Chapter 2

Technologies and Materials Issues Related to Naval and Ocean Engineering

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Technologies and Materials Issues Related to Naval and Ocean Engineering

André Luís Ferreira Marques

Naval & Nuclear Engineer - Rear Admiral (Naval Constructor) (retired) Brazilian Navy. Affiliations: University of São Paulo (USP), Electrical & Computer Engineering - PhD candidate. Paulista University (UNIP), Electrical Engineering (ICET) - Professor. Green Yellow of Brazil - Data Scientist. Brazil. E-mail: aferreiramarques@uol.com.br

Abstract

The sea routes have been part of the globalization movements and help to shape up the world economy heavily. Seafaring has required different ship types, with specific dimensions, propulsion power and engineering materials. More recently, the defense sector has guided the development of naval and marine technologies, mainly in the underwater branch. With the use of nuclear technology, ships have gained a buster in his autonomy and range, setting other challenges tough. Fire aboard and run aground can happen at different world areas, and no ship seems fully protected against them, although their annual frequency has dimmed in the last half century. All these achievements were possible with a broader application of materials technology and selection properly. In the current energy transition and environment protection enhancement, ship materials reliability has caught more attention of ocean and naval experts, who are now applying Machine Learning and Artificial Intelligence, with wireless digital networks, for ship maintenance and hazard analysis, among others, helping to improve the ship performance, especially the economics and safety.

Keywords: naval engineering, ship structures, advanced materials, ship construction, ship design, screw alloys, materials reliability, mechanical fatigue, ship risk management, hydrogen embrittlement, steel toughness, corrosion.

1 Introduction

1.1 The importance of sea communications

Looking to a photograph of the Earth from the outer space, it is easy to see that most of the planet surface is covered by sea waters, connecting continents, people, and cultures. This characteristic has made feasible manifold routes and improved the exchanged of items, services, and other side assets towards History.

In his book [1], Boxer highlighted the importance of the sea communications in the build-up of Portugal as a maritime sea power. Even with few resources, that nation was able, from the XV to the XVIII Century, to expedite a first full version of the globalization, carrying thousands of tons of any kind of goods and people, discovering new lands and so on. Today, more than ninety percent of the world trade is made by sea [2]. Therefore, sea communications have become more and more vital to mankind.

In a closer example, due to the British naval blockade to France, from 1804 to 1815, the war in Europe took a different shape during the Napoleonic era. In other words, the French Empire could not use sea communications to get key raw materials or goods, from Asia, America, and Africa, and made its actions based on a continental approach exclusively. One of the consequences was the move of the Portuguese Court to Brazil, after the French-Spanish invasion of Portugal, in a change of a central power to a colony in the first time in History. In the end, the naval blockade changed our fate for good in the end, opening new lanes to our country, without any parallel among other former colonies. As an initial remark, the dominance of sea communications makes all the difference between countries and societies, showing aftermaths beyond a naive eyesight.

The ship design and its links with economics & environment issues

The use of sea needs all sorts of boats, ships, ferries, among other kinds of maritime transportation means. The design of ships depends on its general purpose, safety standards, the kind of sea routes and weather conditions to be sailed. In the last decade, the ship casualties and accidents have dimmed hopefully [3]. Equally important, to make it real, ship designers and operators have taken the economic feasibility carefully. Due to shorter profit margins, because of recent economic and logistic transients, the shipping companies look nowadays for more reliable and cheaper ship systems.

In another technical perspective, environmental requirements have been narrowed due to the worse climate effects seen in the last two decades and, thus, the environment impact has received more attention in the ship design process. For instance, the change from fossil fuels to electricity to propel a ship has been considered, together with a deeper recycling planning and action of ship materials, mainly in oil tankers and drilling rigs [4]. The ship safety standards have been raised to a degree preventing fuel, oil or cargo spills into the oceans and further harm to marine species and coastlines [5]. Nonetheless, small incidents and even accidents can take place in any ship.

1.2 Overall preview of the chapter

In this chapter, the connections between materials behavior, such as steel and non-ferrous alloys, and ship design issues will be covered, after a quick overview in the types of ships and their general characteristics. Moving on, construction and manufacturing processes, testing, structural failure, and trends in ship materials selection will be addressed. The chapter reading intends to provide a broad view on how some material aspects impact the ship construction and handling technology. Besides, it may present a spark to the readers to get deeper into the items covered.

2 Development

2.1 Types of ships

As a quick opening, this section deals with the ship technical characteristics to allow a better understanding of their kinds and singularities. Normally, the displacement or weight, is the main parameter, being measured in tons, and helps to cluster a certain ship. The overall dimensions also help to define a ship, such as total length (L), beam (B) and draft (H), expressed in meters. Table 1 summarizes some figures and types of ships.

Table 1: main figures related to each type of ships

Ship type	Length m	Beam m	Draft m	Displacement ton	Max Speed knots
Container ship	400	60	15	250.000	23
Large Oil tanker	400	60	30	500.000	18
Harbor tug	30	10	4	75	10
Line cruiser	250	25	7	70.000	20
Frigate	120	15	4	3.500	27
Naval cruiser	170	17	10	10.000	33
Corvette	80	10	3.5	2.000	25
Aircraft carrier	300	70	11	100.000	30
Nuclear attack submarine	100	12	11	9.000	30

2.2 Vessels versus naval ships

The term ‘merchant ship’ or ‘vessel’ refers to the ships used in the general shipping of goods and people in the civilian market, managed by commercial companies, private or state owned. For instance, an oil tanker is a sort of merchant ship (MS) or vessel, the same applicable for ore freighters. On the other hand, the word ‘Naval Ship’ or simply ‘ship’ refers to the military or defense application, such as aircraft carriers, attack submarines, troop cargo ships and so on.

