Marine Composites

Webb Institute
Senior Elective

Design Methods for Ship Structures

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greene
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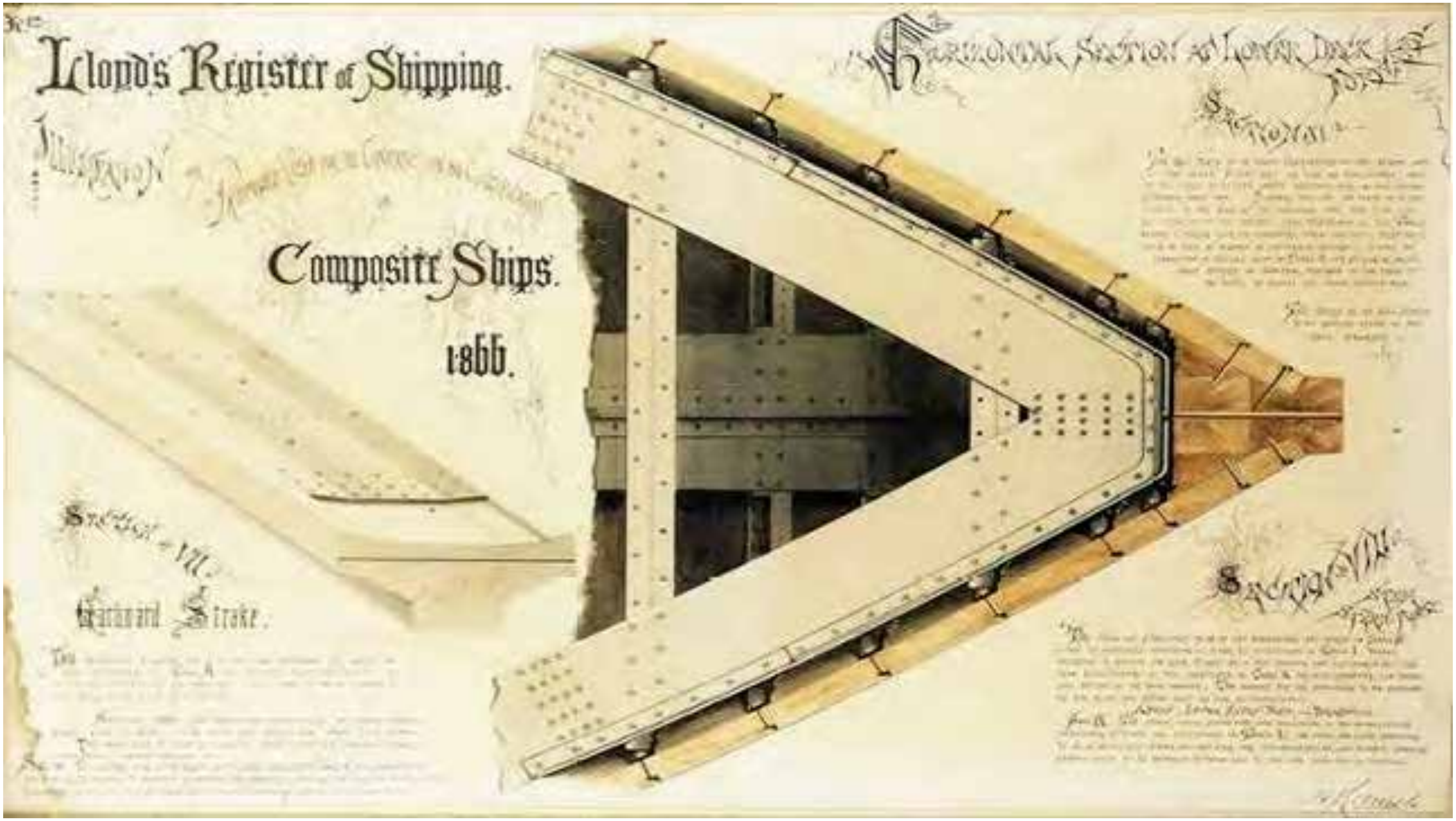
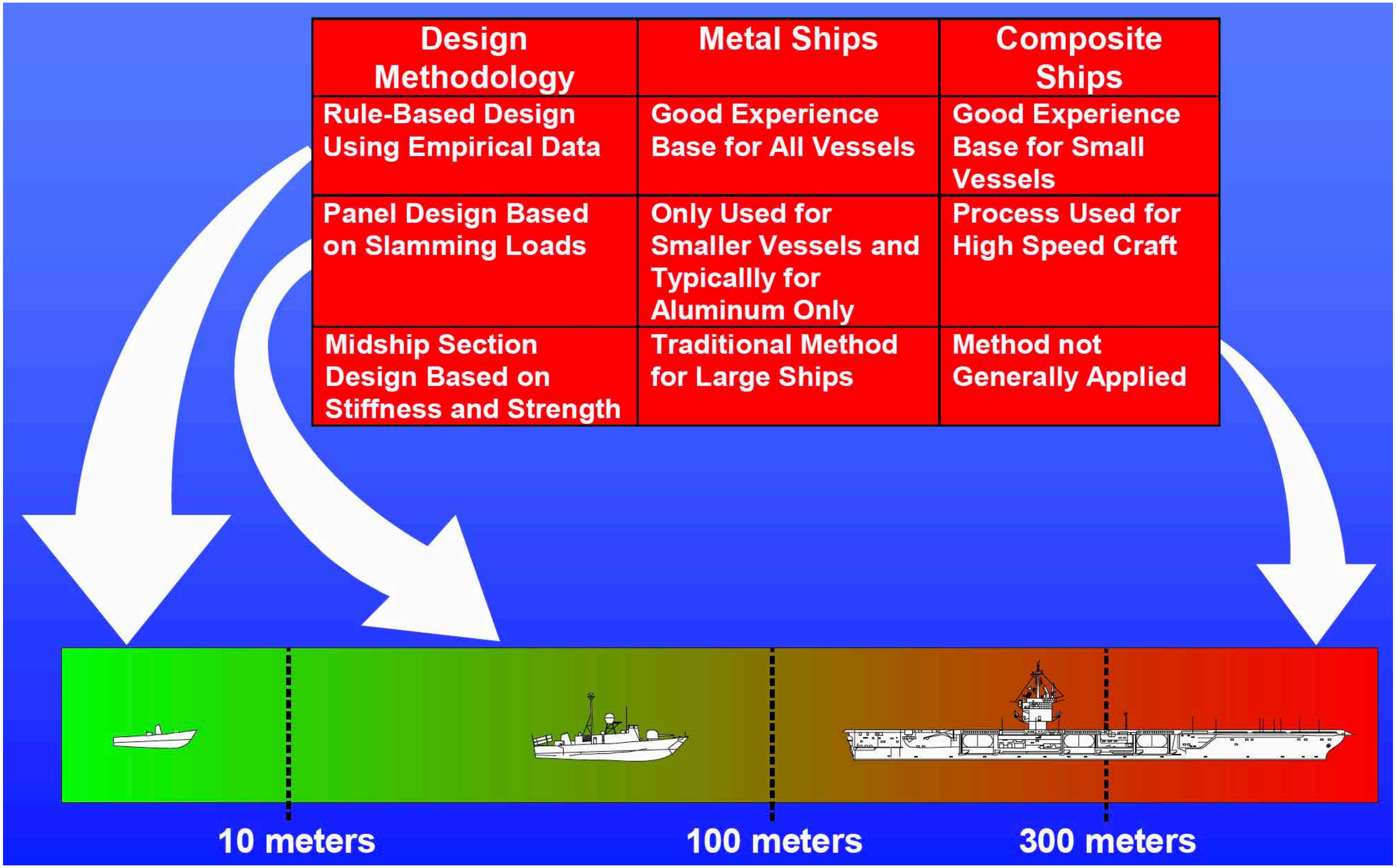
Composite Ships

The title page from Lloyd's Register Rules for Composite Ships, 1866

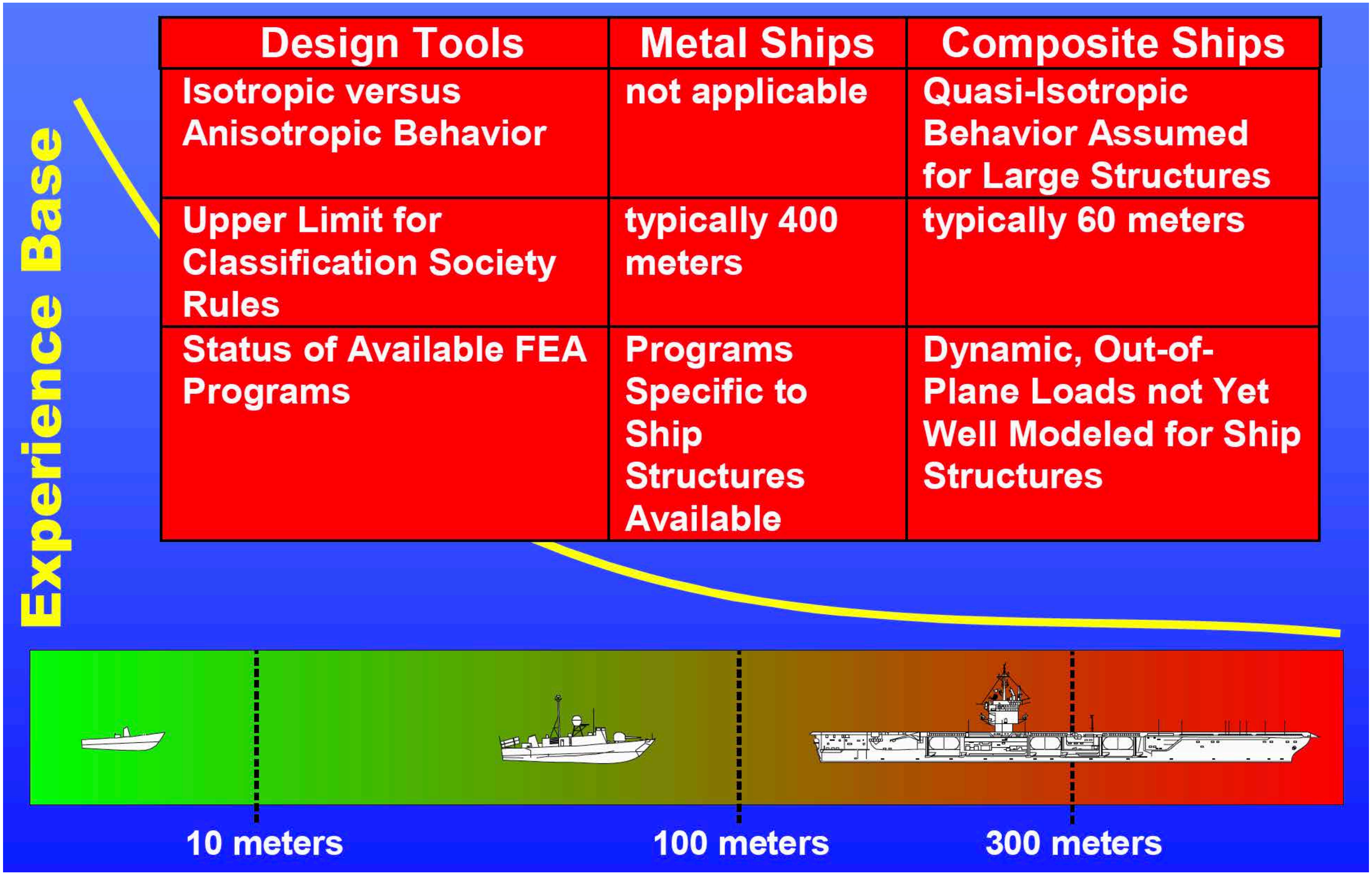


Design Methodology



Design Methodology	Metal Ships	Composite Ships
Rule-Based Design Using Empirical Data	Good Experience Base for All Vessels	Good Experience Base for Small Vessels
Panel Design Based on Slamming Loads	Only Used for Smaller Vessels and Typicallly for Aluminum Only	Process Used for High Speed Craft
Midship Section Design Based on Stiffness and Strength	Traditional Method for Large Ships	Method not Generally Applied

