LOADS, MATERIALS, AND HIGH STRENGTH/LIGHTWEIGHT STRUCTURES

Introduction

To design a marine vehicle, one must know the seaway and cargo loads, as well as the properties of the structural materials. Although a great deal is known about the seaway loads on conventional ships operating at slow to moderate speeds, the effects of high speeds are unknown. Similarly, the seaway loads on novel hull forms are currently unknown. Moderate to large size conventional ships are built of steel, a relatively low cost but high weight material. Smaller, weight-critical craft have been built out of aluminum and fiber reinforced plastic (FRP) composites since the 1950’s. Until now, however, there has not been a need to go to the lighter (more costly) materials for larger ships. The lightweight materials can save weight, which can be used to increase the ship's range or payload. Since the structural weight of a ship is about one third of its displacement, the potential payoffs in weight savings are substantial – in the thousands of tons. This workgroup was tasked to look at both the seaway loads and the structural materials which can be used for fast sealift ships in both the near-term (by 2002), mid-term, and far-term (after 2007).

Outline

This report will discuss in order seaway loads, metals and metallic structures, composites, and, finally, some promising technologies.

Seaway Loads

There are two kinds of seaway loads acting on ships: primary and secondary. Primary loads are bending and torsional moments which flex and twist the hull as if it were a beam or girder. The interaction of the wave buoyancy forces and the weight of the ship cause a bending in the vertical plane (hogging and sagging); see Figure 1. A bending in the transverse plane (lateral bending) and torsional twisting is caused by port to starboard differential buoyancy and rolling in oblique seas. A dynamic component (whipping) from slam impacts increases the vertical and lateral bending moments along the length of the ship. The slam-induced whipping is exacerbated by speed and, in some cases, can approach the magnitude of the wave-induced moments. All of the primary hull girder moments increase in proportion to the square of the length of the ship.

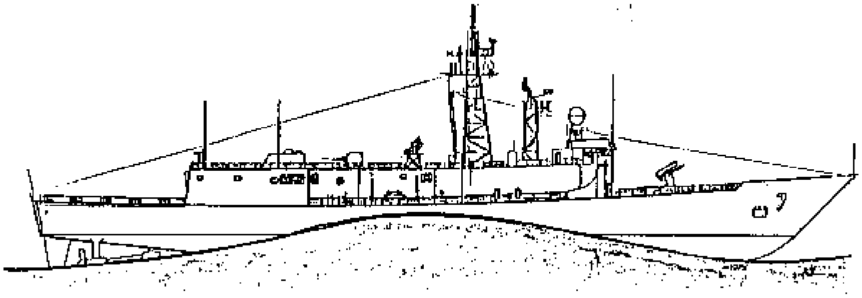

Figure 1 - Hogging Bending Moment

Secondary loads are the static and dynamic pressures acting on local structure. Hydrostatic pressures are caused by the head of water from passing waves and are functions of ship draft and sea state. At slam impacts, a hydrodynamic pressure is caused by large bow motions (pressures then act on the bottom of the bow as it reenters the sea or when the bow flare is immersed). Wave slapping pressures can be significant on the hull sides and transom. Green sea loadings occur when waves crash over the bow striking the weather deck and front of the deckhouse. All of these hydrodynamic pressures are functions of hull geometry and increase with ship speed and sea state.

Status of Loads Predictions

There are a number of analytical tools for predicting seaway loads. SMP95 is a linear strip theory code in the frequency domain that gives good results for the wave-induced portion of hull girder bending but is not applicable for whipping. QLSLAM, DYNRES, and LAMP are time domain codes that have the potential for including whipping in hull girder bending, but all are limited in one way or another. SLAM-2D can predict bow slamming pressures. All of the analytical codes were developed for conventional monohulls and have limited validation. They need significant validation (and possibly modification) for applications to novel hull forms.

Model tests can be used to predict primary and secondary loads for conventional and novel hull forms under extreme sea and operational conditions. The test data are analyzed and presented in a probabilistic format which can account for such variables as expected lifetime, sea conditions, and operational parameters. To attempt to design a ship outside of our current experience base, that is, operating at very high speeds or with a novel hull form, without model tests can lead to two unacceptable states: (1) under-predicting the loads so that the ship suffers significant (and possibly catastrophic) structural failure, and, (2) applying excessive factors of safety (to cover ignorance levels) leading to an overly heavy structure.