In terms of design, naval ships have more strict design criteria, due to the wartime scenario they may find. For example, naval ships are designed to survive to nearby explosions or ‘shocks’, even nuclear attack, and its fallouts, which is not the case for the merchant ships. In the Brazilian Navy, some ships, like the Niteroi class frigates, can provide shelter for nuclear attacks, due to its specific design. On the other hand, merchant ships are required to have insurance contracts, not only for their cargo but also to themselves. Due to the possibility to be attacked and the need to survive in some extend, the insurances companies do not cover naval ships, as also seen with other defense hardware, otherwise the insurance burden will be too costly and closer to infinity. Figure 1 shows the Frigate F-43 ‘Liberal’ of the Brazilian Navy.

Figure 1: Brazilian Navy Frigate F43 'Liberal [6]

Naval ships have structural shape & painting colors (normally Munsell scale 6.5N grey) related to the requirement to avoid being detected easily. Their system reliability and noisy propagation management are key as well, which is not the case for merchant ships, more focused on the economic feasibility of their operation and ownership. Figure 2 shows the special painting configuration of a naval ship during the Second World War.

Figure 2: special camouflage layout of a US naval vessel in the IIWW [7]

2.2.1.1 Surface ships

Among naval and merchant ships, there is another set called 'surface ships', or those which sail on the sea surface, facing two media (air and water) normally within a wave pattern. Surface ships are the most numerous categories and have a wide range of characteristics. Classic examples of surface ships are oil tankers, general cargo ships, transatlantic ships, trawlers, tugs, and others. They are made of a combination of steel, wood, and polymeric materials mostly. The larger the surface ship, the heavier its structure. Figure 3 shows a standard large oil tanker.

Figure 3: a typical large oil tanker [8]

2.2.1.2 Submarines

Submarines make part of a special type of ship, due to its ability to dive several times along its operational life. When submerged, the submarine can navigate at higher speeds, in comparison to the condition at surface. This feature comes from the hydrodynamics details, while sailing in a homogeneous mean [9].

Nonetheless, submarine diving requires a safe and reliable set of systems and procedures, making submarines more expensive ships than surface ships, even with heavier displacement. Bottomline, submarines are complex ships, being used more for defense purposes than merchant applications, dealing with fatigue, noisy management, system redundancy, and other technical details, more carefully. As the sea exploration rises, in the search of different sources of raw materials, like minerals and food, civil applications of submarines have been in focus in the last decades. Figure 4 shows the Brazilian Navy submarine S-41 ‘Riachuelo’, which has a conventional propulsion system.

Figure 4: Brazilian Navy S-40 ‘Riachuelo’ submarine [10]

2.2.2 Oil Drilling Rigs

The discovery and exploration of oil sources at the bottom of the oceans has encourage the continuous design and development of oil drilling rigs in the last seventy years. They can be used to prospect and to extract oil to be stored in large oil tankers, being floatable or fixed depending on the application. Their operation requires manifold support systems, such as long mooring lines, support surface ships, among others.

In the energy transition trend, towards an environment with lower carbon signatures, the oil drilling rigs may have different applications, such as to support large ocean mining operations or as rescue bases in key positions in the middle of sea routes. Figure 5 presents a typical oil drilling rig operated for the Brazilian oil company Petrobras. This oil drilling rig is floatable (no structure link to the bottom of the sea) and sails like a vessel or ship. The materials used in its construction belong to the common list found in shipyards and shops dedicated to ships. Even the hardware focused on the oil exploration can use shipping construction materials.

Figure 5: a standard oil drilling rig used for Petrobras [11]

2.2.2.1 Drones

The expansion of the digital technology has motivated the development of unmanned systems, which show less risk for the human operations. Unmanned underwater systems and unmanned ships are a reality more and more, using digital signal processing in large scale with the application of artificial intelligence and machine learning tools. Drones used in maritime applications has been made of advanced polymeric materials, such as carbon and aramid fibers. Equally important, they also use advanced energy management systems, like high-capacity batteries.

Figure 6 helps to catch some details of an underwater drone used for environment surveys.

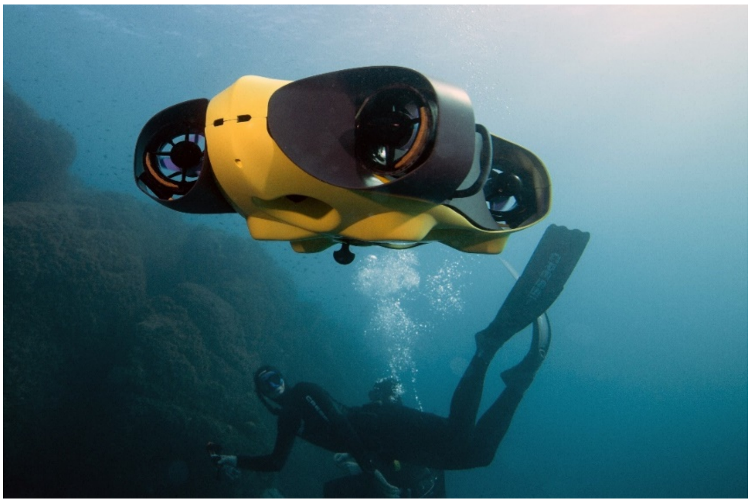

Figure 6: Drone used in underwater environment survey [12]

2.3 Ship general characteristics

As said above, ships can be clustered by its displacement or weight, measured in tons. The L-B-H dimensions have impact in the ship performance, evaluated by ratios, like: L/B, which is related to maneuverability, the B/H (ship stability), $L/(displacement)^{0.33}$ linked to the ship propulsion resistance. Reference [13] has more details about these ratios. These are more individual label for a boat.

For merchant ships the payload capacity and speed are most relevant due to economics. The weapons capacity and its types, autonomy and main purpose define the outline of the naval ships. For instance, the aircrafts (planes, helicopters, and drones) are the main weapons of an aircraft carrier. For strategic submarines, the long-range missiles, with nuclear weapons, are the main military asset.