Design Tools



Design Tools	Metal Ships	Composite Ships
Isotropic versus Anisotropic Behavior	not applicable	Quasi-Isotropic Behavior Assumed for Large Structures
Upper Limit for Classification Society Rules	typically 400 meters	typically 60 meters
Status of Available FEA Programs	Programs Specific to Ship Structures Available	Dynamic, Out-of-Plane Loads not Yet Well Modeled for Ship Structures

Compare to Aerospace Structures

Northrop B-2

MGTOW: 400,000 lbs
Empty Weight: 120,000 lbs
Composites: 80,400 lbs
Carbon-epoxy autoclave
Wingspan 172 feet
Composite cost: ~$10,000/lb
Design stress: ~40,000 psi

Beech Starship

MGTOW: 14,900 lbs
Empty Weight: 10,120 lbs
Composites: 3000 lbs
Carbon-epoxy autoclave
Wingspan: 54.5 feet
Composite cost: ~$1,000/lb
Design stress: ~30,000 psi

VT Shipbuilding Mirabella V

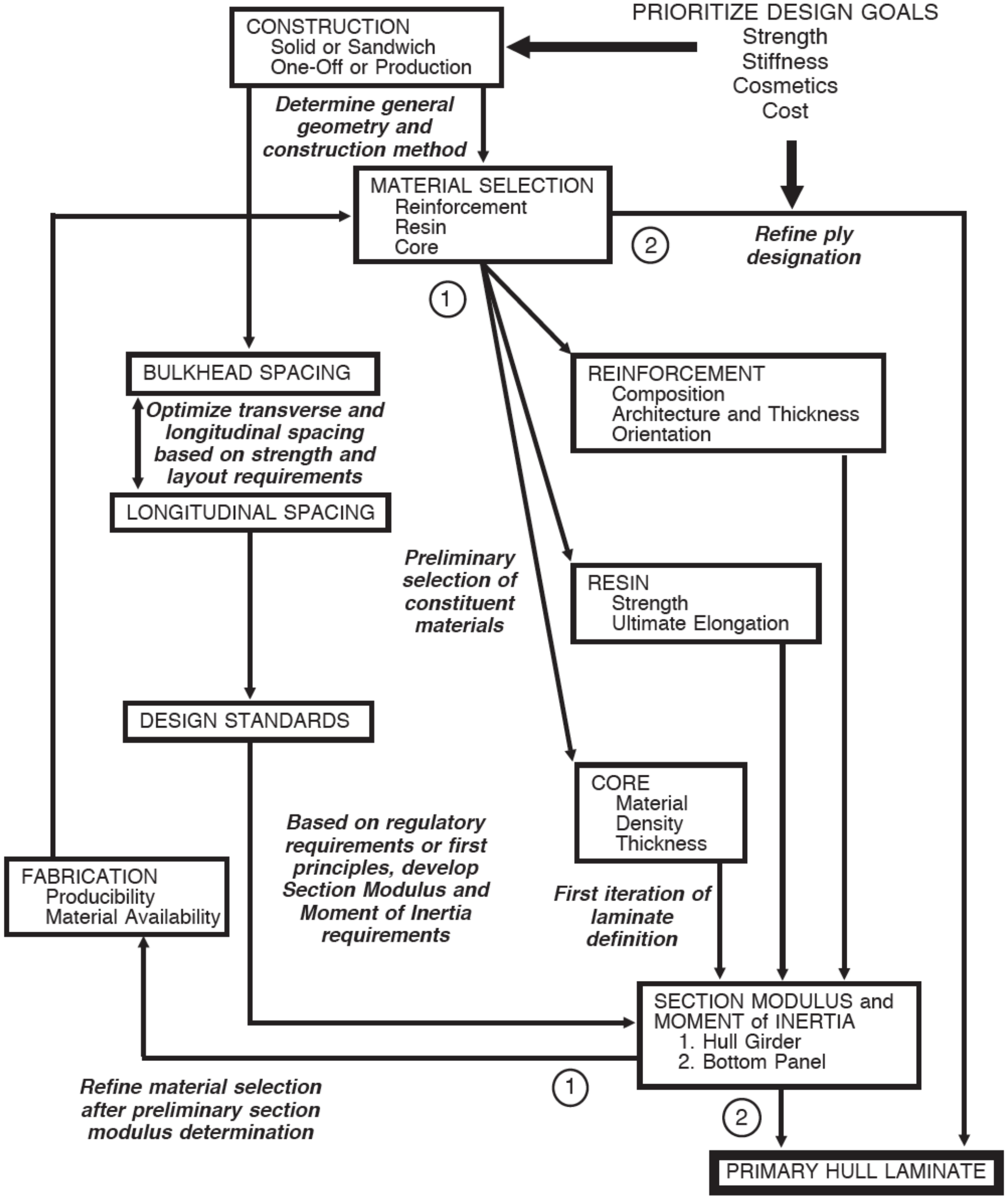
Gross Weight: 1,710,000 lbs
Empty Weight: ~1,200,000 lbs
Composites: ~700,000 lbs
Kevlar-Glass-Vinyl Ester
Length 247 feet
Composite cost: ~$100/lb
Design stress: ~25,000 psi

Types of Loads

Category	Specific Type
Static	combined in-plane loads (buoyancy, cargo)
	large out-of-plane loads (pressures, deflections)
	contact loads (docking, assembly, etc.)
	thermal loads (fire)
Dynamic	shock (>150m/sec) (air and water)
	structural dynamics (slamming, whipping, machinery, rigging)
	wave action, cavitation
	noise, acoustics
Fatigue	low cycle (dives)
	high cycle (whipping, vibration, waves)
Creep	hydrostatic
	equipment foundations
Environment	sea water corrosion
	water absorption
	fire and smoke
	UV exposure

from "*Use of Composite Materials in Load-Bearing Marine Structures*," 1990, National Research Council

Bottom Design Flow Charts



PRIORITIZE DESIGN GOALS
Strength
Stiffness
Cosmetics
Cost

CONSTRUCTION
Solid or Sandwich
One-Off or Production

Determine general geometry and construction method

MATERIAL SELECTION
Reinforcement
Resin
Core

Refine ply designation

BULKHEAD SPACING

Optimize transverse and longitudinal spacing based on strength and layout requirements

LONGITUDINAL SPACING

REINFORCEMENT
Composition
Architecture and Thickness
Orientation

Preliminary selection of constituent materials

RESIN
Strength
Ultimate Elongation

DESIGN STANDARDS

CORE
Material
Density
Thickness

FABRICATION
Producibility
Material Availability

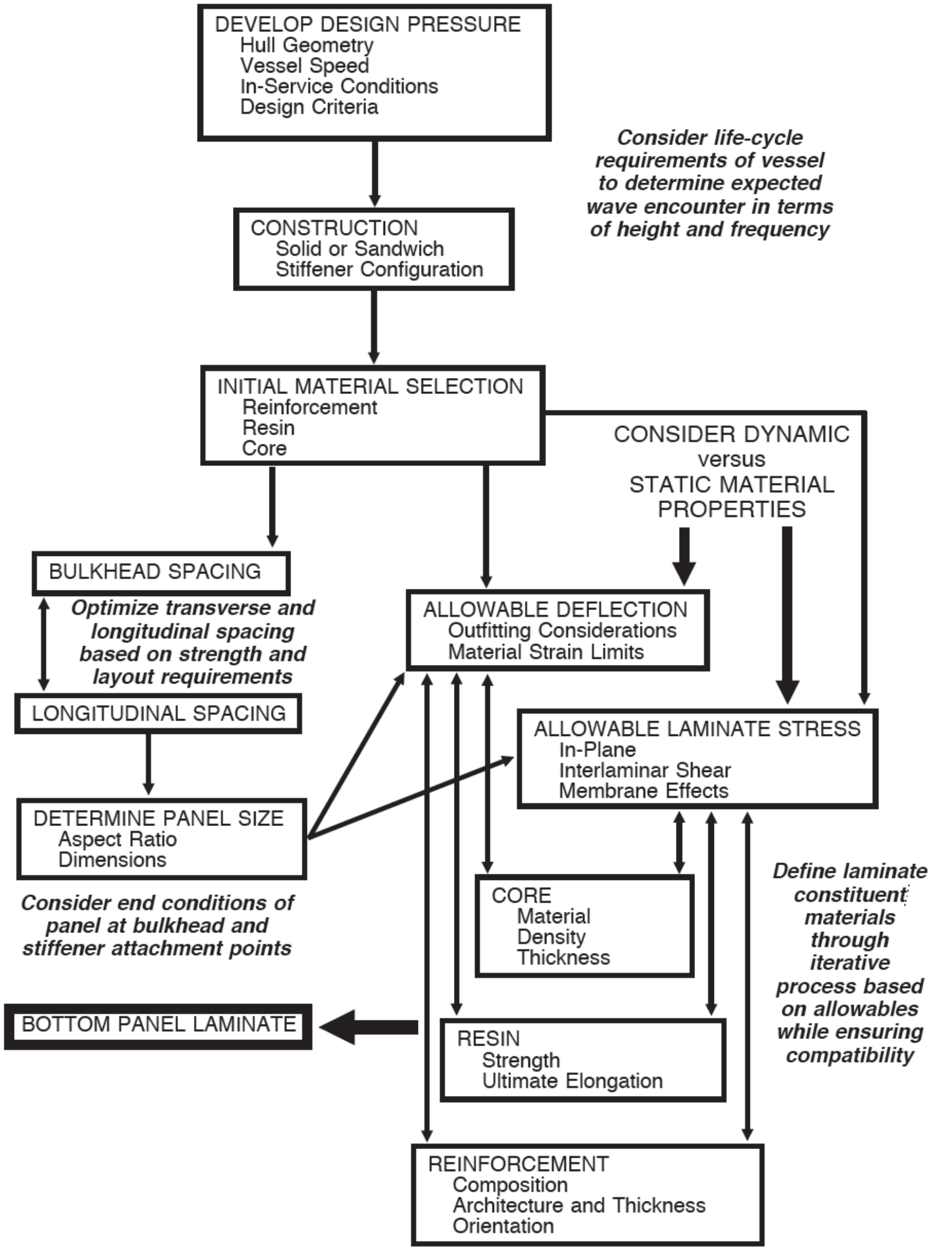
Based on regulatory requirements or first principles, develop Section Modulus and Moment of Inertia requirements

