Distribution of Longitudinal Strains of a 38.5 Meter GRP Hull (above) and Longitudinal Strain Gage Location (below) [X.S. Lu & X.D. Jin, "*Structural Design and Tests of a Trial GRP Hull*," *Marine Structures*, Elsever, 1990]

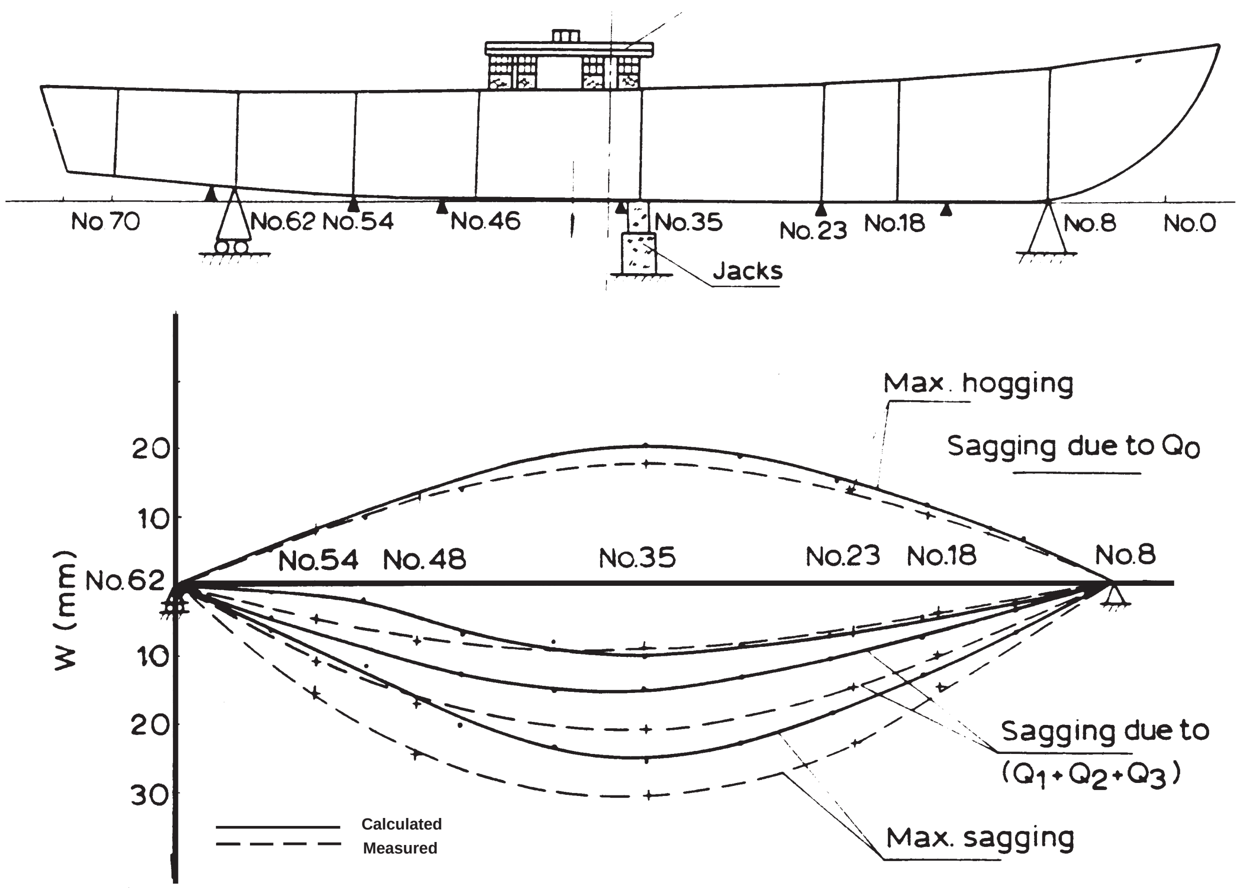

Figure 3-14 Predicted and Measured Vertical Displacements for a 38.5 Meter GRP Hull [X.S. Lu & X.D. Jin, "*Structural Design and Tests of a Trial GRP Hull*," *Marine Structures*, Elsever, 1990]

Other Hull and Deck Loads

Green water loading is used to calculate forces that hull side, topside and deck structure are exposed to in service. Green water loading is dependent on longitudinal location on the vessel and block coefficient (C_B) as well as the distance that a vessel will be from a safe harbor while in service. This methodology was originally published in the 1985 DnV *Rules for Classification of High Speed Light Craft*. [3-10]