Load Reduction Methods

One approach to reducing the structural weight budget for a ship is to reduce the primary and secondary seaway loads. Smaller loads require less structure. Hull or bow forms which can reduce slamming not only save structural weight but can in all likelihood improve seakeeping and resistance. Since very long ships (over 300 meters) are severely affected by primary hull girder bending, one approach would be to articulate the hull into several smaller hulls linked together. Dynamic seaway loads can also be avoided by traveling below the surface, a shallow draft submarine. Detailed design studies must be performed to compare the structural weight effects against increased resistance.

Metals Overview

Larger ships are predominantly made of steel while smaller weight-critical ships (under 100 meters), are frequently made of aluminum. Aluminum has one third the density of steel and a fatigue allowable stress one half that of steel. At a first level approximation for ships governed by hull girder bending (ships over 100 meters long), aluminum can save one third of the structural weight of a steel vessel. There are no technical reasons why large ships cannot be fabricated from aluminum. However, aluminum is five to eight times more expensive than steel, and aluminum has relatively low resistance to fire. For a non-combatant, fire protection would be required in a few key locations.

Some of the high-strength steels are twice as strong (yield strength) as ordinary steel, yet they do not save much weight in large ships. The reason is that the high strength steels have very nearly the same fatigue allowable stresses as ordinary steel and hence require just as much material to resist hull girder bending. The extra strength can only be used to resist secondary loads. The fatigue limitations of aluminum and high strength steels result from their as-welded properties. Improved welding methods (or eliminating welding by adhesive joining methods) can increase the fatigue allowable stresses for both aluminum and high strength steels. For example, flush ground welding of aluminum increases the fatigue strength to two thirds that of ordinary steel resulting in a fifty-percent structural weight saving. Weight savings for high strength steels would be proportional to any increases in fatigue allowable stresses from advanced welding/joining techniques. Such advanced welding and joining techniques are certainly possible in the far term.

Sandwich Metals

Sandwich metal structures consist of two thin, face sheets of metal joined together by a corrugated core; see Figure 2. The separation of the face sheets provides high bending stiffness at a low weight. Stainless steel LASCOR panels have been used on Navy ships for over a decade to save weight for platforms, hanger doors, and enclosures.

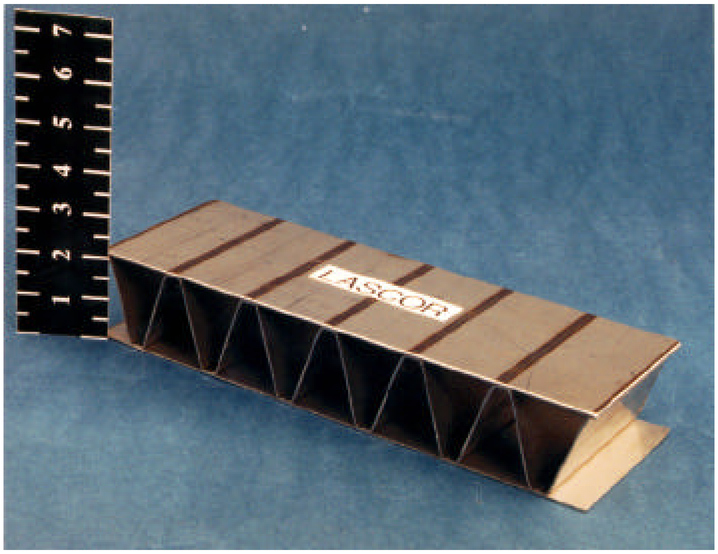

Figure 2 - Typical Metal Sandwich Panel

Sandwich metal structures have a number of advantages over conventional steel construction:

(1) Compared to conventional steel structures, metallic sandwich structures have reduced weight and increased stiffness. They are ideal for secondary structures such as internal decks, ramps, hatch covers, bulkheads, and deckhouses with weight savings of 20 to 50 percent over conventional steel construction.

(2) They provide reduced fabrication and outfitting costs. LASCOR panels are 20% cheaper to build and install than steel grillages. They have a high dimensional stability which helps reduce assembly and fit-up costs in the shipyard. Outfitting of distributive systems and installation of insulation costs are also reduced because of the smooth surfaces resulting from the elimination of most of the stiffeners.

(3) The elimination of stiffeners on decks and bulkheads increases the usable volume within the total ship.

