THE SOCIETY OF NAVAL ARCHITECTS AND MARINE ENGINEERS
One World Trade Center, Suite 1369, New York, N.Y. 10048
Papers to be presented at Extreme Loads Response Symposium
Arlington, VA, October 19–20, 1981

Selection of Structural Materials for Extreme Loads Environments

Robert H. Sterne, Jr., Lukens Steel Co., Coatesville, PA

ABSTRACT

A variety of ferrous and non-ferrous metals are used in the construction of large ocean going vessels. The purpose of this paper is to generally review available structural materials and highlight characteristics which are critical in extreme loads environments.

Specific material properties are reviewed in light of the evolution of manufacturing technology with resultant improvements in such factors as strength, notch toughness, and fatigue resistance.

The scope of the paper includes treatment of steel, aluminum, copper and cupronickel alloys and titanium. Specifications which are currently available for designer's use are reviewed as a function of yield and tensile strength.

BACKGROUND

A search of the historical records shows that the first metal-hulled ship built in the USA was launched in 1825. The Codorus was plated with iron rolled by the Brandywine Iron and Nail Factory in Coatesville, Pennsylvania. She was built in York, Pennsylvania and steamed up the Susquehanna River on her maiden voyage (Figure 1).

FIGURE 1

Measuring 60 feet in length, the Codorus drew only six inches of water. Those first hull plates measured 1/4" by 24" x 37", while the boiler itself used 3/8" thick plate (Figure 2).

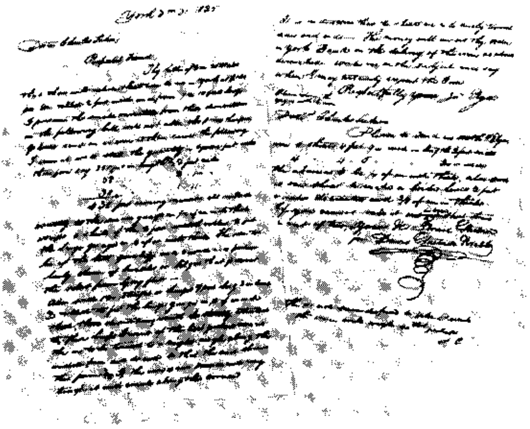

FIGURE 2

There was no hull steel specification--

all of that came later.

EVOLUTION

Following the Codorus, a long line of larger vessels were built, first with iron plated hulls, and later with steel. Through the nineteenth century and into the twentieth, riveting was the predominate method of joining metal plate together to form the structure.

The American Bureau of Shipping (ABS) was incorporated in 1862, and began the technical process of writing rules for shipbuilders and designers. The 1980 rules(1) referenced in this paper apply to ocean going vessels 61 m (200 feet) and over in length.

A separate set of ABS rules exists for Building and Classing Offshore Mobile Drilling Units(2), originally published in 1968, and revised in 1973 and in 1980.

Rules for aluminum vessels were last published in 1975. In addition, a number of ABS publications describe Rules for Barges(3), Floating Dry Docks(4), Underwater Systems and Vehicles(5), and Great Lakes Ore Carriers(6).

Further, ASTM(7) has adopted ABS materials specifications, and API publishes steel specifications(8) for offshore drilling platforms. And this is just for the USA. Other countries have their own (although similar) rules.

MATERIALS CHARACTERISTICS

It's obvious from what has just been described that there is a high degree of complexity to both shipbuilding rules and the materials specifications that are permitted for construction.

However, this symposium has been assembled to address extreme loads. From the standpoint of materials application, extreme loading can be addressed in light of the following characteristics which can be written into the specification (Figure 3).

Materials Characteristics

- Tensile and Yield Strength
- Fabricability
- Notch Toughness
- Fatigue Resistance
- Lamellar Tearing Resistance

FIGURE 3

STRENGTH REQUIREMENTS

The sort of loading anticipated will dictate to some degree the strength level of the material. The size of the structure and its response to the sea state is another important factor. Within the confines of other desired properties, economics will have a bearing.

Subsea structures are subjected both to compressive and tensile loads, but must also be designed with buoyancy in mind, where higher strength to weight ratio materials have an advantage. Here, yielding often is the key characteristic.

In short, selection of the proper level of yield or tensile strength depends on the integration of the other design criteria into the particular hull or other structure.