First iteration of laminate definition

SECTION MODULUS and MOMENT of INERTIA
1. Hull Girder
2. Bottom Panel

Refine material selection after preliminary section modulus determination

PRIMARY HULL LAMINATE



DEVELOP DESIGN PRESSURE
Hull Geometry
Vessel Speed
In-Service Conditions
Design Criteria

Consider life-cycle requirements of vessel to determine expected wave encounter in terms of height and frequency

CONSTRUCTION
Solid or Sandwich
Stiffener Configuration

INITIAL MATERIAL SELECTION
Reinforcement
Resin
Core

CONSIDER DYNAMIC versus STATIC MATERIAL PROPERTIES

BULKHEAD SPACING

Optimize transverse and longitudinal spacing based on strength and layout requirements

LONGITUDINAL SPACING

ALLOWABLE DEFLECTION
Outfitting Considerations
Material Strain Limits

ALLOWABLE LAMINATE STRESS
In-Plane
Interlaminar Shear
Membrane Effects

DETERMINE PANEL SIZE
Aspect Ratio
Dimensions

Consider end conditions of panel at bulkhead and stiffener attachment points

CORE
Material
Density
Thickness

Define laminate constituent materials through iterative process based on allowables while ensuring compatibility

BOTTOM PANEL LAMINATE

RESIN
Strength
Ultimate Elongation

REINFORCEMENT
Composition
Architecture and Thickness
Orientation

Determine In-Service Profile

USCG 47-foot Motor Lifeboat

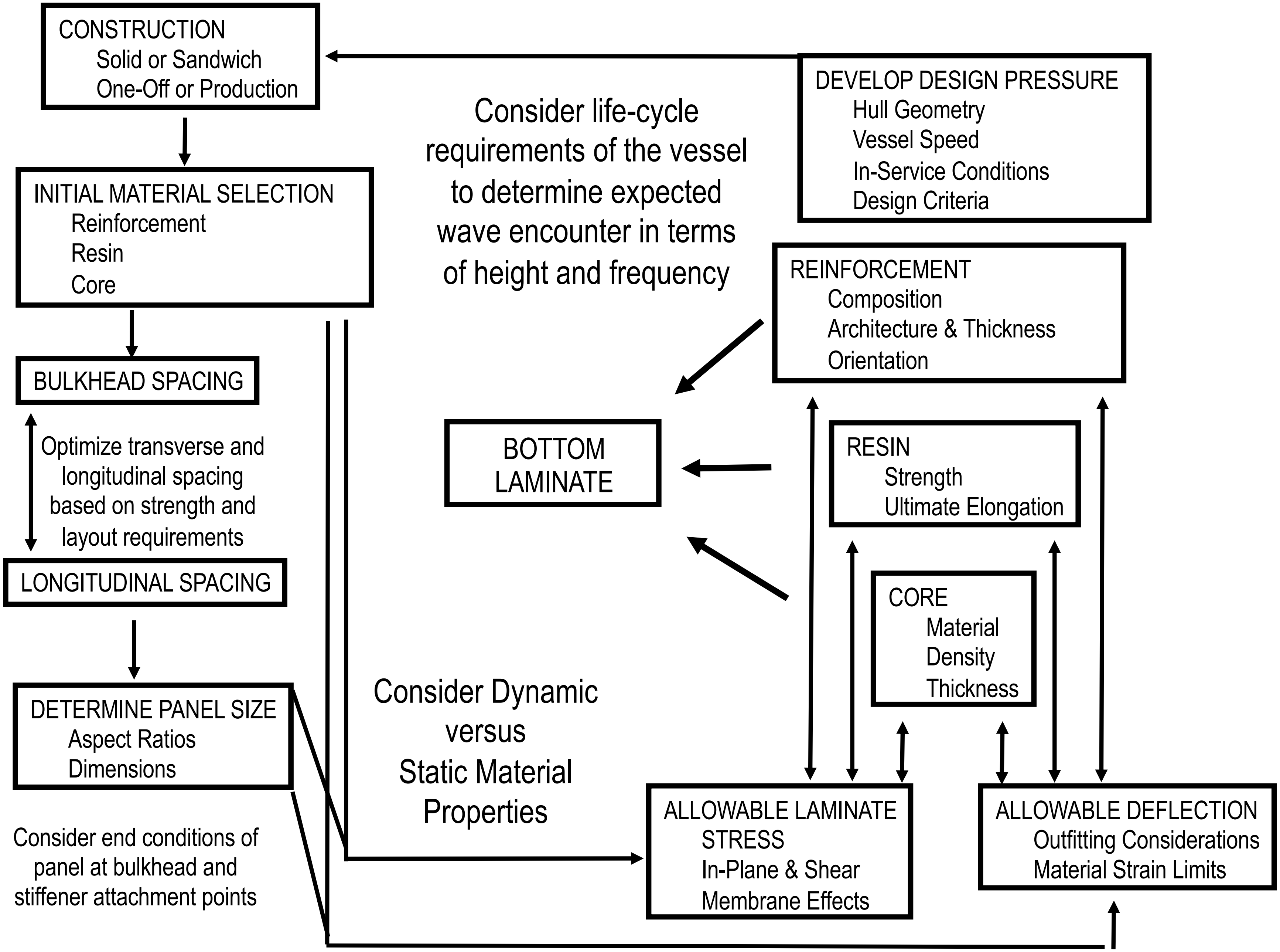
Larson 98 Model 226 LXI Advertised for Sale: "used very little"

America’s Cup

Oracle Team’s AC72 foils on her fourth day of testing. San Francisco, 1 October 2012. Photo: Guilain Grenier / Oracle Team USA

ORACLE TEAM USA chose Dassault Systèmes’ 3DEXPERIENCE platform applications to design and simulate the boat’s composites layups, which are critical to optimizing its strength/weight ratio. Dassault Systèmes’ claims the 3DEXPERIENCE platform integrates composites design, simulation and manufacturing solutions.

Bottom Laminate Design



CONSTRUCTION
Solid or Sandwich
One-Off or Production

INITIAL MATERIAL SELECTION
Reinforcement
Resin
Core

BULKHEAD SPACING

Optimize transverse and longitudinal spacing based on strength and layout requirements

LONGITUDINAL SPACING

DETERMINE PANEL SIZE
Aspect Ratios
Dimensions

Consider end conditions of panel at bulkhead and stiffener attachment points

Consider life-cycle requirements of the vessel to determine expected wave encounter in terms of height and frequency

DEVELOP DESIGN PRESSURE
Hull Geometry
Vessel Speed
In-Service Conditions
Design Criteria

REINFORCEMENT
Composition
Architecture & Thickness
Orientation

BOTTOM LAMINATE

RESIN
Strength
Ultimate Elongation

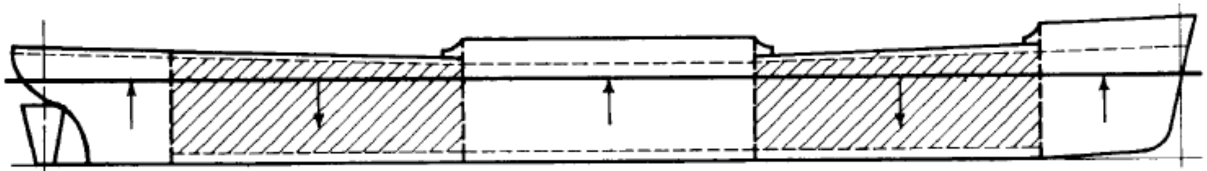
CORE
Material
Density
Thickness

Consider Dynamic versus Static Material Properties

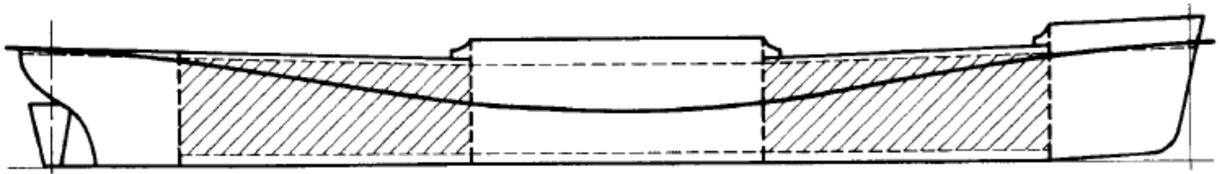
ALLOWABLE LAMINATE STRESS
In-Plane & Shear
Membrane Effects