(4) Metallic sandwich panels have improved thermal and fire performance. The space within the core offers inherent thermal insulation and protection against the spread of fires.

(5) The high stiffness of sandwich panels reduces vibrations. Panels can also be sound isolated from surrounding structures.

(6) Laser welded sandwich panels are ideal applications of automated fabrication techniques. They can be pre-fabricated as panels at high efficiency factories before shipboard installation in the shipyard.

One of the issues with sandwich structures is corrosion protection of the voids within the core. Stainless steel applications, currently used in the fleet, are one solution. They have suffered no corrosion or fatigue damage after a decade of service. Another solution, which has been successfully tested in the field with ordinary steels (carbon steels), is to fill the void spaces with foam. Although our experience is limited to steels, sandwich panels can also be made from corrosion tolerant metals such as aluminum or titanium. Such lightweight materials can further reduce structural weight and would be available in the mid-to far-term.

Other issues will be resolved as shipyard experience increases with metallic sandwich panels. Draft design standards exist but must be formally documented and approved by the Navy and regulators for commercial applications. The fatigue performance of sandwich panels must be further defined and validated. This will allow a reduction in the factors of safety now assumed, resulting in lighter more reliable structures.

In the far term, techniques to form complex shapes, not just flat or singly curved panels, must be developed and optimized. The ability to form hybrid metallic sandwich structures also has far term potential for weight and cost reductions.

Exotic Metals

Titanium has a yield strength higher than most high strength steels with a density of only 57 percent that of steel. The potential weight savings exceed that of aluminum and it has much better fire resistance as well. Titanium alloys have been used extensively in the aerospace industry in this country and have received some attention in the automotive industry. Timetal 10-2-3 (Ti-10V-2Fe-3Al) is used in the main landing gear of the Boeing 777. Timetal 15-3 (Ti-15V-3Cr-3Sn-3Al) has been used in environmental control system ducting, firefighting bottles, door springs, and small nut clips. This alloy has good formability and was used for more than one hundred formed parts on the B1B bomber. The superplastic alloy SP-700 has been used in place of stainless steel in steam turbine blades, hand tools, and golf club heads.

Titanium has already been used for submarines in the former Soviet Union. The biggest issue with titanium is its cost. It is thirty times more expensive than steel. In addition, it is more difficult to weld. And, it must be imported from Russia. Fatigue tests of welded components are needed to develop design criteria in order to design a titanium ship in the mid-to far-term time frames.

Magnesium and beryllium alloys are two of the more exotic metals which have not been used on ships but which have far term potential:

(a) Magnesium based alloys exhibit very low densities and high specific strengths. The density is approximately two thirds that of aluminum and one fifth that of steel. It has the best strength-to-weight ratio of any cast metal and exhibits good damping capacity, castability, machinability, corrosion resistance, and electromagnetic interference shielding properties. The chemical compositions and tensile properties of the most common Mg-based casting alloys are presented in Table 1. Mg-Al-Mn alloys constitute nearly 90 percent of all structural applications of magnesium. However, they are unsuitable for use above 150° C due to poor creep strength. Mg-Al-Si based alloys, such as AS41A, exhibit improved creep resistance up to 175° C while still maintaining good elongation, yield strength, and ultimate tensile strength. Although magnesium is subject to galvanic corrosion, the susceptibility can be reduced by careful control of alloy chemistry.

(b) Beryllium-aluminum alloys containing greater than 60 percent (by weight) beryllium are favorable materials for applications that require light weight and high stiffness. These alloys have 22 percent lower density than aluminum with three times the elastic modulus and a 40 percent lower coefficient of thermal expansion. Some aluminum-beryllium alloys have been developed for aerospace applications. The AlBeMet series of alloys was initially selected for a folding fin on the SR-71 Blackbird. The properties of some of the beryllium-aluminum alloys are presented in Table 2. AlBemet 162 is a promising alloy with a high cycle fatigue limit of 10^7 cycles at 30.5 ksi. It is immune to stress-corrosion cracking at 90 percent of yield stress in saltwater at 65° C for 169 hours and in salt at 315° C for 100 hours.