FABRICABILITY

Today, the vast majority of metals used in marine structures are welded together. Coupled with the need for forming, tensile ductility is a necessary ingredient in any metal used for hulls, platform legs, or for the pressure hull of submersibles.

Shipyard welding conditions are usually far from ideal, with little control over metal temperature, wind, precipitation and other environmental conditions. Metals used, thus, should have a high level of tolerance to these varied conditions. One current Ship Structure Committee project is directed at improving the weldability of ship hull steels of 50 KSI yield strength(9) at high heat inputs.

Tolerance for fabrication errors is another desired characteristic. A recent Ship Structure Committee report (10) puts further definition on this problem.

High strength (>60 KSI minimum Y.S.) and non-ferrous materials generally require environment control in the fabrication process.

NOTCH TOUGHNESS

Brittle fracture (Figure 4) has been recognized as probably the leading cause of ship materials failures since World War II(11 and 12). The amount of materials research and development work done to solve this problem is staggering, and has resulted in numerous improvements in specifications through the adoption of both steelmaking and testing safeguards.

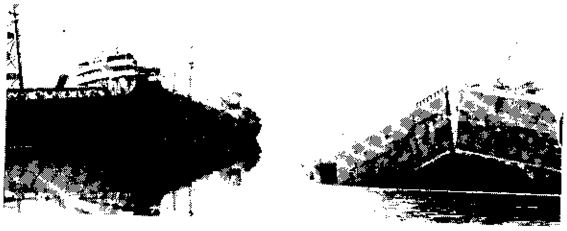

FIGURE 4

Notch toughness--the ability of metals to resist brittle fracture--was recognized as an essential materials characteristic in the 1945-1950 time period. Specification changes have been gradually made since that time requiring testing to establish a minimum level of notch toughness in certain critical hull areas. The Charpy V-notch test has been used as the primary qualification test (Figure 5 and Figure 6).

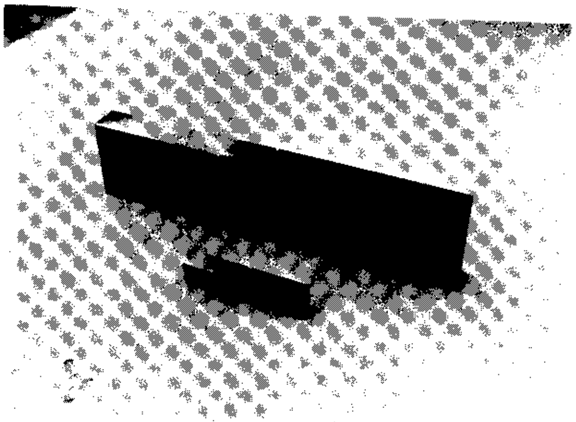

FIGURE 5

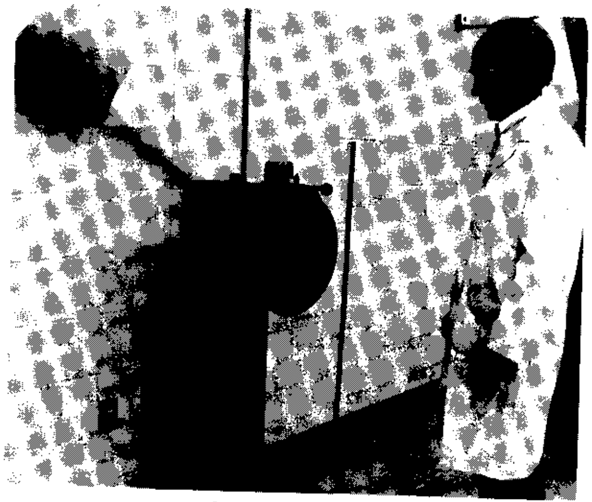

FIGURE 6

Development of more sophisticated test methods has continued in the last twenty years. The Fracture Analysis Diagram (Figure 7) approach advanced

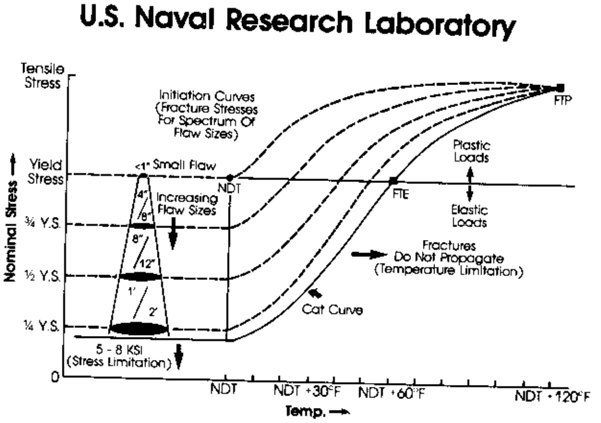

FIGURE 7

by Pellini and co-workers relied on the Drop Weight Test--a "go, no-go" test that established a lower temperature boundary below which steel plates were considered to be brittle(13) (Figure 8).