Another way to categorize a ship is its structural pattern that can be longitudinal or transverse, considering the bow-stern axis. For small boats, there were longitudinal framing as a common sense. Nevertheless, the transverse framing is the current way to build-up the ship structure nowadays. For instance, submarines have circular ring steel structures, with circularity difference smaller than 3%, due to the compression loads while diving.

Figure 7 presents the two patterns of ship structures. Note the set of beams, longitudinal and transverse, making a grid where the spacing depends on the structure design criteria. In the outer part, metal plates close the spaces between the grid points. Bulkheads can be found transversally, segregating blocks and large parts of the ship, providing the longitudinal tightness. For bulkheads, the main structure design load is buckling (compressive loads) of metal sheets. Normally, the keel is the lowest and largest beam, laying longitudinally.

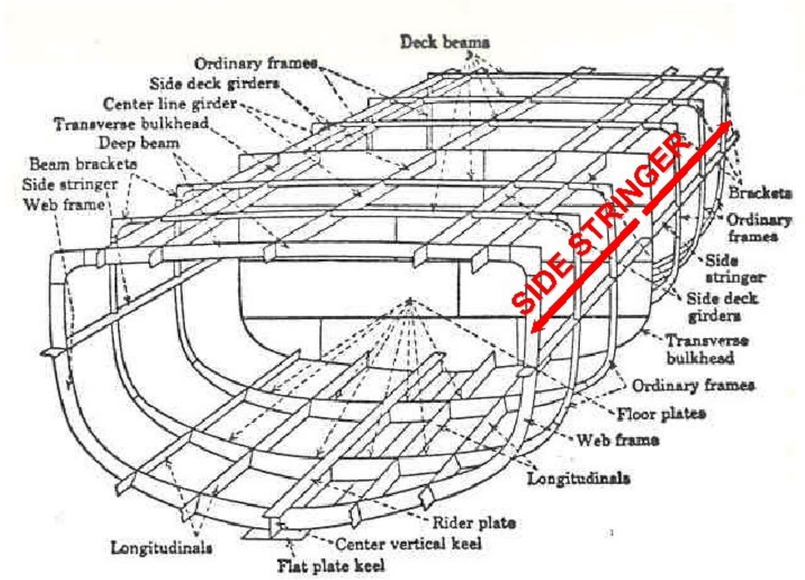

Figure 7: longitudinal and transverse framing patterns of ships [14]

Today ship construction is also based on modules, optimizing the construction schedules, done inside assembling buildings preferably to improve the fabrication quality. Figure 8 shows the assembling of ship structural blocks in a drydock, with tasks being done simultaneously.

Figure 8: Ship modular construction in a shipyard [15]

2.4 Overall ship design criterion

In a broad view, ships are taken as an integration of systems: structures, propulsion, electric, auxiliaries, navigation, and others. These systems are combined according to design techniques also present in the aerospace industry, by the design and review steps, trying to maximize the solutions to the common trade-offs.

In addition, the ship design also considers at its very start the examples done previously, as 'similar or reference' ships, to explore the best answers, practices and experiences achieved.

2.4.1 How a ship is designed

A classical method to design a ship is the convergence or 'spiral' technique. Once the overall technical requirements have been defined, the ship designer starts to define the main dimensions: L, B, H, displacement etc. Following the steps of Figure 9, at the end of each turn, the designer has a set of ship characteristics that differ smaller and smaller from the previous turns, if the design has been properly conducted. Design reviews take place at any moment to confirm this trend and the fulfilment of the technical requirements. For instance, the ship design need to consider different logistic chains, where some chains change more frequently than others, and this feature must be considered in the convergence indicated above.

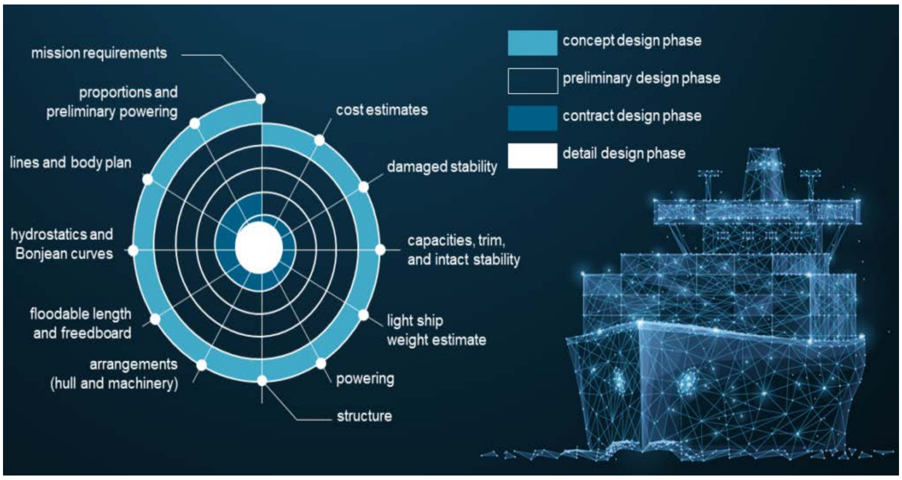

Figure 9: Spiral design scheme for ships [16]

2.4.2 Conceptual, Preliminary and Detailed Design

After receiving the general guidelines from the ship owner, the first stage is the conceptual design, when the design team has convergence of the main initial figures, according to main requirements, the technical rules selected, and the comparison to similar ships. Also in this step, the design team has an order of magnitude of the margins to be considered in the next phases.

Normally, as the design advances, the margins tend to decrease. At the end of the first phase, the line drawing of the ship will be done, allowing to check how the design cope with the stability and safety requirements. Figure 10 presents an example of a line drawing of an oil tanker.