Table 1 - Properties of Cast Magnesium Alloys

Alloy	Composition (% Weight)			Tensile Properties		
	Al	Mn	Zn	Yield Strength (MPa)	Ult. Strength (MPa)	ε (%)
AZ91D	9.0	0.13	0.7	150	230	3
AM60B	6.0	0.13	-	115	205	6
AS41A	4.3	0.35	-	150	220	4
AE42	4.0	-	-	110	244	17
AZ91E-T6	8.7	0.13	0.7	145	275	6
SE41A-T5	-	-	4.2	104	205	3.5
ZC63-T6	-	0.25	6.0	125	210	4.0

Table 2 - Properties of Beryllium and Aluminum Alloys

Alloy	Elastic Modulus (GPa)	Density (g/cc)	Thermal Cond. (W/m-K)	CTE (ppm/K)
AlBeMet 162	200	2.1	210	13.9
AA6061	69	2.8	170	23.6
Beryllium	300	1.8	210	11.5
Alum-Lithium	90	2.5	120	23.6

Composites Overview

Composite structures consist of fiber reinforcements (such as E-glass or carbon) encapsulated in a resin matrix (such as vinyl ester or phenolic). Composite materials can be used to produce single skin, stiffened, or sandwich structures; see Figure 3. They have been used for primary structures on small vessels for many years. They are also applicable for secondary structures such as decks, foundations, doors and hatch covers, enclosures, deckhouses, stacks, and masts.

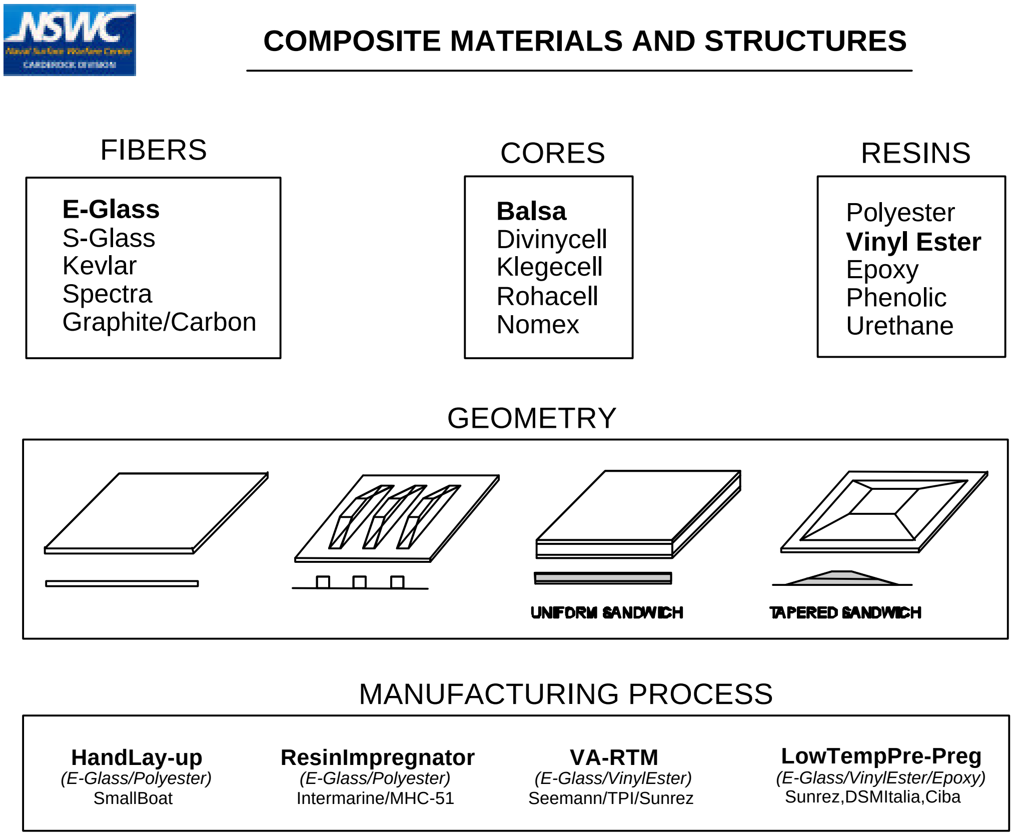

Figure 3 - Composite Structures

In the near term, E-glass and carbon composites are good for reducing weight in secondary structures but they have a low stiffness for the primary hull structure in large ships (over 100 meters). Long term, more exotic fibers may provide higher stiffness so composites, or composite-metallic hybrids, may be suitable for the primary structure of large or very large ships (over 300 meters).