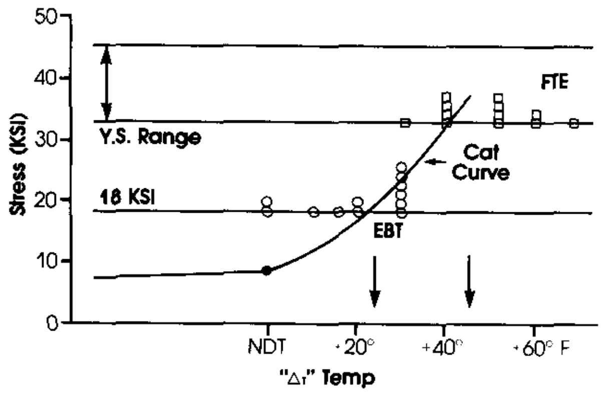

FIGURE 8

Reference 13 more completely explains the concept of the fracture analysis diagram and its application to ship structures.

The dynamic tear test was developed at the U.S. Naval Research Laboratory to provide a more quantitative measurement of notch toughness, and to overcome the deficiencies of the Charpy V-notch test; i.e., a relatively blunt notch and a short crack run. Although it is not currently used as an acceptance test, a reasonable correlation has been established between dynamic tear and the Charpy V-notch data(14) (Figure 9).

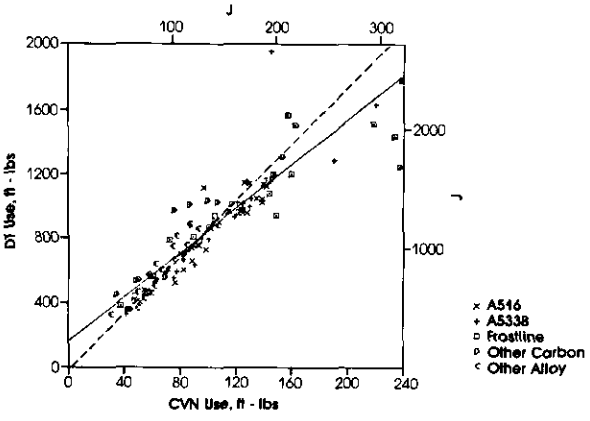

FIGURE 9

This has allowed designers to specify levels of notch toughness that can correlate more closely with their expectations of the loading which the marine structure will experience.

Improvements in manufacturing methods such as vacuum degassing, desulfurization and consumable remelting have allowed the designer to specify higher levels of notch toughness. Shown here are some of the available manufacturing methods to produce higher quality levels through melting (Figure 10).

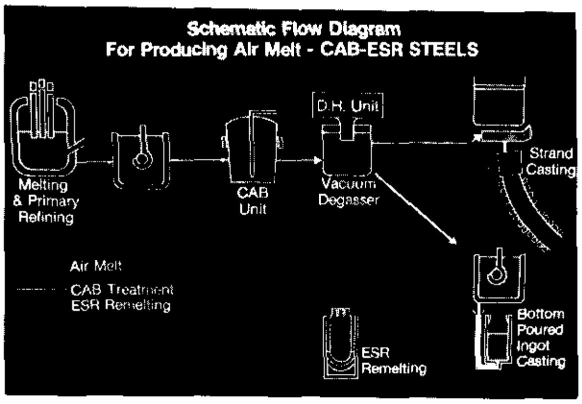

FIGURE 10

FATIGUE RESISTANCE

Nearly all welded structures have discontinuities present which can act as locus points for the initiation and propagation of fatigue cracks. Such discontinuities may be due to design (such as sharp hatch corners), result from fabrication (such as weld cracks) or be present in the material itself.

Selection of materials and welding procedures to improve fatigue resistance must, of course, be integrated into proper design. Recent improvements in steel refining practices(15) as well as microalloying practices have better fatigue resistance under certain conditions; specifically with low sulfur content (≥ 0.010%) and with sulfide shape control (Figure 11).