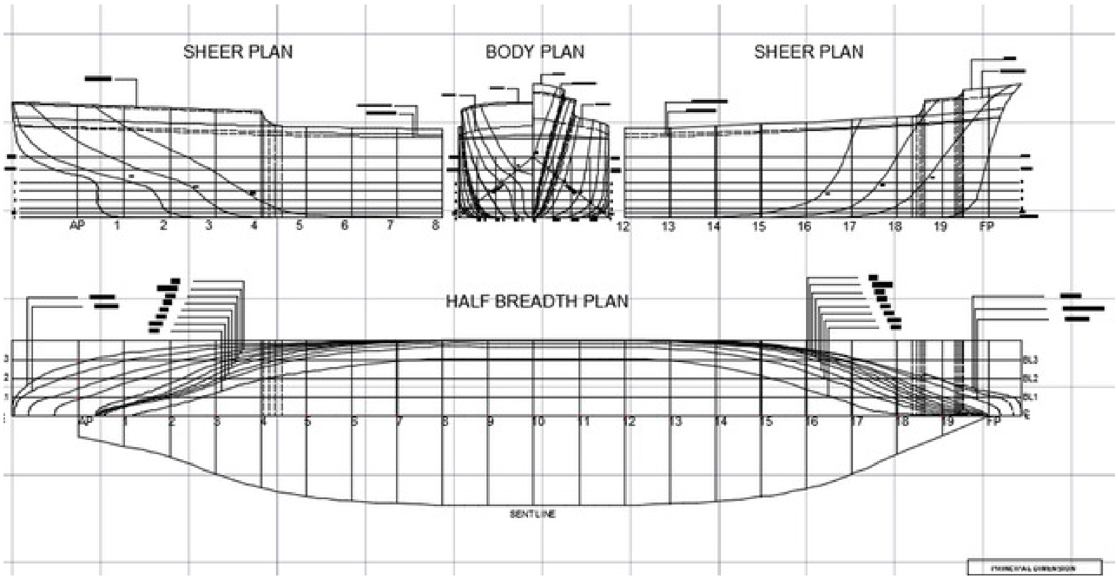

Figure 10: Ship lines or body plan of a cargo ship [17]

The upper part of the drawing shows the longitudinal view cuts of the ship, and, at the middle, there is a transverse view cut where the right side shows the fore section, towards the bow, and the left side the aft part, towards the stern. The lower part of the drawing shows a bird eye´s view and the cuts as horizontal planes, taken vertically.

The application of this drawings aims the determination of manifold ship parameters linked to the stability, the determination of the wet surface, the overall power required and surface and volume estimate to the quantity of metal sheets necessary for the shipyard construction. The drawing also allows to have a better insight of the number of metal blocks to be welded and, consequently, an first ideal about the ship cost.

In the preliminary design, the main systems of the ship have the hardware chosen, with a better figure of dimensions, weight, system performance and other technical features. For instance, the propulsion system will be quite defined in terms of power, fuel consumption, volume required, operational temperature range, brand of motors, size, and shape of the screw and so on.

The structures will have their size, materials selection, layout, weight, and others also defined, indicating the best construction techniques to be taken. In addition, the module construction scheme will be also clearly set. Thus, the approved preliminary design allows the ship owner to sign the construction contract with a shipyard.

The detailed design encompasses the construction steps in deep, defining all the wiring paths across the ship structures and bulkheads, the definition of the all the supports of motors, electric hardware, piping, the whole set of welding drawings and its procedures applicable to each structure, among others. Normally, the shipyard design team takes charge of the detailed design documents. The overall cost of the ship will have a clearer figure so far. The material purchase by the shipyard starts after the contract has been signed, with priority to the long lead items, or those with a long time to be delivered. As soon as the detailed design documents have been approved, the construction itself can start.

Even during the construction, the ship systems are tested, progressively, according to each technical specification. In the end, after the ship launching into the protected waters of the shipyard, the outfitting starts and continues towards the final tests, which take place with ship moored and at sea, before the acceptance by ship owner.

2.4.3 Availability, maintenability, acessability

For a shipping company, as well airlines, the main objective is to keep the transport mean (ship or airplane) in operation, integrated into logistic chains, action that sustain the profit and the business.

To carry on, the ships and auxiliary system must be available as much as possible, requiring constant attention to the maintenance types and all the intelligence behind.

In this matter, all hardware has its own code of maintenance, overhauling and updates, which must be managed by modern digital systems, including the purchase of spares, lubricating oils, inspection services, which now have more drones and robots than in the last decade. Therefore, the data management system handles a set of sensors, now with Internet of Things (IoT), providing blocks of measurements of technical variables along time, or time series.

In parallel, some material techniques also are considered, such as the management of material behavior as a function of time, and one of them is the Fracture Mechanics.

This field takes care to understand how a crack may appear and how it can propagate inside the crystal lattice or other material structures. Since the 50´s, a better knowledge of crack growth has used more and more laboratory testing, searching for the reasons for material failures and how to prevent or mitigate them. The shipping industry considers all this technical endeavor from the mechanical and material engineering fields.

2.4.4 Reliability-centered maintenance

For any main economic goal, profit rules the enterprise planning and execution and, among the strategic view, the maintenance phase demands special attention due to the probability of incidents and accidents, in case of catastrophic breakdowns, which will wind up as extra costs, turning down the profit margin in the end. By the way, it may fall into a vicious turnaround.

Therefore, once the enterprises can predict the maintenance required goals and metrics, as much as possible, the economic feasibility of systems, hardware and even software apply prediction models related to the reliability centered maintenance.

The main objective is to avoid failure and, equally important, to bound the operational associated costs by the early fault detection, as an example. Another task is the monitoring of the vibrations mode, allowing to assess the change in the whole set of natural frequencies, associating them to some specific system optimization in the end.

Most system engineers have in mind to describe the operational limits, and in this endeavor, they need to determine, or state, when a specific item or a set of items must be replaced.

One fair example is the aerospace industry, based on data collected from manifold sources. Accident analysis has provided indications on how a certain item, such as a shaft bearing or pump gasket, may crack down and provoke an accident/failure, after a spilling or initiating event. As a common sense, an incident or accident come from a sum up or combination of small causes, linked sequentially or by other arrangements. The reliability centered maintenance focuses the management of these details, allowing the maximum availability of hardware, system, or their combinations.