Composites offer many advantages compared to standard metallic structures:

(1) They are lightweight. Weight reductions of 35 to 50 percent, compared to steel, can currently be realized for secondary structures made of E-glass. Since secondary structures comprise a significant fraction of the total structural weight, this translates into a total ship weight savings of about 8 percent of a large vessel (nominally 800 feet long).

(2) Composite structural elements have better dimensional stability than steel elements. This is an aid to the fit-up and assembly in the shipyard and results in lower fabrication costs and better overall dimensional tolerances.

(3) They have reduced noise and vibration properties. Composites have inherently better damping and compliance than metallic structures. They also have the potential to be adapted into smart structures, i.e. structures that can monitor and/or alter their properties in service.

(4) Fires are more easily contained in composite structures because of their low thermal conductivity. The cores in composite sandwich panels are good thermal insulators.

(5) The designer has increased flexibility to tailor the composite structure to the particular need. Complex geometries can be designed to optimize the strength, stiffness, or to enhance producibility by minimizing the number or location of joints.

(6) Composites have lower life cycle maintenance costs than steel structures. Fewer inspections, less painting, and fewer repairs are needed over the life of the ship because of the reduced corrosion and fatigue damage of composites over metallic structures.

There are a number of issues associated with composites:

(1) Flammability, smoke, and toxicity dangers are concerns that are foremost with composites. They are handled in several ways. For unmanned spaces in secondary structures not subject to severe fire threat, a thin thermal barrier coating, no coating, or passive fire protection may be used. For manned spaces in secondary or primary structure, thermal protective insulation is used. Research has shown the potential of multi-layered, balsa-cored sandwich structures for containing fires and preventing structural collapse or excessive deflections. The French combatant *La Fayette* uses

balsa-cored sandwich construction for this purpose. Also, the potential use of phenolics and other fire retardant resins has been demonstrated for small fires burning for 20 to 30 minutes.

(2) Composite designs are normally limited by stiffness, not strength. For hybrid structures, such as a composite deckhouse on a steel hull, the lower stiffness results in lower stresses and better fatigue performance. However, for the primary hull structure of large ships, the low stiffness may be a problem for conventional propeller shafts. Other propulsors (such as waterjets, electric drive, and podded propulsion) may render this issue moot.

(3) Conventional composite fabrication processes are quality control critical. Because of this issue, new fabrication processes such as vacuum assisted resin transfer methods (VARTM) have been developed to provide consistent quality control from part to part.

(4) There are limited design data and analytical tools. Design data and tools are becoming increasingly available for more common materials (e.g., glass polyester or vinylester) and for structural configurations, joints, and fabrication processes. However, in most cases, experimental validations are still needed.

(5) There is minimal large ship experience. The largest composite ship hulls are those of naval minehunters and minesweepers, with lengths of 50 to 60 meters.

(6) Inspection and repair methods are generally available for most composite structures. However, inspection can become difficult for thick, sandwich structures.

Summary of Material Properties

The following is a summary of the material properties as they currently exist. It is expected that as composites become more widespread, their unit costs will decrease in the far term. The following unit costs are material costs only. Producibility issues and fabrication costs are not included in this summary. In general, the structural material costs of a steel ship are very small compared with fabrication, installation, and equipment/machinery costs. Relative stiffness is represented by Young's Modulus (Modulus of Elasticity).

Table 3 - Material Properties Summary

Material	Density Lb/ft^3	Yield Strength Ksi	Young's Modulus Ksi	Fatigue Stress Ksi	Fire Resistance	1995 Costs $/Lb
ABS Grade A steel	491	34	29,600	20	Good	0.29
ABS Grade AH steel	491	55	29,600	20	Good	0.34
Aluminum (5086-H34)	166	16-22	10,000	10	Poor	1.65
Titanium	280	140	16,500		Fair	10.00
Sandwich Panel-LASCOR (stainless steel)	245-320	55	29,600	20	Good	
Composite Resins						
- Vinyl Ester	70	11-12	490		Poor	1.74
- Phenolic	72	5	530		Good	1.10
- Epoxy	75	7-11	530			3.90
Composite Fibers						
- E-glass	162	500	10,500			1.14
- S-glass	155	665	12,600			5.00
- Carbon-PAN	110	350-700	33-57,000			12.00
- Kevlar 49	90	525	18,000			20.00
Composite Cores						
- Balsa	7	1.3	370	N/A	Insulator	3.70
- Honeycomb Nx HRH-78	6	N/A	60	N/A		13.25
Composite Laminates						
- Solid Glass/Polyester	96	20	1,400			2.50
- Glass/Poly Balsa Sandw.	24	6	400			4.00
- Glass/VinE PVC Sandw.	18	6	400			5.00
- Solid Carbon/Epoxy	97	88	8,700			10.00
- Carbon/Epoxy Nomex	9	9	500			20.00