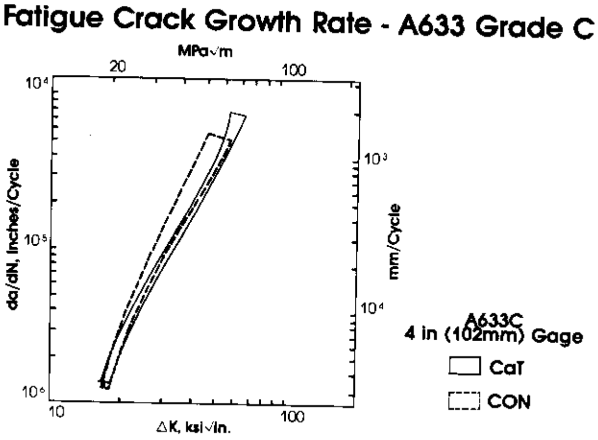
Fatigue Crack Growth Rate - A633 Grade C

FIGURE 11

RESISTANCE TO LAMELLAR TEARING

Lamellar tearing results when metals are strained through the thickness. When cracking results, it usually is associated with non-metallic inclusions, in a plane parallel to the surfaces of the material (Figure 12).

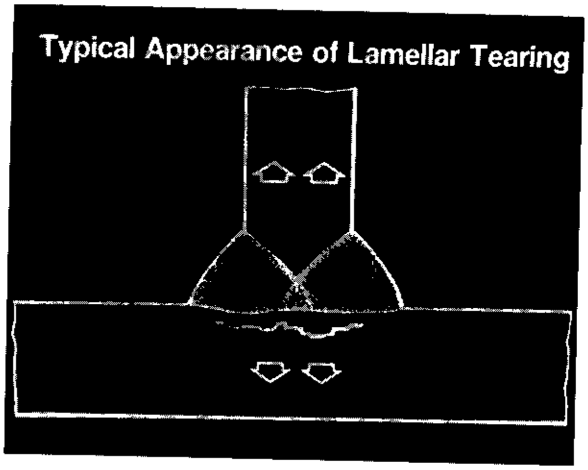
Typical Appearance of Lamellar Tearing

FIGURE 12

Such lamellar tearing can be found in highly restrained welded joints, such as in K-braces (Figure 13) in offshore platforms. Numerous factors bear on the solutions to lamellar tearing (Figure 14).

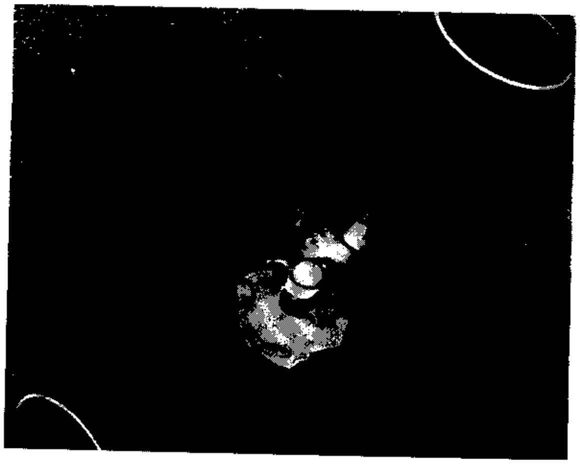

FIGURE 13

Factors Affecting Lamellar Tearing

- Design
- Quality Control and Inspection
- Fabrication Procedures
- Material Selection

FIGURE 14

Experience has shown that material with good through-gage (Z direction) ductility is more resistant to lamellar tearing (Figure 15).

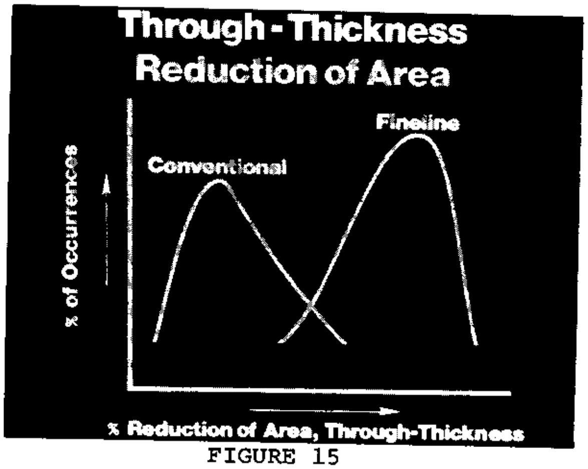
Through-Thickness Reduction of Area

FIGURE 15

Minimum percentage reduction of area in the Z direction is commonly specified. Current steelmaking practices allow the production of products with less than 0.010% sulfur (Figure 16)