Reference [18] presents some insights about the use of Machine Learning or other digital tools for this aim. In that case, a Structural Monitoring System considers the pattern recognition technique, of cracks or other singularities, to assess how safe a structure has been. In a ship, this means to install a set of strain gauges in key spots, building up a strain measuring log, and to compare the results against a certain safety criterion, linked to the structural safety design approach. After some time of operation, the strain pattern will look up different from the start, due to the reasons discussed in previous items above (i.e. fatigue). The reliability centered maintenance approach compares the evolution of the strain pattern against recommend values gathered from laboratory testing, under the scope to avoid failure.

3 Ship & Marine Technology

3.1 Materials for ship construction

In modern shipbuilding industry, several kinds of materials have been used following the development of polymeric and metallic alloys mostly. Steels have dominated the field, where high tensile steel carbon steel (HTS) figures on the top.

Notwithstanding, the first ship built with steel dates from the end of the 18th Century, but the metallurgy processes at that time were more likely to the Middle Ages, when steel or cast iron were used to join ship wood parts as rivets. In the middle of the 19th Century, steel making improved with a more scientific and engineering approach with support of testing laboratories. With the improvement of the electric technology, during the 20th Century, steel making has matured, and welding has been the main technique to joint steel parts.

Nonetheless, Aluminum alloys, Copper-Nickel alloys, as well as carbon fibers, has their own niche. Take the example of the high-performance yachts, sailing with speeds higher than 30 knots (around 55 km/h), combining advanced concepts of aerodynamics and hydrodynamics, alongside an optimized materials selection. It is worth noting the use of several types of wood, combining resistance and lower density, in comparison to the metallic alloys, for specific applications and due to traditional reasons.

Take the example of a medium size aircraft carrier, with the displacement around 9.000 tons, which has almost 7.500 tons of steel (96% carbon and 4% stainless). The other 1.500 tons are composed by 1.100 tons of copper alloys and 400 tons of Aluminum. The small quantity of stainless steel avoids the fabrication cost to reach stratospheric levels.

The key material properties required for general ship hull applications are high strength, corrosion resistance, fatigue resistance and good ductility for fabrication processes. Thinking on the steels, the only answer for this requirement is low carbon alloys. Table 2 presents the most common alloys selected for ship structure applications.

Table 2: Carbon steel alloys for hull structures

Steel Codification	Yield strength min (MPa)	Tensile strength min (MPa)	Elongation (min) (%)	Main composition C-Mn-Si (%)
A	230	450	22	0.22-3.0-0.3
B	230	450	22	0.21-0.6-0.3
D	230	450	22	0.21-0.6-0.3
A32	310	550	22	0.18-1.2-0.4
A36	350	600	21	0.18-1.3-0.4

Take a common steel alloy used in the automotive industry, the HTS has a mechanical strength 5 times higher, while the ductility shows a ratio of 4.

However, when dealing with submarine hull structures, where the safety factor remains around 1.5-1.8, and the fabrication requirements are tighter than those from the surface ships, other alloys are used, known as high strength low alloy (HSLA) or high yield alloy (HY).

In terms of material stress, due to technical requirements, the design of ship structures normally requires staying at most around the elastic yield, with few cases inside the inelastic field of the materials. Some technical rules are based on the Von Mises design criterion, but others are based on the Tresca criterion.

The materials above deal with the main structure of the ships, or the structure responsible for the ship tightness. For inner structures, known as secondary or even tertiary, with a smaller ship tightness impact, other materials may be used, looking for the affordable economics too. Nonetheless, the designer must have attention in the materials compatibility to avoid corrosion stresses, due to “chemical pile” activation.

One famous example are some naval ships, built during the 60´s and 70’s, where the main hull used carbon steel plates, but the superstructure was made with Aluminum alloys, taking the concept to reduce the overall displacement. Consequently, some stress corrosion developed forcing costly repair in the end.

Another interesting case is the screw or propeller, where the conditions above are magnified. Summing all of them up, the copper alloy can withstand the intense corrosive effects of saltwater.

As the propellers have special shapes, following helix lines, with varied thicknesses, ductility has a strong importance, alongside the obvious corrosion resistance. Common rotation speeds fall within 60 and 100 rpms, shaping up a low cycle fatigue case.

Cavitation is a phenomenon to prevent during high propeller speeds because it causes erosion due to implosion of vapor bubbles generated on the blades.

The roughness of the blades serve as an initiation spot for the occurrence of cavitation and the blade surface finishing demands a constant attention. The most common propeller materials are shown in Table 3.

Table 3: materials used in ship or submarine propellers

Alloy Codification	**Yield strength min (MPa)**	**Tensile strength min (MPa)**	**Elongation (min) (%)**	**Main composition (%)**
Cooper-Aluminum	200	500	20	60Cu-2Al-3Mn
Cooper-Aluminum-Nickel	180	500	30	9Al-4Ni-2Fe
Stainless Steel	550	850	15	13Cr-4Ni-0.06C
Sonoston	270	570	25	36Mn-3.5Cu-3Al
Carbon Fiber	3000	4.000	2	---

One of these alloys of special application is the Sonoston, developed in the 60´s with high damping and mechanical strength, for many applications including military ships.

In ship screws, it is not possible to impose external damping appendices, while handling general vibration issues.

One of the solutions is to use alloys such as Sonoston, based on Manganese, with a mechanical damping capacity over 20 times of other metallic alloys.

The Sonoston alloy also shows a ductile fracture profile with temperatures below -100^{o}C.

Stress corrosion crack can be observed, and it turns to be a disadvantage, but with thicker parts and suitable anodic protection, this drawback has been managed satisfactorily [19].

In the nuclear propulsion, the materials selection takes other boundary conditions, due to the radiation effects, higher stress fields and the risk management.

In more than 95% of the nuclear-powered ships, mostly submarines nowadays, the pressurized water reactor (PWR) is used, where the primary circuit operates with pressures around 150 atm, and the secondary circuit (Rankine cycle) works with pressures of 60 atm.