ALLOWABLE DEFLECTION
Outfitting Considerations
Material Strain Limits

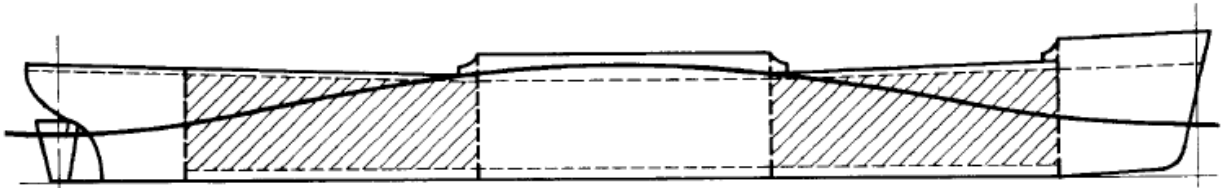
Hull as a Longitudinal Girder



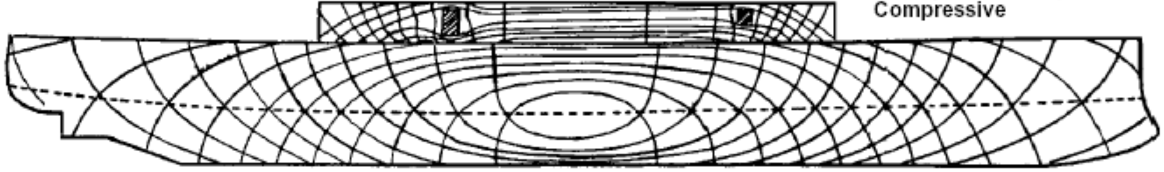
(a) VESSEL IN STILL WATER



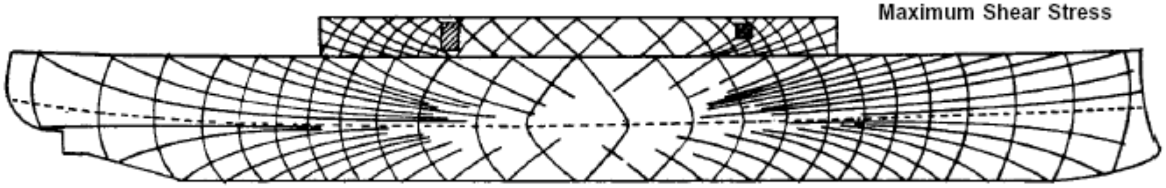
(b) VESSEL IN SAGGING CONDITION



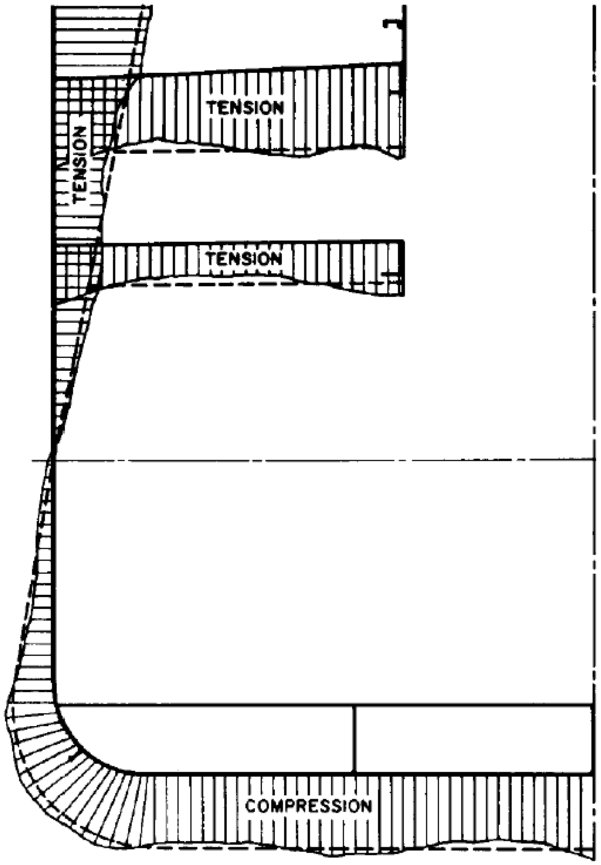
(c) VESSEL IN HOGGING CONDITION



Principal Stresses, Tensile and Compressive



Maximum Shear Stress



Vessel in Hogging Condition

Required Midship Moment of Inertia

$$I = \frac{L}{QC}\frac{SM}{K} \qquad \mathrm{cm}^2\text{-}\mathrm{m}^2$$

Material	Q	C	K, 10m	K, 30m	K, 50m	K, 70m	K, 90m
Steel	1.0 for ordinary steel 0.78 for H32 steel 0.72 for H36 steel	1.0	10.89	16.50	22.10	27.40	33.00
Aluminum	$0.9 + 115/\sigma_y$ $635/(\sigma_y + \sigma_u)$	0.9	3.63	5.50	7.37	9.13	11.00
Composites	$400/0.75\ \sigma_u$	0.8	0.36	0.55	0.74	0.91	1.10

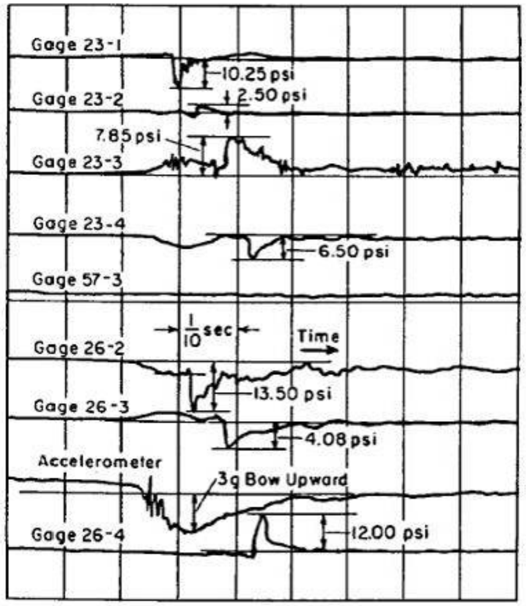
For composite laminates with modulus greater than ABS basic laminate, K may be adjusted by the ratio of E_o/E_b

ABS GUIDE for High Speed Naval Craft, 2007 Part 3 , Chp 2, Sect 1, Primary Hull Strength

Longitudinal Girder
Composite Material Concepts

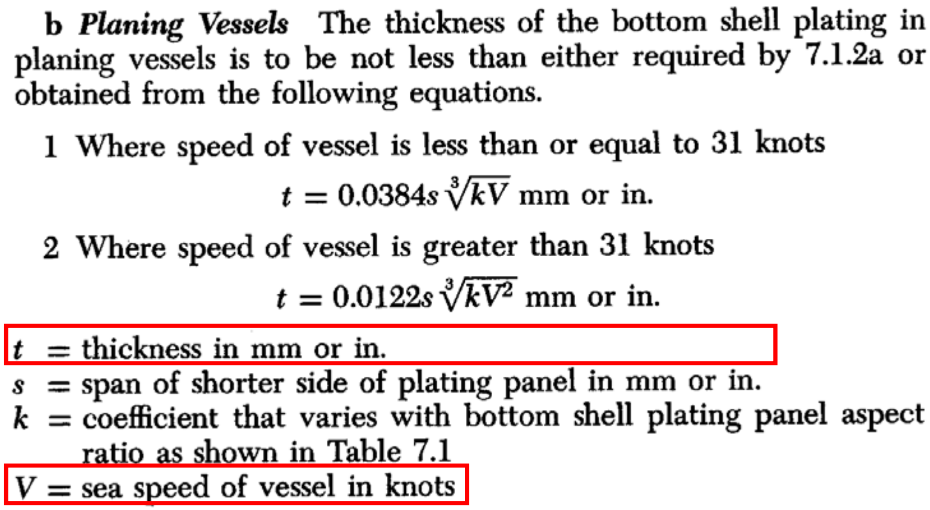
- Critical design consideration for long, slender hulls
- Consider hauling/blocking loads in addition to SWBM
- Longitudinal girder stiffness critical for propulsion shaft alignment in power boats and headstay tension for sailboats
- Unidirectional reinforcement on the top of longitudinal improves global as well as local strength and stiffness
- Maximize the use of longitudinal fibers in bottom and deck; use ±45° fibers (double-bias) near neutral axis
- Maximize the amount of continuous longitudinal reinforcement (without seams) in midship area

Develop Design Pressure



Pressures Recorded by Heller and Jasper on Patrol Craft at 28 Knots, 1960

Rule-Based Design Pressure



b ***Planing Vessels*** The thickness of the bottom shell plating in planing vessels is to be not less than either required by 7.1.2a or obtained from the following equations.

1 Where speed of vessel is less than or equal to 31 knots

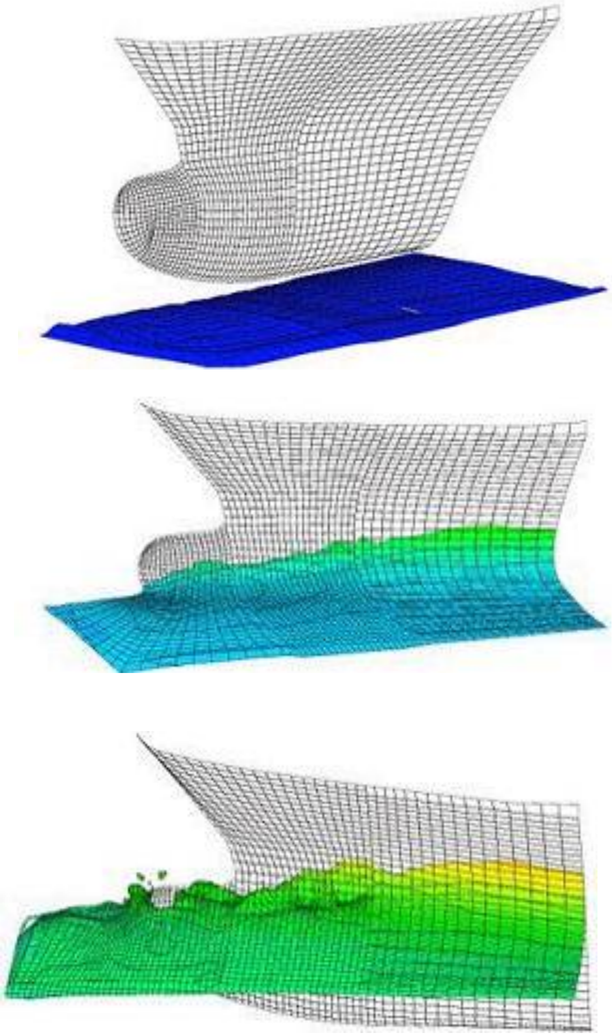
$$t = 0.0384s\sqrt[3]{kV} \text{ mm or in.}$$

2 Where speed of vessel is greater than 31 knots

$$t = 0.0122s\sqrt[3]{kV^2} \text{ mm or in.}$$

t = thickness in mm or in.
s = span of shorter side of plating panel in mm or in.
k = coefficient that varies with bottom shell plating panel aspect ratio as shown in Table 7.1
V = sea speed of vessel in knots