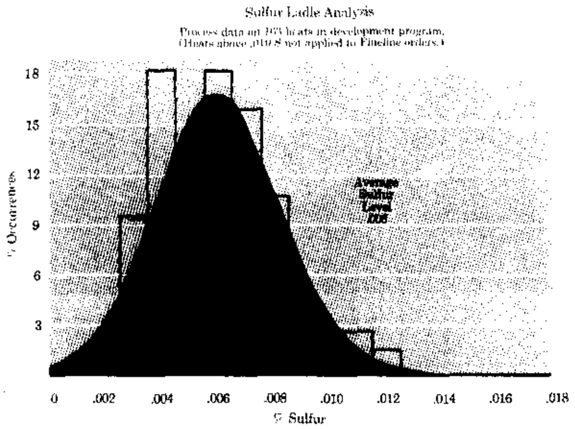

FIGURE 16

and with inclusion shape control (Figure 17).

COMPARISON OF CONVENTIONAL SULFUR AND LOW SULFUR SHAPE CONTROLLED MICROCLEANLINESS

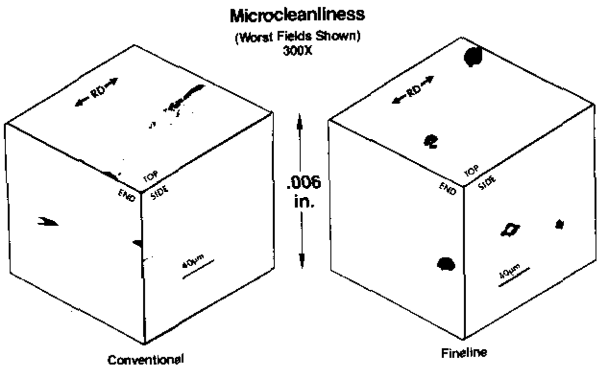

FIGURE 17

AVAILABLE MATERIALS - STEEL

Specifications have been developed for ship steels in an evolutionary manner as research and development indicated the proper directions, based on designers needs. These will be addressed on the basis of increasing strength.

30-40 KSI YIELD STRENGTH

These are the ordinary strength hull steels described by ABS and ASTM A131 as Grades A, B, CS, D, E and DS. All have 34 KSI minimum yield strength (Y.S.) and 58/71 KSI ultimate tensile strength (U.T.S.) (Figure 18).

Specification	**A131 Grade A**	**A131 Grade B**	**A131 Grade CS**	**A131 Grade D**	**A131 Grade E**	**A131 Grade DS**
Type of Steel	Carbon	Carbon	Carbon	Carbon	Carbon	Carbon
Requirements for Delivery	A6	A6	A6	A6	A6	A6
Tensile Strength (Ksi)	58/71*	58/71*	58/71*	58/71*	58/71	58/71
Yield Strength (Min. Ksi) (Yield Point If Designated YP)	34 YP**	34 YP**	34 YP**	34 YP**	34 YP**	34 YP**
Spec. Thickness (Max. in.)	2	2	2	2	2	2
Lukens Thickness (Max. in.)	2	2	2	2	2	2
Chemical Composition (%) Carbon (Max.)	.26 to ½" Incl.; .23 Over 1½-2"	.26 to ½" Incl.; .23 Over ½-2"	.16	.21	.18	.16
Manganese	2½ x C	.80/1.10 May be .60/1.10 when Cold Flanged	1.00/1.35	.60/1.40 to 1" Incl. .70/1.40 Over 1-2" Incl.	.70/1.50	1.00/1.35

*55/65 UTS when Ordered for Cold Flanging
**30 YS when Order for Cold Flanging

FIGURE 18

The mechanical properties of these grades have changed little over the last thirty years, but the chemical analysis has been adjusted to improve notch toughness. Moreover, normalizing--to further improve notch toughness--is required by ABS for Grades CS and E for all thicknesses, and for Grade D over 1.375". Charpy testing is required for Grades B, D and E at temperatures between 0°F and -40°F. Note that rimmed steel--once commonly used--is now prohibited except for Grade A under 1/2".