Due to the flow of cooling and neutronic moderator agents (light water), which induces vibration in the nuclear fuel, fatigue resistance plays a key role too.

Moreover, most of the hardware is designed not to be changed during the ship lifespan, closer to 30 years, requiring thus a high reliability and endurance standard.

For instance, the primary circuit pump is designed to last for 30 years or more, dealing with high pressure, transients, and high fatigue cycle.

On the other hand, in the same energy system, the piping also deals with high pressure, transients, but in a lower fatigue cycle.

Table 4 summarizes the key materials used in the primary circuit of a typical PWR reactor for nuclear propulsion.

Table 4: Common materials used in PWR circuits of nuclear propulsion

Hardware	Material	Yield Strength (MPa)	Mechanical Strength (MPa)	Elongation (%)
Reactor Vessel	SA504 or SS304L	200	500	40
Reactor Internals	SS 304/347/316	200	500	40
Fuel Cladding	Zr-4, Zr alloys	380	500	30
Main Pipe	SS 304/316	200	500	40
Steam generator tubes	600MA or 690TT (325 ^{o}C)	220	570	46
Steam generator shell	Low Carbon Steel	300	600	30

To present more details, Figure 11 shows most of the materials used in the primary circuit, which deals with the nuclear fuel elements, and in the secondary circuit, more specific to generate steam and use it to produce propulsion power or electricity.

Note the vertical border line, which separates the two circuits, also showing the containment limits, regarding pressure and nuclear material tightness.

Although the picture shows ‘carbon steel’ for the pipelines in the secondary circuit, nowadays ‘stainless steel’ has been used instead.

Due to the technical requirements, few components inside the primary circuit need to be exchanged during the nuclear facility lifespan.

The classical example is the steam generator, the largest item near the border line, which deals with two pressure loads or, approximately, 150 atm in the primary side, and 60 atm in the secondary circuit. It normally shows problems related to corrosion (e.g., stress-corrosion cracking).

In some extent, the pressurizer also may show corrosion issues, normally associated to the two-phase regime (water-steam) operating condition.

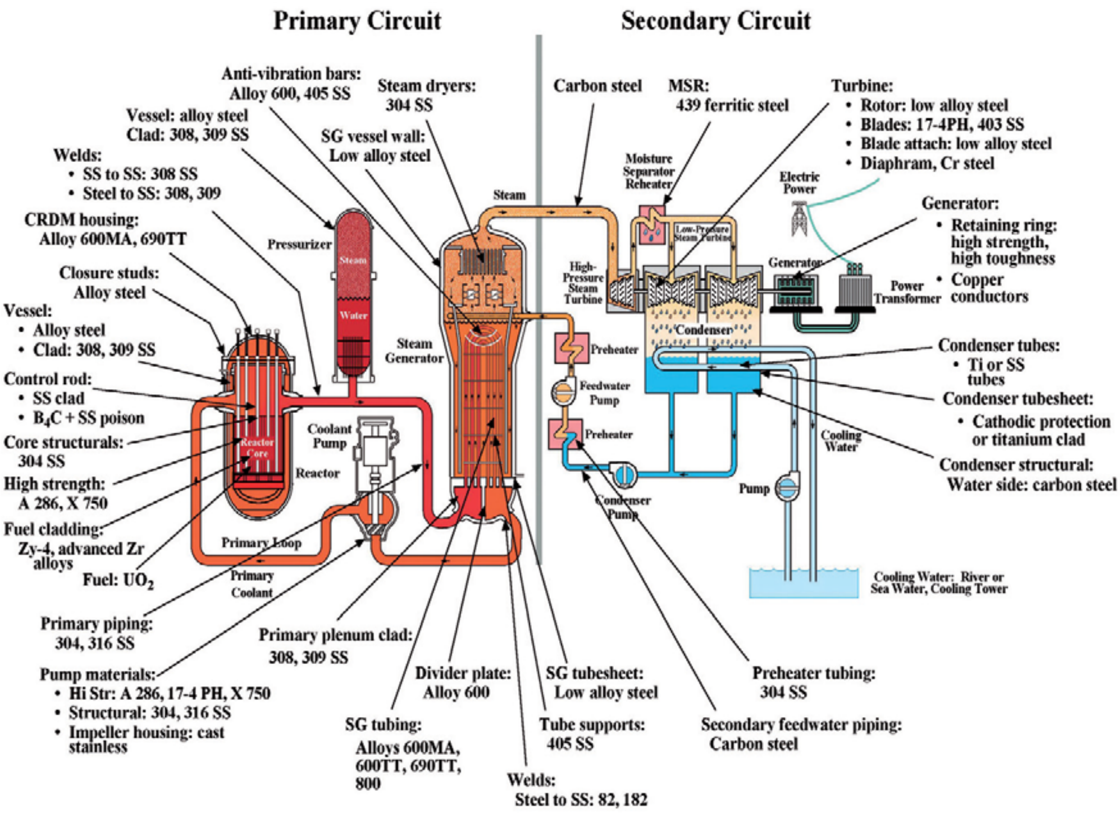

Figure 11: materials among equipment of the primary and secondary circuits [20]

3.2 Ship construction and manufacturing processes

3.2.1 Testing – material characterization

As required by industrial design codes, within the quality control sphere, materials must be checked against their real properties, before allowing their use in fabrication or construction.

In other words, the materials must have its properties within the code range. Thus, material properties are confirmed with the testing of samples.

The American Society of Testing Materials (ASTM) is an example of standard to be considered in this matter, alongside the American Society of Mechanical Engineers (ASME), which focuses the hardware design (e.g., structures, pumps etc.).

Due to reasons related to the safety, reliability and insurance, the material characterization has a high importance, to protect the environment and to avoid huge losses in court disputes.

In the shipbuilding industry, the American Bureau of Shipping (ABS) has its own standards applicable to boats and ships.