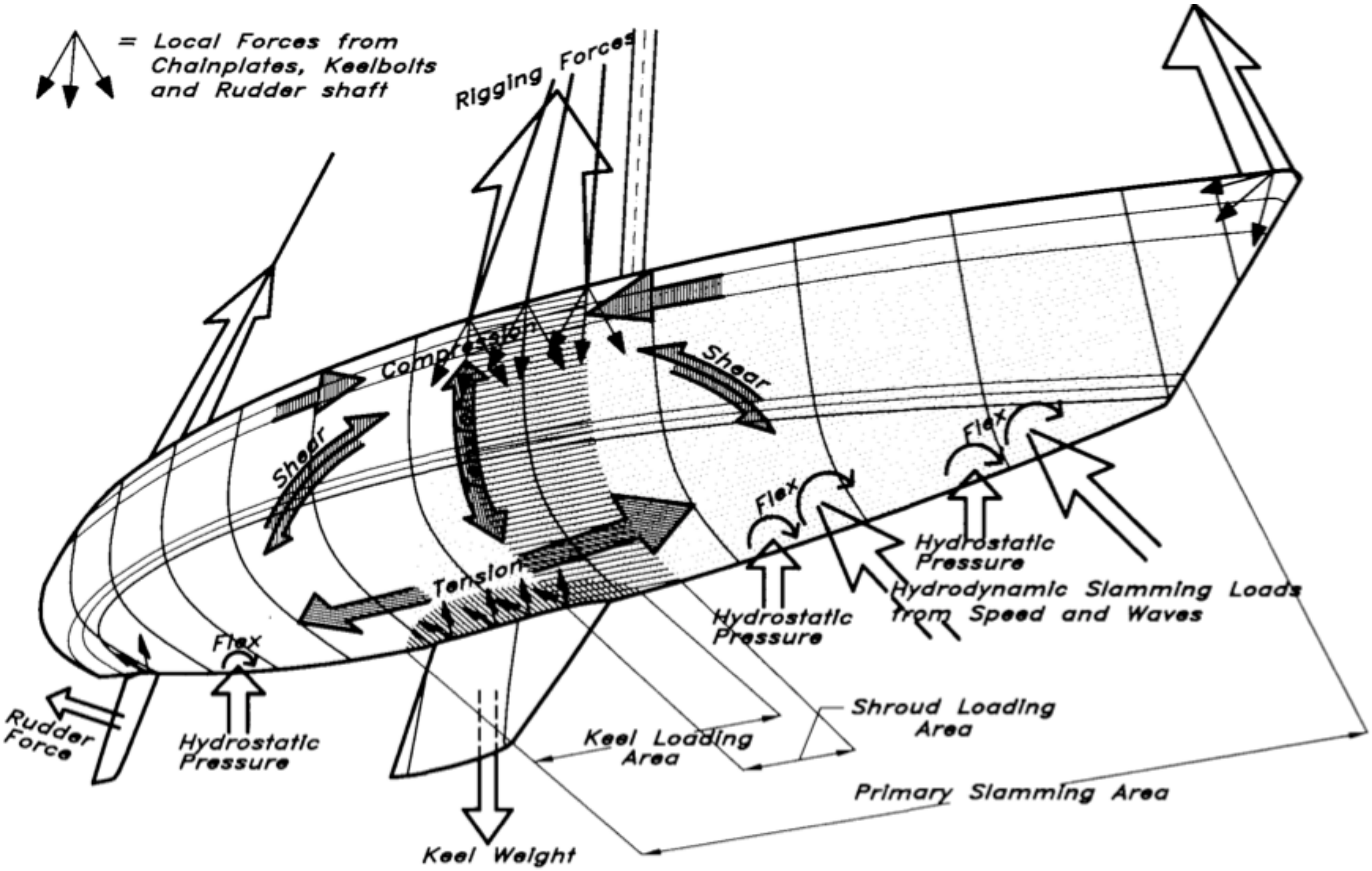
from *ABS 1978 Rules for Reinforced Plastic Vessels*, Section 7



Three-Dimensional Slamming Simulation by Germanischer Lloyd AG

Sailboat Hull Loads

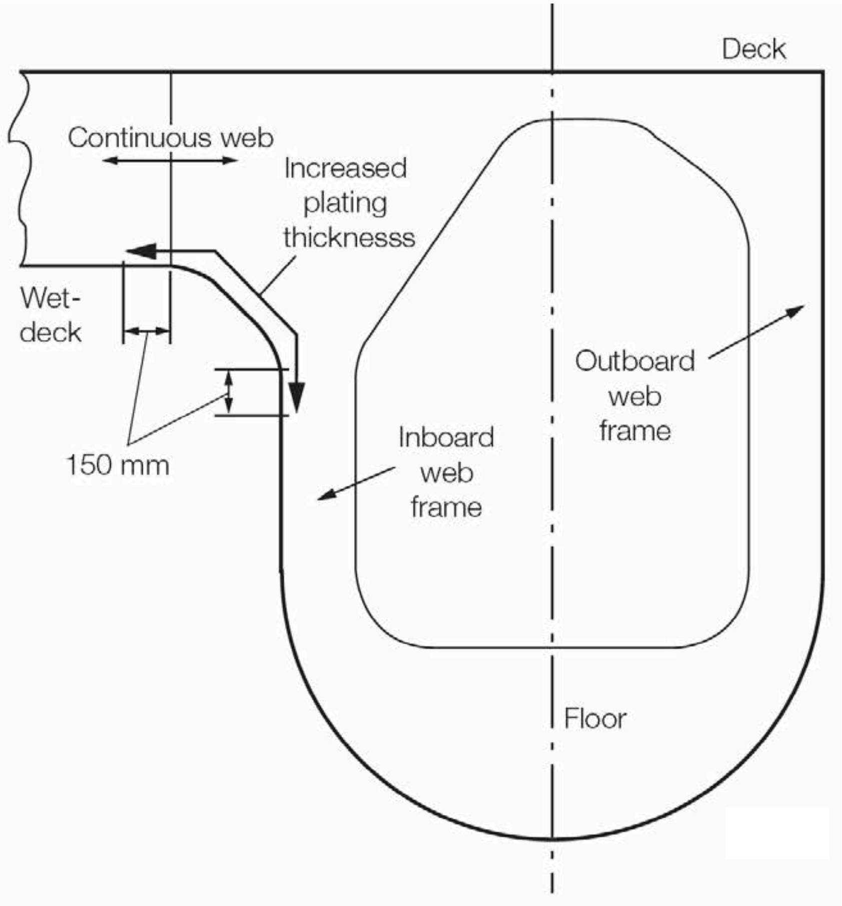
Loads acting on a vessel while under sail



Larsson, L. and Eliasson, R.E., Principles of Yacht Design, 1994, Camden, Maine, International Marine

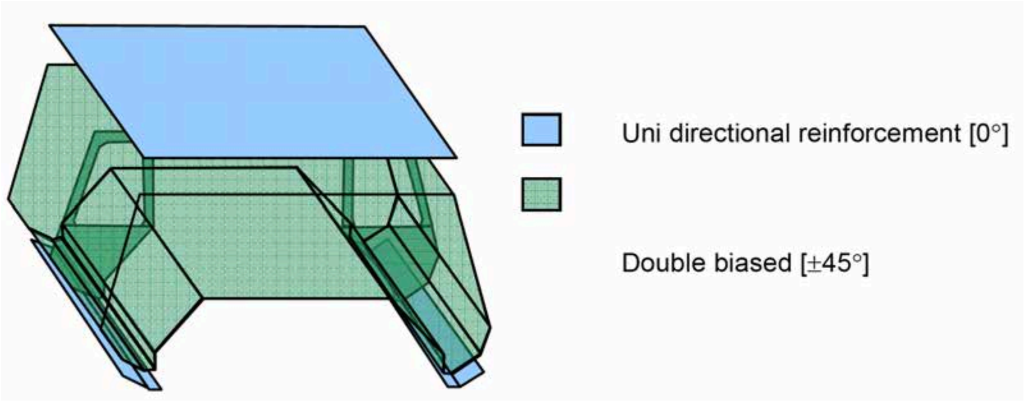
Multihull Structure

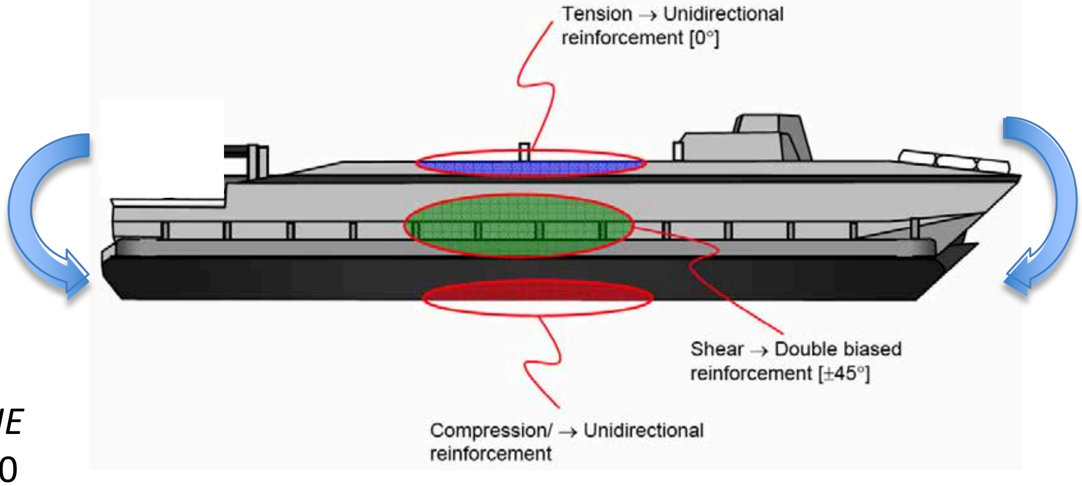
End connection detail, wet-deck structure



LLOYD'S REGISTER *RULES AND REGULATIONS FOR THE CLASSIFICATION OF SPECIAL SERVICE CRAFT*, July 2010
Scantling Determination for Mono-Hull Craft