40-60 KSI YIELD STRENGTH

ABS rules incorporate two levels of strength which are generically similar, Grades H32 and H36 (Figure 19).

Specification	**A131 AH32**	**A131 DH32**	**A131 EH32**	**A131 AH36**	**A131 DH36**	**A131 EH36**
Type of Steel	Carbon	Carbon	Carbon	Carbon	Carbon	Carbon
Requirements for Delivery	A6	A6	A6	A6	A6	A6
Tensile Strength (ksi)	68/85	68/85	68/85	71/90	71/90	71/90
Yield Strength (Min ksi) (Yield Point If Designated YP)	45.5 YP	45.5 YP	45.5 YP	51 YP	51 YP	51 YP
Spec Thickness (Max. in)	2	2	2	2	2	2
Lukens Thickness (Max. in.)	2	2	2	2	2	2
Chemical Composition (%) Carbon (Max.)	18	18	18	18	18	18
Manganese	90/1 60	90/1 60	90/1 60	.90/1 60	90/1 60	90/1 60
Phosphorus (Max.)	04	04	04	.04	04	04
Sulfur (Max)	04	04	04	.04	04	04
Silicon	10/ 50	10/.50	10/ 50	10/.50	10/ 50	10/ 50
Chromium	25 Max.	25 Max	25 Max	25 Max	25 Max	25 Max
Nickel	40 Max.	40 Max	40 Max	40 Max	40 Max	40 Max
Molybdenum	08 Max.	08 Max	08 Max	08 Max	08 Max	08 Max
Copper	35 Max	35 Max	35 Max	35 Max	35 Max	35 Max
Other Elements	06 Al Acid Soluble Max . 065 Al Total Max	06 Al Acid Soluble Max . 065 Al Total Max.	06 Al Acid Soluble Max . 065 Al Total Max	05 Cb Max 10 V Max 06 Al Acid Soluble Max.. .065 Al Total Max	05 Cb Max 10 V Max 06 Al Acid Soluble Max.. .065 Al Total Max	05 CB Max 10 V Max 06 Al Acid Soluble Max . 065 Al Total Max
Heat Treatment Required –		Lukens Requires All Gages be N	N	-	Lukens Requires All Gages be N	N

FIGURE 19

These steels have either 45.5 KSI or 51.0 KSI minimum Y.S. and 68-85 or 71-90 KSI U.T.S.

More careful control of chemical analysis and manufacturing practice is required for DH and EH including fine grain practice, impact testing and either controlled rolling or normalizing based on thickness.

In addition, several ASTM specifications are attractive for use in this strength range (Figure 20). These latter steels can be produced with toughness certification to -80°F in certain grades and thicknesses (Figure 21).

ASTM High Strength Steels For Ship Application

ASTM A537 Class 1	50 Min.
Class 2	60 Min.
ASTM A633 Grade A	42 Min.
Grade B	42 Min.
Grade C	50 Min.
Grade D	50 Min.
Grade E	60 Min.
ASTM A678 Grade A	50 Min.
Grade B	60 Min.
ASTM A737 Grade A	50 Min.
Grade B	50 Min.
Grade C	60 Min.

FIGURE 20

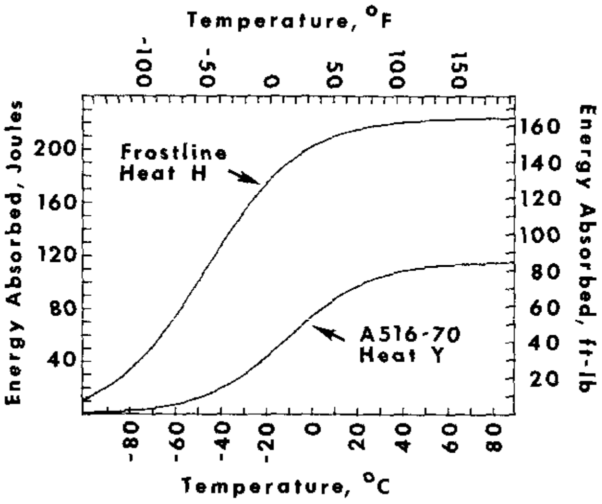

FIGURE 21

OVER 60-100 KSI YIELD STRENGTH

An increasing number of carbon and low alloy steels are available in this strength range; all require quenching and tempering to develop the required strength levels. A number of proprietary specifications are available as well, but will not be discussed here (Figure 22).