Other best-know classification societies are Lloyd´s Register (UK), Det Norske Veritas Germanischer Lloyd (Germany) and Bureau Veritas (France).

For instance, ships with cryogenic or low temperature tanks, for the transport of liquified fuels or special substances, such as acids, the presence of Silicon (Si) in carbon steels must be low and tightly controlled, to avoid brittle failures.

The main material tests applicable to the shipbuilding industry are:

- Chemical composition
- Tensile strength test
- Charpy / Izod test
- Transition temperature test

3.2.2 Welding

Welding is the most common bond process used in ship construction, focusing metallic joints. The Welding Handbook is published by the American Welding Society (AWS) and describes the welding techniques in detail, where the thermal flux management is fundamental for the material properties changes.

During the welding, high heat flux goes throughout the material thickness, making crystal modifications like the heat treatment processes.

In case of a fast cooling of the weld joint, the local material hardness may increase beyond the acceptable levels. Thus, the temperature transient in the weld joint can affect the local mechanical strength and ductility, towards the crack inception and material failure unfortunately.

3.2.2.1 Heat Affected Zone (HAZ)

In the welding processes used in the shipbuilding, due the phenomenon briefly described above, the HAZ is a key factor to be controlled. The American Welding Society (AWS) has technical guidelines on this matter and the HAZ shows its relevance in the hull construction of submarines and reactor pressure vessels. Reference [21] has more data to get deeper.

Figure 12 presents a combination of graphs: on the left-hand side, it shows the steel microstructures developed from the join center position, or the place of the peak temperature.

These microstructures come from different heat transfer pattern and temperature profile as a function of time. On the right-hand side, there is the phase diagram of a typical low carbon steel. The vertical axis shows the temperature, and the horizontal axel has the Carbon concentration (%).

Near the welding joint, there is a set of 5 types of microstructures, which one with different mechanical properties, then with a heterogeneous material profile. This fact must be considered in the mechanical design, to cope with the worst-case scenario for the safety factor. That is the main reason to take heat treatment for welding of thick steel plates, such as the ones present in shipbuilding, to make the material more homogeneous after the welding.

Another solution focuses the use of alloy carbon steel, to handle the lack of homogeneity from the heat flux and temperature distribution.

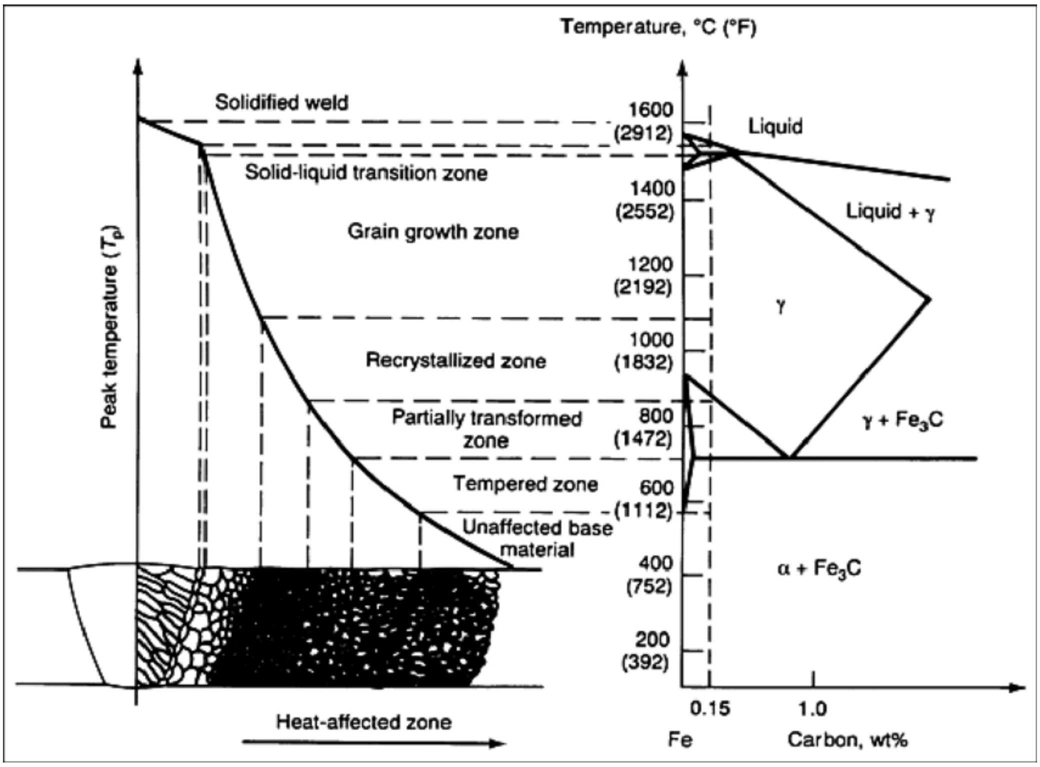

Figure 12: the HAZ typical weld contour [21]

3.2.3 Plate rolling

Most of the steel parts in a ship starts from a plate geometry made with a set of thicknesses and dimensions.

The plates are made in the steel factory by plate rolling, using large cylinders, or rollers, under compression loads on the steel flowing, which is already solid but with temperatures close to the transition threshold, showing a vivid orange reddish color.

This operation sets some residual stresses on the material, after some operations such as quenching, and thus annealing also takes place to handle the final mechanical properties.

3.2.4 Cutting

Prior to any further operation, the steel plates need to be cut into shapes closer to the final geometries required to make up the structural components. In this operation, the steel plates geometries are checked against the optimal scheme to generate the least quantity of material disposal, as also seen in the clothing industry.

Depending on the thickness, several cutting tools can be used, such as gas torch or plasma technology, normally underwater this last one. The main concept is to dim the microstructure are affected by these processes, preserving the material as homogenous as possible. It is worth noting this kind of detail is taken since the preliminary design, allowing dimensions and margins related to the optimization of the whole set of materials.