Reinforcement architecture selected to resist global loads

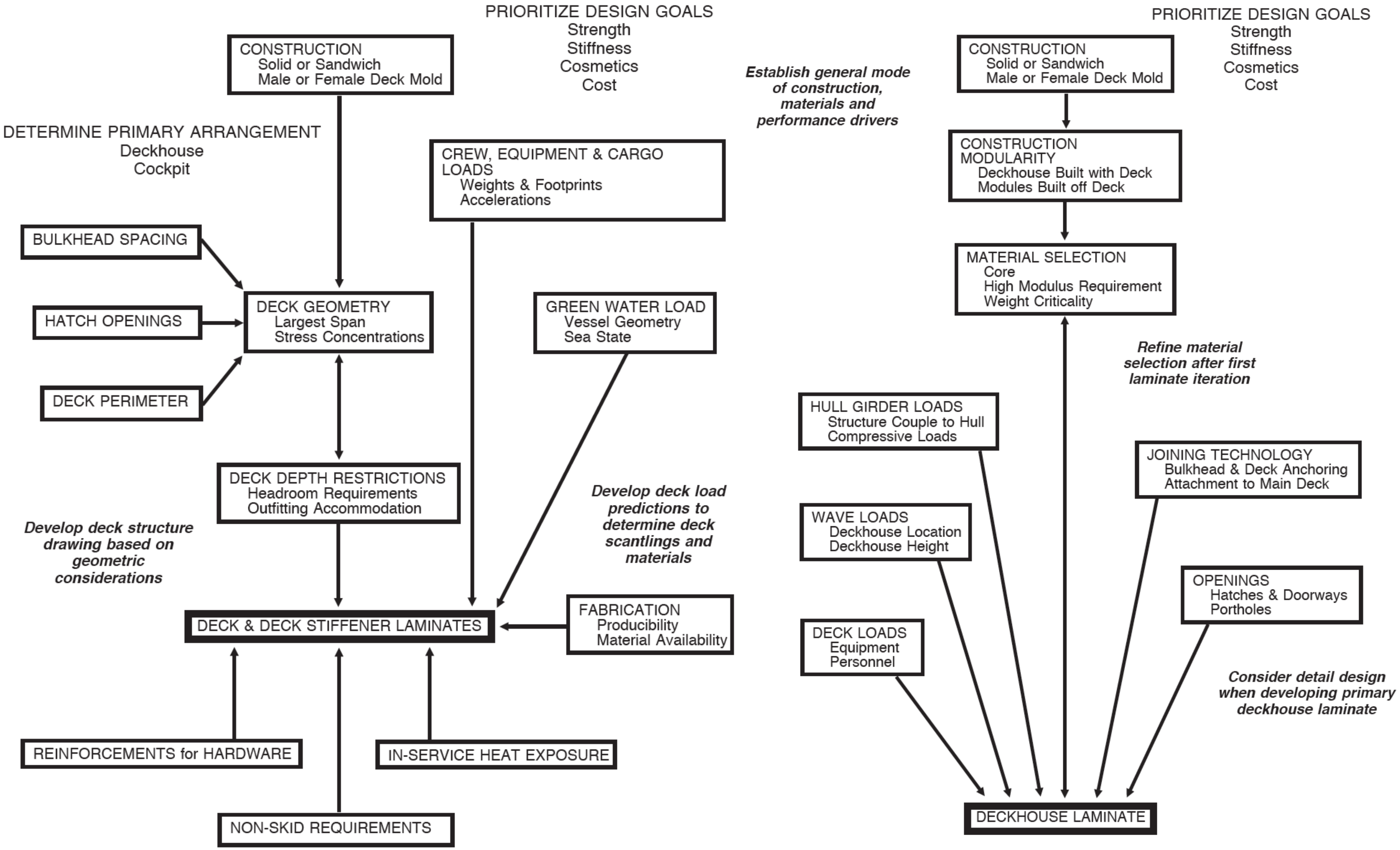




Multihull and Surface Effect Ship Considerations

- Torsional loads may be design-limiting for multihulls, SESs, and vessels with large deck openings
- ±45° fibers (double-bias) or unidirectionals aligned ±45° can be effective to resist torsional loads
- Ensure that ±45° fibers are continuous, minimizing butt joints
- For catamarans, the design transverse bending moment must be calculated to determine the load acting on the cross structure connecting the hulls
- Termination of multihull transverse structure at the main hulls is a critical design element

Deck Design Flow Charts



PRIORITIZE DESIGN GOALS
Strength
Stiffness
Cosmetics
Cost

CONSTRUCTION
Solid or Sandwich
Male or Female Deck Mold

DETERMINE PRIMARY ARRANGEMENT
Deckhouse
Cockpit

CREW, EQUIPMENT & CARGO LOADS
Weights & Footprints
Accelerations

BULKHEAD SPACING

HATCH OPENINGS

DECK PERIMETER

DECK GEOMETRY
Largest Span
Stress Concentrations

GREEN WATER LOAD
Vessel Geometry
Sea State

DECK DEPTH RESTRICTIONS
Headroom Requirements
Outfitting Accommodation

Develop deck structure drawing based on geometric considerations

Develop deck load predictions to determine deck scantlings and materials

DECK & DECK STIFFENER LAMINATES

FABRICATION
Producibility
Material Availability

REINFORCEMENTS for HARDWARE

IN-SERVICE HEAT EXPOSURE

NON-SKID REQUIREMENTS

Establish general mode of construction, materials and performance drivers

PRIORITIZE DESIGN GOALS
Strength
Stiffness
Cosmetics
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CONSTRUCTION
Solid or Sandwich
Male or Female Deck Mold

CONSTRUCTION MODULARITY
Deckhouse Built with Deck
Modules Built off Deck

MATERIAL SELECTION
Core
High Modulus Requirement
Weight Criticality

Refine material selection after first laminate iteration

HULL GIRDER LOADS
Structure Couple to Hull
Compressive Loads

JOINING TECHNOLOGY
Bulkhead & Deck Anchoring
Attachment to Main Deck

WAVE LOADS
Deckhouse Location
Deckhouse Height

OPENINGS
Hatches & Doorways
Portholes

DECK LOADS
Equipment
Personnel

Consider detail design when developing primary deckhouse laminate

DECKHOUSE LAMINATE

Typical Deck Live Loads

Type of Compartment	Live Load	
	kPa	Pounds/ft^2
Living & control spaces, offices (main deck & above)	3.59	75
Living spaces (below main deck)	4.79	100
Offices & control spaces (below main deck)	7.18	150
Shop spaces	9.58	200
Storerooms	14.36	300
Weather portions of main deck	11.97	250

Prioritize Design Goals

Strength

Norsafe Free-Fall Lifeboat

Stiffness

America's Cup Yacht STARS and STRIPES

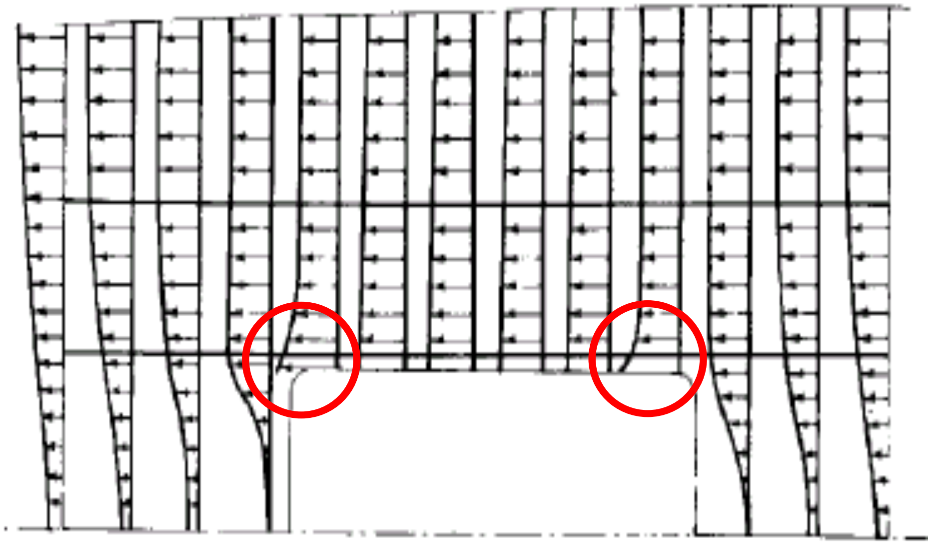
Cosmetics

Hinckley's Picnic Boat

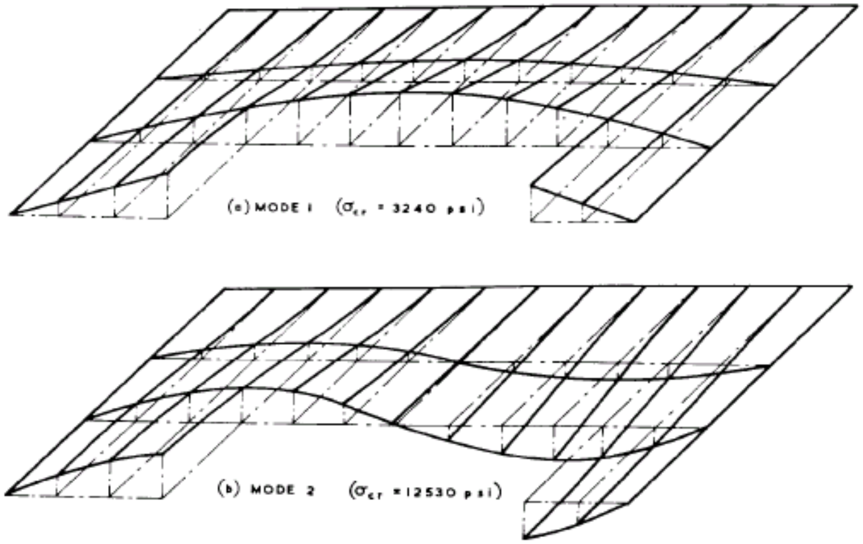
Cost

Sunfish Built by Vanguard Sailboats

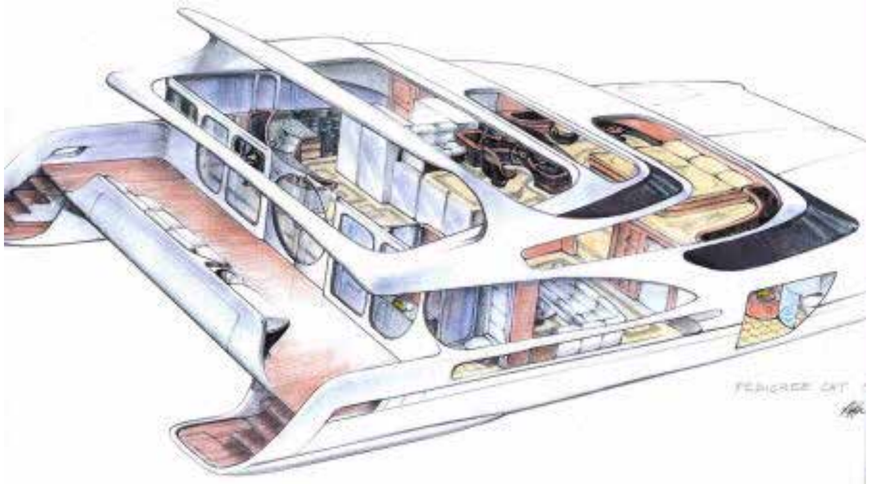
Develop Deck Geometry



Distribution of Longitudinal Stress at Hatch Opening from C.S. Smith



Deck Buckling Mode Near Hatch Opening from C.S. Smith



Pedigree 525 Catamaran Showing Spacious Interior (Styling by Phil Aylsworth)