Hull Side Structure, Topsides and Weather Decks

The design pressure used for designing side shell structure that is above the chine or turn of the bilge but below the designed waterline is given by DnV as:

$$p = 0.44\, h_0 = \left[k_l - \frac{1.5\, h_0}{T} \right] 0.0035\, L \ \text{(psi)} \qquad \text{(3-13a)}$$

$$p = 10\, h_0 = \left[k_l - \frac{1.5\, h_0}{T} \right] 0.08\, L \ \text{(Mpa)} \qquad \text{(3-13b)}$$

where:

h_0 = vertical distance from waterline to the load point

k_1 = longitudinal factor from Figure 3-15 based on C_B

$C_B = \dfrac{35\,\Delta}{L\,B\,T}$ (English units)

$= \dfrac{\Delta}{1.025\,L\,B\,T}$ (metric units)

B = greatest molded breadth at load waterline

For side shell above the waterline and deck structure, design pressure is given as:

$$p = a\, k_l\, (c\, L - 0.053\, h_0) \qquad \text{(3-14)}$$

where:

for topsides:
a = 0.044 (English)
= 1.00 (metric)

for decks:
a = 0.035 (English)
= 0.80 (metric)

with a minimum pressure of 1 psi (6.5 Mpa) for topeside structure and 0.75 psi (5.0 Mpa) for decks. Service factor, c, is:

c	Nautical Miles Out
0.080	> 45
0.072	≤ 45
0.064	≤ 15
0.056	≤ 5

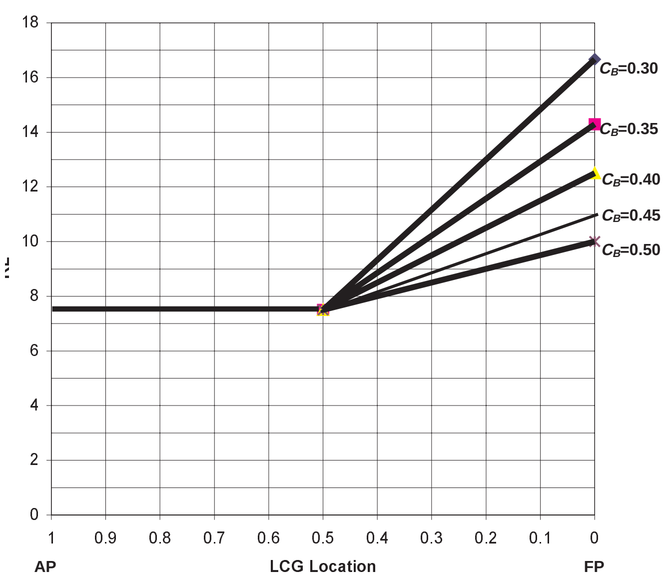

Figure 3-15 Green Water Distribution Factor, K_L [NAVSEA *High Performance Craft Design Manual*]

Deckhouses and Superstructures

For deckhouses and superstructure end bulkheads, the expression for design pressure is the same as for side shell structure above the waterline, where:

for lowest tier of superstructure not protected from weather:

$$a = 0.088 \text{ (English)}$$
$$= 2.00 \text{ (metric)}$$

for other superstructure and deckhouse front bulkheads:

$$a = 0.066 \text{ (English)}$$
$$= 1.50 \text{ (metric)}$$

for deckhouse sides:

$$a = 0.044 \text{ (English)}$$
$$= 1.00 \text{ (metric)}$$

elsewhere:

$$a = 0.035 \text{ (English)}$$
$$= 0.80 \text{ (metric)}$$

with a minimum pressure of 1.45 + 0.024 L psi (10 + 0.05 L Mpa) for lowest tier of superstructure not protected from weather and 0.725 + 0.012 L psi (5 + 0.025 L Mpa) elsewhere.

Compartment Flooding

Watertight bulkheads shall be designed to withstand pressures calculated by multiplying the vertical distance from the load point to the bulkhead top by the factor 0.44 (English units) or 10 (metric units) for collision bulkheads and 0.32 (English units) or 7.3 (metric units) for other watertight bulkheads.

Equipment & Cargo Loads

The design pressure from cargo and equipment are given by the expression:

$$p = 2.16 \times 10^{-3} (g_0 + 0.5\, a_v) \text{ (psi)} \qquad (3\text{-}15a)$$

$$p = \rho H (g_0 + 0.5\, a_v) \text{ (Mpa)} \qquad (3\text{-}15b)$$

For the metric expression, ρH = 1.6 for machinery space; 1.0 for weather decks; and 0.35 for accommodation spaces. ρ shall be 0.7 and H shall be the vertical distance from the load point to the above deck for sheltered decks or inner bottoms. [3-9, 3-10]