A more realistic comparison of the various materials is their net effect in a structure. Tables 4 through 7 (Reichard, 1988) present the relative weights of panels having equal stiffness and equal strength under both in-plane (axial) and bending loads. Composites are more advantageous than steel or aluminum when compared on an equivalent strength basis rather than on stiffness basis.

Table 4 - Panels of Equal In-Plane Stiffness*

Material	Skin Thick. (inch)	Core Thick. (inch)	Elastic Modulus (ksi)	Weight (lb/sqft)
Steel	0.08	0	30,000	3.36
Aluminum	0.25	0	10,000	3.62
E-Glass (0,90)	1.14	0	2,200	9.99
Kevlar (0,90)	0.60	0	4,200	4.49
Carbon (0,90)	0.35	0	7,200	2.87
Uni-E-Glass	0.57	0	4,400	4.99
Uni-Kevlar	0.30	0	8,400	2.24
Uni-Carbon	0.17	0	14,400	1.43
E-Glass/Core (0,90)	0.57	5	2,200	15.15
Kevlar/Core (0,90)	0.30	3	4,200	7.59
Carbon/Core (0,90)	0.17	1.75	7,200	4.68
Uni-E-Glass/Core	0.28	3	4,400	8.09
Uni-Kevlar/Core	0.15	1.5	8,400	3.79
Uni-Carbon/Core	0.09	1	14,400	2.47

* All panels have a stiffness of 2.50 pounds*inch

Reichard, Ronnal, P., "Material Selection for Boats and Ships," Second International Conference Marine Applications of Composite Materials, Florida Institute of Technology, Melbourne FL, 21-23 March, 1988.

Table 5 - Panels of Equal In-Plane Strength*

Material	Skin Thick. (inch)	Core Thick. (inch)	Yield Strength (ksi)	Weight (lb/sqft)
Steel	0.19	0	80	7.56
Aluminum	0.26	0	58	3.74
E-Glass (0,90)	0.34	0	44	3.00
Kevlar (0,90)	0.25	0	60	1.89
Carbon (0,90)	0.14	0	105	1.18
Uni-E-Glass	0.17	0	88	1.50
Uni-Kevlar	0.13	0	120	0.94
Uni-Carbon	0.07	0	210	0.59
E-Glass/Core (0,90)	0.17	1.75	44	4.80
Kevlar/Core (0,90)	0.13	1.25	60	3.18
Carbon/Core (0,90)	0.07	0.75	105	1.96
Uni-E-Glass/Core	0.09	1	88	2.53
Uni-Kevlar/Core	0.06	0.5	120	1.46
Uni-Carbon/Core	0.04	0.5	210	1.11

* All panels have a maximum strength of 15.00 lbs/inch width

Table 6 - Panels of Equal Flexural Stiffness*

Material	Skin Thick. (inch)	Core Thick. (inch)	Mom. of Inertia (inch^4)	Weight (lbs/sqft)
Steel	0.74	0	0.0335	29.74
Aluminum	1.06	0	0.1004	15.39
E-Glass (0,90)	1.76	0	0.4543	15.46
Kevlar (0,90)	1.42	0	0.2386	10.71
Carbon (0,90)	1.19	0	0.1387	9.80
Uni-E-Glass	1.40	0	0.2262	12.25
Uni-Kevlar	1.13	0	0.1196	8.51
Uni-Carbon	0.94	0	0.0697	7.79
E-Glass/Core (0,90)	0.23	2	0.4539	6.04
Kevlar/Core (0,90)	0.16	1.75	0.2380	4.15
Carbon/Core (0,90)	0.15	1.375	0.1385	3.83
Uni-E-Glass/Core	0.15	1.75	0.2272	4.41
Uni-Kevlar/Core	0.13	1.375	0.1185	3.31
Uni-Carbon/Core	0.11	1.125	0.0692	2.96