Complex Deck Geometry

Fabrication Challenges – Ensure Fiber Wet-Out and Avoid Fiber Bridging

Infusion of Fathom 40 in Anacortes, WA, USA

Design Challenge – Avoid Stress Concentration

Production deck assembly built by Sabre Yachts

Initial Material Selection

Reinforcements

Parameter	E-Glass	Carbon	Kevlar®
Workability	Good	Fair	Fair
Cost	Excellent	Poor	Fair
Static Strength	Good	Excellent	Good
Dynamic Strength	Good	Good	Excellent
Elevated Temperature Performance	Good	Good	Fair

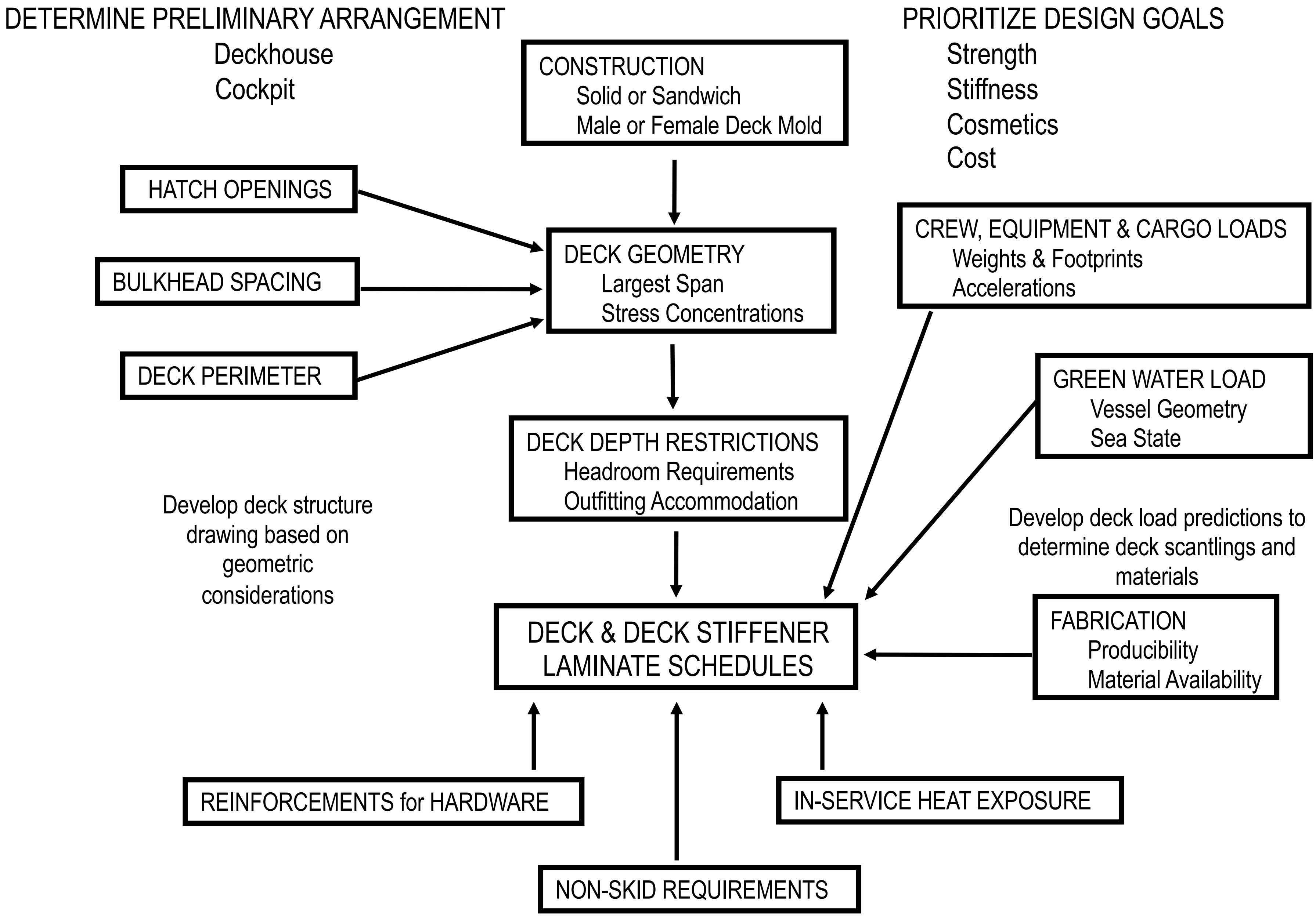
Resins

Parameter	Polyester	Vinyl ester	Epoxy
Workability	Excellent	Excellent	Good
Cost	Excellent	Good	Fair
Static Strength	Fair	Good	Excellent
Dynamic Strength	Fair	Good	Good
Elevated Temperature Performance	Fair	Good	Good

Cores

Parameter	Balsa	PVC Foam
Workability	Good	Good
Cost	Excellent	Good
Static Strength	Good	Fair
Dynamic Strength	Fair	Good
Elevated Temperature Performance	Good	Poor

Deck Laminate Design



DETERMINE PRELIMINARY ARRANGEMENT
Deckhouse
Cockpit

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Male or Female Deck Mold

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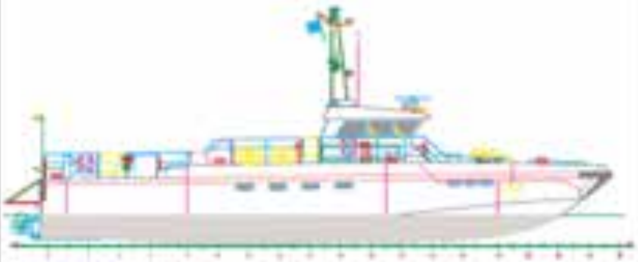
LASS Project



24 m all-composite passenger high-speed craft

88 m aluminum high speed catamaran with an FRP composite superstructure

199 m RoRo vessel with an aluminum deck house

188 m RoPax vessel with an FRP composite superstructure

The LASS project focused on developing lightweight fire protection systems for aluminum and composite construction. “Typical weight reduction when using aluminum or FRP composites have been over 50% compared to a conventional steel design and cost analysis has demonstrated possible pay-back times of 5 years or less for the lightweight material investment.”

The LASS project demonstrated that a 30% weight saving could be achieved for the maritime platforms shown.

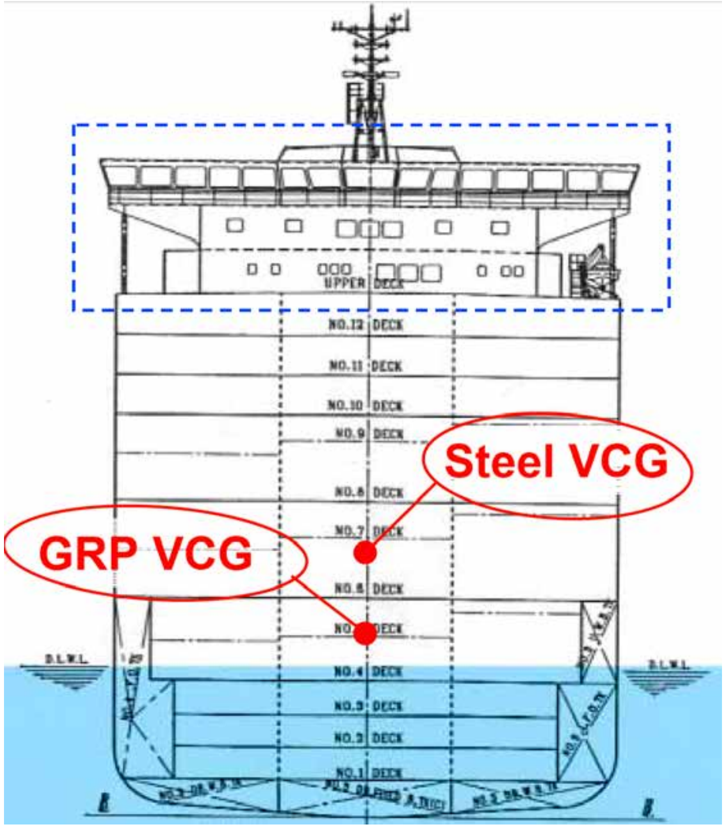
T. Hertzberg, LASS, Lightweight Construction Applications at Sea, SP Technical Research Institute of Sweden, Mar 2009.

Composite Superstructure

Aircraft Carrier Island

Projected weight savings: 15-19 LT
KG Improvement: 0.022

Commercial Ship Superstructure



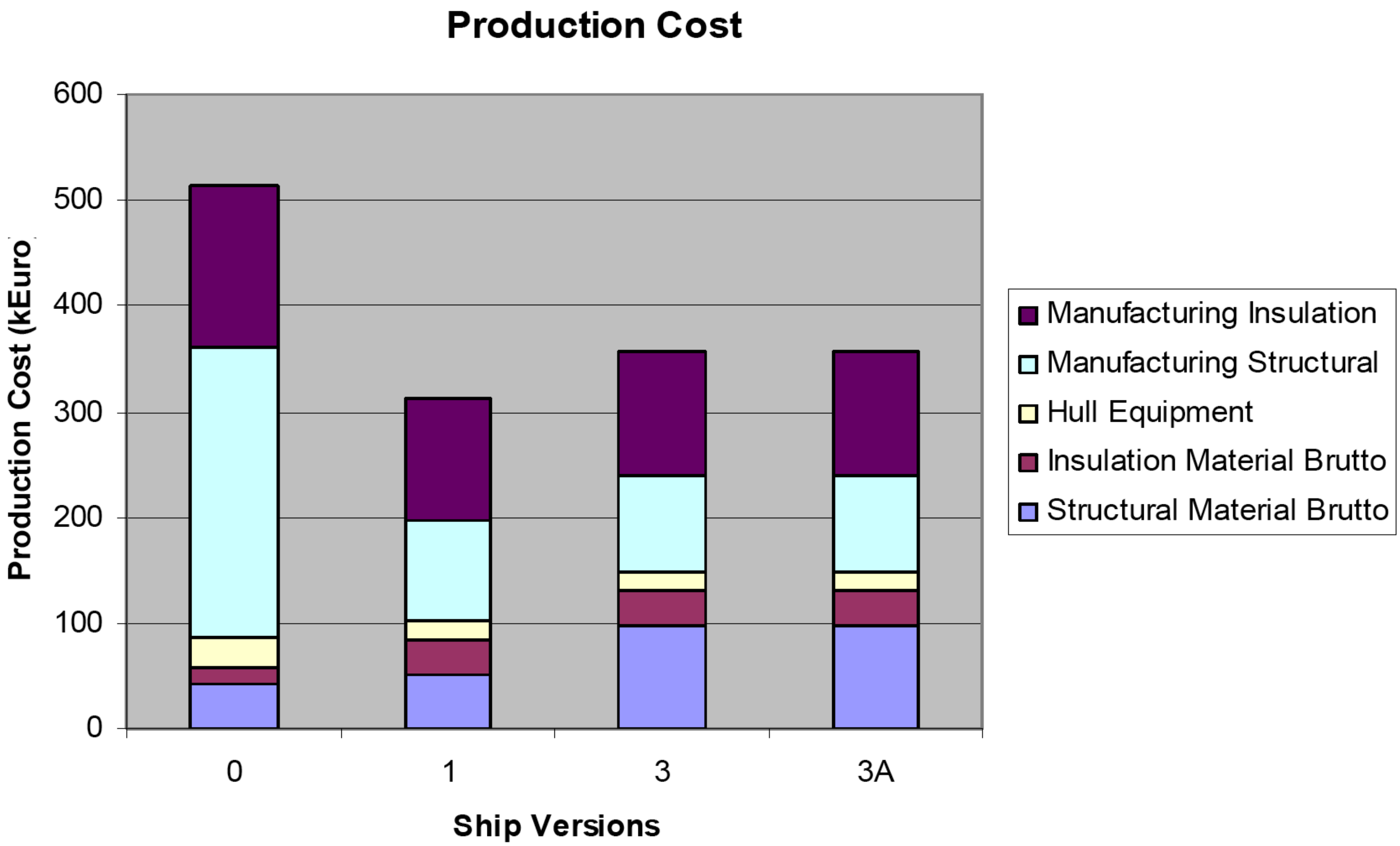
Steel superstructure weight ~ 600 tons,
GRP sandwich weight ~ 300 tons
[Robert Petersson, KOCKUMS, 2005]