Quenched and Tempered Carbon Steels >60-100 KIS Y.S.

ASTM A678 Grade C	75 KSI Y.S. to 3/4" 70 KSI Y.S.>3/4 - 1-1/2" 65 KSI Y.S.>1-1/2 - 2"
ASTM A724 Grade A	70 KSI Y.S. to 5/8"
Grade B	75 KSI Y.S. to 5/8"
Proprietary Specifications	80 KSI to~2" 90 KSI to~1-1/2" 100 KSI to~1-1/4"

FIGURE 22

These grades have notch toughness certification available at temperatures as low as -75°F and are often the most economic materials available based on strength/weight/price considerations.

Q&T ALLOY STEELS OVER 100 KSI Y.S.

Use of steels in this strength range has been limited. Small submersibles have used HY130-140 to Mil-S-24271, available to 2" or heavier. Future military requirements envision broader use of HY130.

Both PH15-7Mo and PH17-4Mo precipitation hardening, high strength stainless steels, have been used in hydrofoil struts. These materials combine the advantage of high strength and corrosion resistance with good fracture toughness.

Alloy steels likewise are available and have been used, not only in military vessels, but also in a variety of commercial ships with unusual design requirements (Figure 23) such as the Glomar Explorer.

FIGURE 23

Figure 24 shows quenched and tempered alloy steels at 60-100 KSI Y.S.

Quenched and Tempered Alloy Steels 60 - 100 KSI Y.S.

ASTM A543 Class 3	70 KSI Y.S. to 10″
HY80	80 KSI Y.S. to 8″
ASTM A543 Class 1	85 KSI Y.S. to 8 - 10″
Class 2	100 KSI Y.S. to 5 - 6″
HY100	100 KSI Y.S. to 8″
A514	100 KSI Y.S.} Gages Vary By
A517	100 KSI Y.S.} Grade - 1-1/4″ - 6″

FIGURE 24

MATERIALS TO CONTAIN LIQUEFIED CARGOS

Ladings such as LPG, Propane and LNG require special low temperature steels, which are defined by the IMCO Gas Code as a function of temperature (Figures 25 and 26):

Chemical Requirements and Minimum Service Temperature

	Grade		
	V-039	**V-051**	**V-060**
Carbon, Max., %	0.20	0.16	0.12
Manganese, %	0.90 - 1.35	1.15 - 1.50	1.30 - 1.65
Phosphorus, Max., %	0.04	0.04	0.04
Sulphur, Max., %	0.04	0.04	0.04
Silicon, %	0.10 - 0.50	0.10 - 0.50	0.10 - 0.50
Nickel, Max., %	0.80	0.80	0.80
Chromium, Max., %	0.25	0.25	0.25
Molybdenum, Max., %	0.08	0.08	0.08
Copper, Max., %	0.35	0.35	0.35
Aluminum (Acid Soluble), Max., %	0.060	0.060	0.060
Aluminum (Total) Max., %	0.065	0.065	0.065
Columbium (Niobium), Max., %	0.05	0.05	0.05
Vanadium, Max., %	0.10	0.10	0.10
Minimum Service Temperature	-34C (-30F)	-46C (-50F)	-55C (-67F)
Stamping	AB V-039	AB V-051	AB V-060

FIGURE 25

Impact Requirements

	Transverse Specimens		Longitudinal Specimens	
Specimen Size MM (in.)	**Minimum Average kg m (ft lb)**	**Minimum One Specimen kg m (ft lb)**	**Minimum Average kg m (ft lb)**	**Minimum One Specimen kg m (ft lb)**
10x10 (0.394 x 0.394)	2.8 (20)	1.9 (13.5)	4.2 (30)	2.8 (20)

FIGURE 26

These grades are C-Mn fine grain steels in the 0°F to -67°F range.

Below -67°F, nickel containing fine grain practice steels are allowed with nickel content increase from 2¼% to 9% as design temperatures drop to -320°F. Austenitic stainless steels are permitted to -320°F, as is Invar, a 36% nickel iron. B209, Type 5083 aluminum alloy is permitted to -320°F.

ALUMINUM AND ALUMINUM ALLOYS

Ocean going uses of aluminum, with several exceptions, have been confined to LNG containment of several designs, and to deckhouses and some superstructures of U.S. Navy combatants.