* All panels have a stiffness (EI) of 1.00 pound-inch^2

Table 7 - Panels of Equal Flexural Strength*

Material	Skin Thick. (inch)	Core Thick. (inch)	Yield Strength (ksi)	Weight (lbs/sqft)
Steel	0.19	0	80	7.56
Aluminum	0.26	0	58	3.74
E-Glass (0,90)	0.34	0	44	3.00
Kevlar (0,90)	0.88	0	17	6.65
Carbon (0,90)	0.14	0	105	1.18
Uni-E-Glass	0.17	0	88	1.50
Uni-Kevlar	0.44	0	34	3.33
Uni-Carbon	0.07	0	210	0.59
E-Glass/Core (0,90)	0.12	1.25	44	3.47
Kevlar/Core (0,90)	0.20	2	17	5.09
Carbon/Core (0,90)	0.09	0.75	105	2.19
Uni-E-Glass/Core	0.09	0.875	88	2.46
Uni-Kevlar/Core	0.15	1.375	34	3.61
Uni-Carbon/Core	0.05	0.625	210	1.52

* All panels have a maximum moment capacity of 7.50 foot*pounds

Summary of Weight Savings

Following is a summary of the projected weight savings for the various materials in the near, mid, and far terms. All of the weight savings are relative to ordinary steel (ABS grade A) of conventional stiffened plate construction. The percentage reductions are applied to the structural weight (SWBS 100) of the entire ship.

Table 8 - Summary of Weight Savings (Percent)

Material	Near Term	Mid Term	Far Term
Aluminum	30	30 - 40 with new alloys	50 with improved joining technologies
Titanium & Advanced Metals	High Risk	40 - 55 secondary structure, 15 overall	20 - 60 overall
Metal Sandwich (LASCOR)	35 - 50 secondary structure, 10 overall (steel)	40 - 55 secondary structure, 15 overall (steel)	45 - 60 secondary struct, 20 - 30 overall (hybrid metals)
Composites (300' ship length)	20 - 40 with Glass or Carbon fibers	30 - 45 with Glass or Carbon fibers	35 - >65 with new fibers & resins
Composites (800' ship length)	8 with Glass or Carbon fibers	35 - 45 with Glass or Carbon fibers	50 - >65 with new fibers & resins

Summary of Required Technology Development

The following is a summary of the technologies which must be developed to use the various materials and structural concepts in the near, mid, and far terms.

Table 9 - Technology Development Needs

Material	Near Term	Mid Term	Far Term
Aluminum	State-of-the-Art for ship lengths < 300', untried >300'	new alloys with better fatigue properties	improved joining technology for better fatigue properties
Titanium & Advanced Metals	no time for multi-year R&D effort	define fatigue & strength properties	improved joining tech. for shipyards
Metal Sandwich (LASCOR)	approved design standards & rules (steel)	validate fatigue properties & improve corrosion resistance	form complex shapes & develop hybrid metal applications
Composites (300' ship length)	State-of-the-Art for ship lengths < 200', better fire resistance	improved & validated design tools	develop high strength fibers & resins
Composites (800' ship length)	improve fabrication methods	improve inspection & repair methods	experimental validations

In addition, there are a number of other technologies that may become available for far-term applications. These technology thrusts include smart structures, adaptive structures, fiber placement/resin infusion, automated welding/joining, modular vessel components, and improved analytical/design methods. They are not only being pursued to reduce structural weight in future ships, but may also be effective in improving performance, enhancing fatigue and corrosion properties, reducing costs, and improving system reliability. Limited work is going on in these technologies around the world and in different industries, but it is not directed toward high speed transport ships. The industries developing such technologies include aerospace, transportation, infrastructure, electronics, and offshore. A comprehensive approach is needed to develop and transition these technologies to fast sealift ships in the far term.

Conclusions

There are several structural and material technologies that can beneficially impact high-speed, sealift ships in significant ways. Since there are multiple technology paths, it is likely that at least some of them will be sufficiently developed in the future for sealift ships. However, a serious commitment is needed to develop these technologies. One of the important requirements is experimental validation in the marine environment so that these technologies can be used with confidence. The potential payoffs are significant, on the order of thousands to tens of thousands of tons of structural weight. These weight savings can be used for increasing fuel capacity or payloads.