Compare Manufacturing and Life-Cycle Costs

Version 0: aluminum.
Version 1: Sandwich with glass/vinylester.
Version 3: Sandwich with carbon/vinylester.
Version 3A: Version 3 with two water jet propulsions and 33% smaller fuel tank.

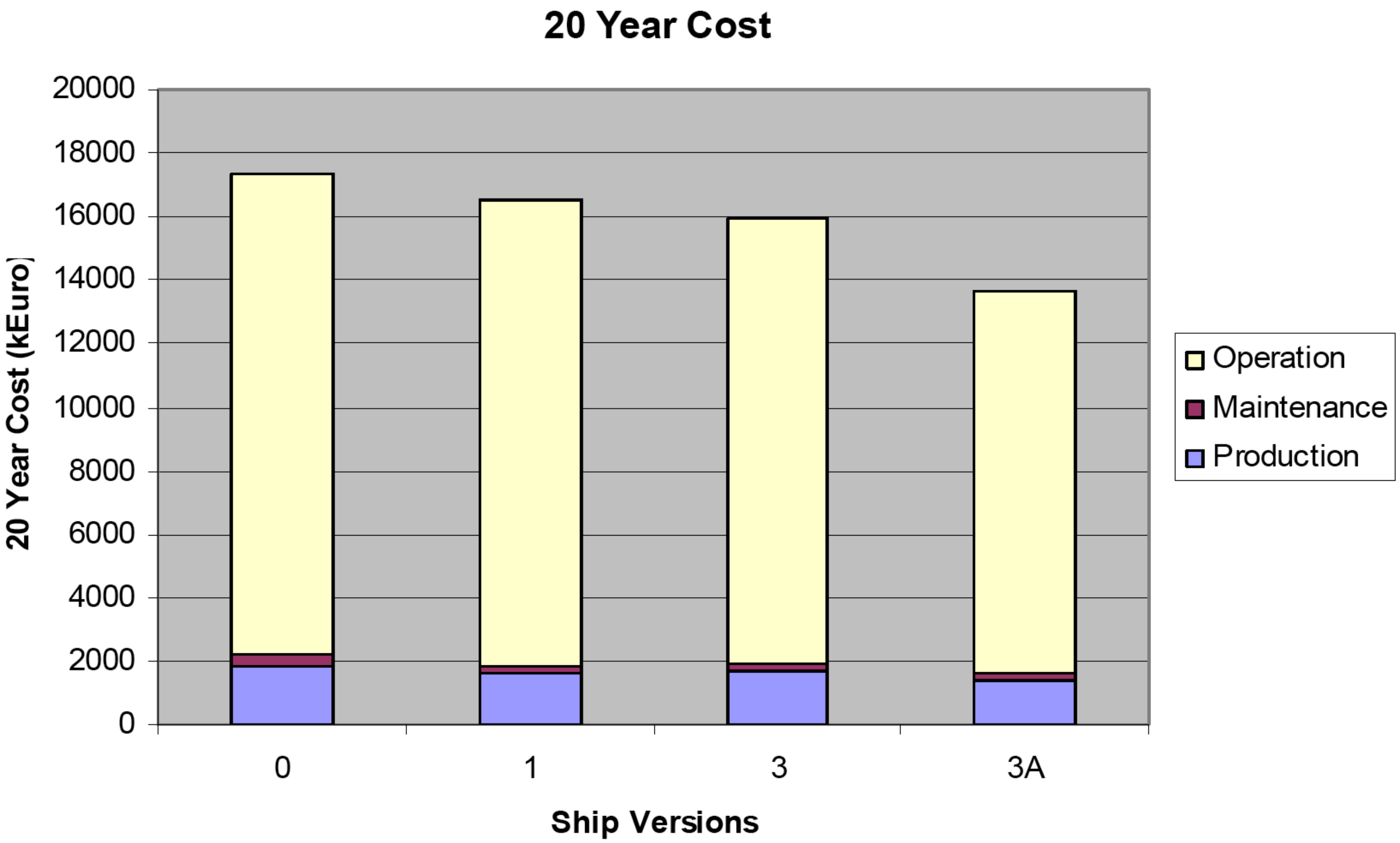
Kurt Olofsson, "Case study WP3a; a high-speed craft with composite hull," LASS-SP report 2009_13.

Compare Manufacturing Costs



Kurt Olofsson, “Case study WP3a; a high-speed craft with composite hull,” LASS-SP report 2009_13.

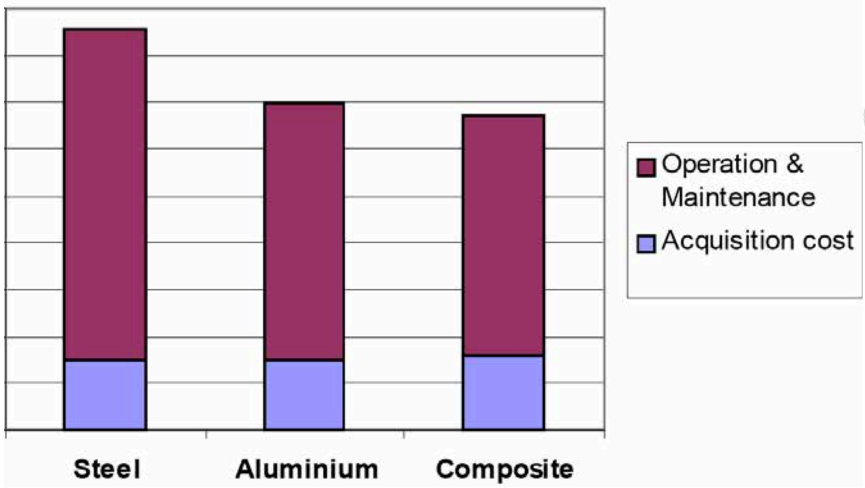
Compare Life-Cycle Costs



Kurt Olofsson, “Case study WP3a; a high-speed craft with composite hull,” LASS-SP report 2009_13.

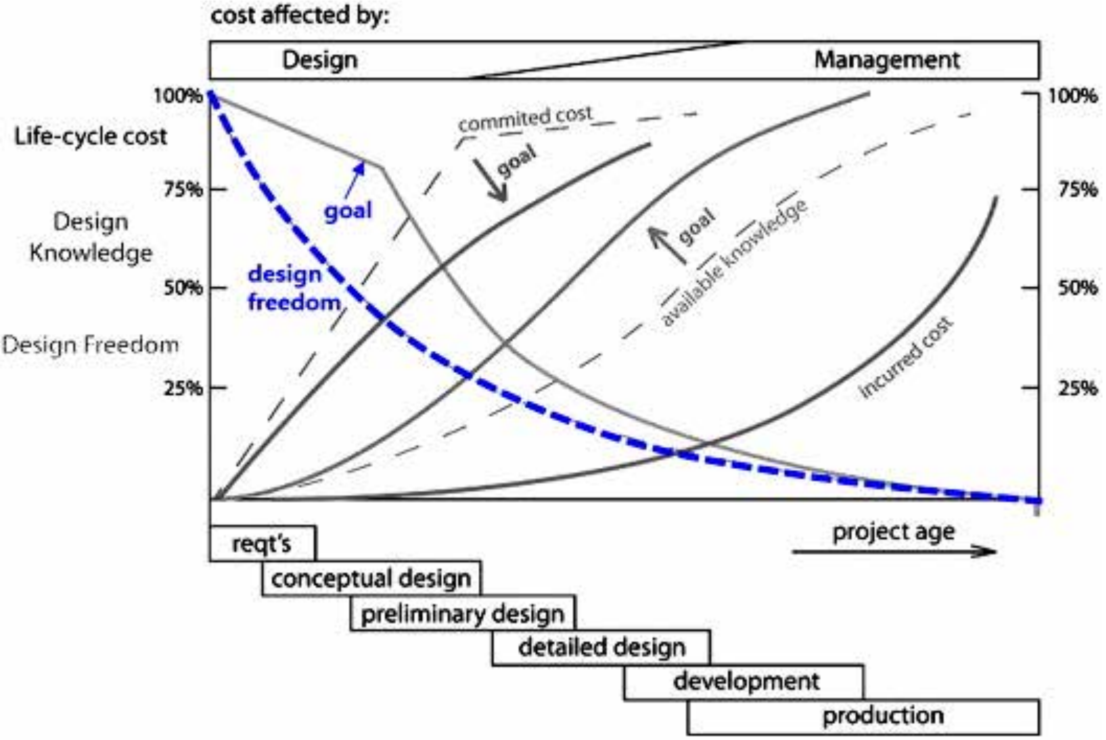
Life Cycle Cost

High Speed Ferry Life Cycle Cost Comparison



Robert Petersson, KOCKUMS, 2005

Product life-cycle cost related to the design process



Hee Jin Kanga, Young-Soon Yangb, Jin Choia, Jong-Kap Leea, and Dongkon Leea, “Time basis ship safety assessment model for a novel ship design,” Ocean Engineering, Volume 59, February 2013

Composite Boats

Annual growth rate of U.S. composites consumption in marine industry and boat unit sales [Lucintel]