Hydrofoil hulls are being fabricated from aluminum plate both for commercial and military service. Here, weight is a major design consideration.

COPPER AND CUPRONICKEL

In a structural sense, much attention has been directed toward use of cupronickel or cupronickel clad steel in the hulls of small shrimp boats(16). Economic analysis of use of either sheathing or integrally bonded clad in large containerships has shown some advantages, but as yet no large ships have been built.

An experimental rudder was installed on the Westward Venture, a 26 knot Ro-Ro for the evaluation of cupronickel sheathing. Experience to date has been satisfactory (Figure 27).

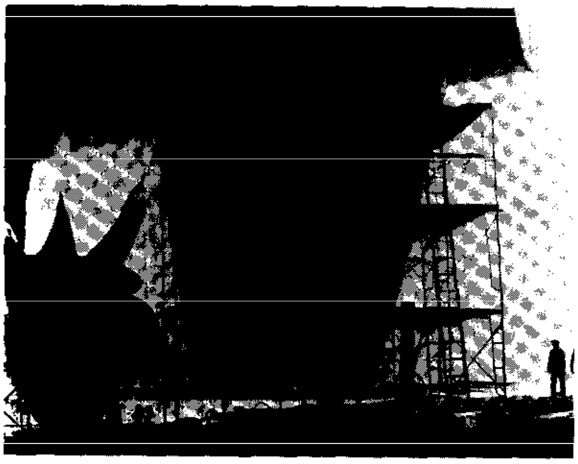

FIGURE 27

TITANIUM

High performance submersibles have used titanium in their hull structures. "Alvin", originally fitted with an HY100 pressure hull, has been reconstructed with a titanium alloy hull.

However, no commercial vessels use titanium in hull components.

SUMMARY

This survey of the current state of the art is intended to provide an overview of the available materials for ship hull construction. Space will not permit more than a brief discussion of the critical factors which affect hull performance under extreme loads.

Primary emphasis has been placed on steel since it is the most widely used material of construction for large ocean going ships.

Emphasis has been placed on the properties which, in extreme load environments, will contribute to hull integrity, or in their absence, to hull failure.

Despite an intensive research and development program over 35 years, more work remains ahead. Improving the weldability of medium strength hull steels is of high priority and is moving ahead at a good rate.

Continued cooperation between naval architects, materials producers, regulatory agencies and shipbuilders will insure progress toward our common goal of improving ship hull integrity.

REFERENCES

1. ABS Rules for Building and Classing Steel Vessels (Annual)
2. ABS Rules for Building and Classing Aluminum Vessels (1975)
3. ABS Rules for Building and Classing Steel Barges for Offshore Service (1973)
4. ABS Rules for Building and Classing Steel Floating Dry Docks (1977)
5. ABS Rules for Building and Classing Underwater Systems and Vehicles (1975)
6. ABS Rules for Building and Classing Bulk Carriers for Service on the Great Lakes (1978)
7. ASTM Standards 1980, Part 4
8. API Specification 2H "Steel for Offshore Drilling Rigs"
9. SR-Project 1256--Investigation of Steels for Improved Weldability
10. Effect of Weld Defects - SRC
11. Hawthorne, J. R. and Loss, F. J. "Fracture Toughness Characterization of Shipbuilding Steels" SSC 248, 1975, Washington

12. Rolfe, S. T., Rhea, D. M. and Kuzmanovic, B. O. "Fracture Control Guidelines for Welded Steel Ship Hulls" SRC 244, 1974, Washington

13. Pellini, W. S. and Puzak, P. P. "Fracture Analysis Diagram Procedures for the Fracture-Safe Engineering Design of Steel Structures" USNRL Report 5920

14. Pense, A. W. "Evaluation of Fracture Criteria for Ship Steels Plus Weldments" SR 1265, Report in Publication

15. Wilson, A. D. "The Fatigue and Toughness Properties of a C-Mn-Cb Plate Steel" ASME Journal of Engineering Materials and Technology, Volume 102, July, 1980 pp. 269-279

16. Prager, M. and Thiele, E. W. "Welding a Copper Nickel Clad Ship - Copper Mariner II", Welding Journal, Volume 59, No. 7, July 1979 and Manzolillo, J. L., Thiele, E. W. and Tuthill, A. H. CA-706 Copper Nickel Alloy Hulls: The Copper Marine Experience & Economics -- Presented at SNAME Annual Meeting 11/11-13/76