3.2.5 Bending

As used in mechanical structures of different sizes, the bending process is responsible to produce any sort of curved shapes, mainly in the bow (fore) and stern (aft) ship areas. In addition, bending is used in the resistant hull transition geometries, from the bottom (horizontal) to the main deck (vertical). This shipbuilding application has a strong link with the same applicable in the automotive industry. Normally, the steel plate thickness for the shipbuilding industry remains closer to 2 inches or 50 mm, which must be considered when planning the bend operation. Figure 13 shows the bend structures normally found in oil tankers ships.

Figure 13: Bend plates for oil tanker ships [22]

3.2.6 Machining

In the same fashion of large mechanical structures, machining is quite present for plate preparation to welding. In this case, the notch between two plates must have its shape according to the detailed design. The notch is produced by the machining the two plates. Propulsion shafts are also machined following the detailed design, considering assembling clearances and the softening of sharp corners, to prevent cracks from stress concentration and fatigue.

3.2.7 Metal forming

In some special parts of the ships, with special geometries formats, the metal forming is required, with the application of pressing for instance. The classical case comes from the spheric tanks used to transport liquified substances, such as natural gas, because with this format, the internal stresses are smaller, with lighter structures too. The bow structural hull of submarines is also made by pressing of carbon steel alloys, in small parts to be welded and assembled in the final stage of the manufacturing.

Another example is forging, which is seen for instance in the fabrication of propulsion shafts or assembling bases of heavy hardware, such as the diesel engines for large oil tankers. These engines have peculiar characteristics like large dimensions and weight around tens of tons, using thus just one per ship.

3.2.8 Additive processes

With the technology advance of the polymeric materials, mainly for high tech sailing, additive techniques have been used in the construction of advanced boats, following the aerospace industry trends. Modern outfitting techniques, used for small internal items, can been seen with the use of bonding procedures.

3.3 Main ship systems

As an integration of several hardware, a Work Breakdown System (WBS) helps to present an overall view of the main ship systems. According to Reference [23], the main ship systems are known as:

a) Structures
b) Propulsion
c) Electric
d) Auxiliaries

The ship structures consist of a set of supports and resistant components, requiring monitoring, inspection, and maintenance, like the other systems.

The propulsion components also make a system division because they cover several types of energy management details, using different types of fluids and mechanical parts, and more recently, advanced digital control techniques.

A specific field is dedicated to the electricity, covering subjects as electric motors and generators, automation, switchboards, power converters.

Finally, the auxiliaries take care of all other systems, such as ventilation, air conditioning, hydraulics, steering devices, damage control items.

Additional ship system division may be set, depending on the logistic or management needs.

3.4 Ship structural load profiles

In short words, the main ship structure can be taken as a metallic beam, in a closed profile, being thus a hyperstatic structure. For sea going ships, the main structural load comes from:

- the overall displacement, according to the weight internal arrangement.
- the sea wave patterns, mainly during high seas and storms.
- the propulsion resistance, more significant at high speeds.
- The ship maneuvers, in high angle turns.

In some special cases, specific loads can be observed during the take-off and landing of aircrafts, weapons launching and towing operations, which are kind of common for the naval ships. Specifically, submarines have a more homogenous structure load profile once they go underwater most of the time. The compressive load varies with the diving depth. In general, modern submarines can sail at 300 m deep, corresponding to an external pressure of 30 atm roughly.

3.4.1 Wave loads

The simplest wave configuration faced by the ship structure can be seen in Figure 14, with two cases basically. With the concept said above, the ‘ship beam’ can have a tension, or compression, distribution leading the main stress profile, due to the buoyancy.

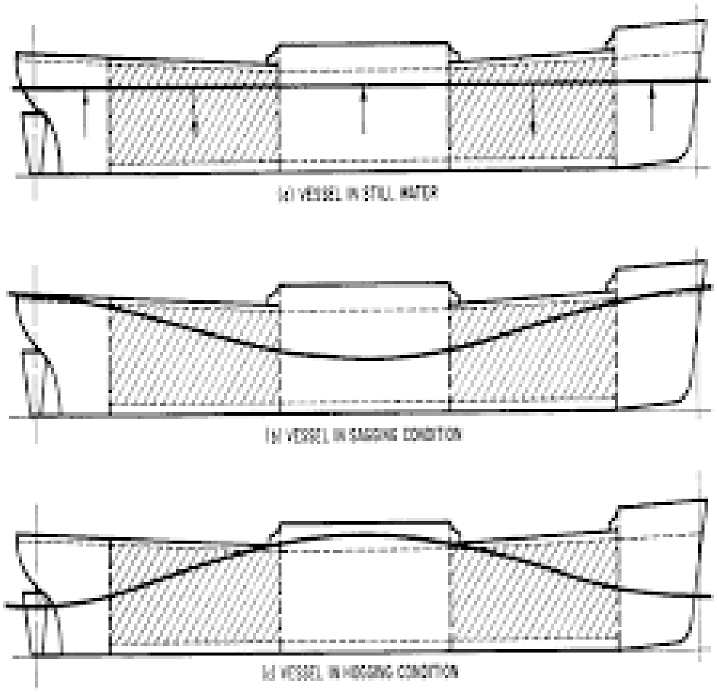

Figure 14: Buoyance wave loads to ship structures [24]

As the buoyance varies along the ship length, according to the wave pattern, the structural stress also changes. In the first picture, the load is equally distributed along the ship length, in a homogeneous fashion, and the structural stress seems quite uniform along the ship length. Nonetheless, as seen on the second picture, the extreme parts of the hull (bow and stern) have more buoyancy and the main hull section (midships) has lower buoyancy. The hull can be taken as bean with tension in the lower part and compression in the upper part. From the last picture, the opposite occurs, alternating the stress profile, typical framework for a fatigue analysis (low cycle).

3.4.2 Other loads

Another way to compute the external load, comes from the water column at every point of the ship structure, which is more relevant in underwater structures, such as submarines, drones and some oil drilling rigs. Winds also represent a key load, mainly for high superstructures, seen in transatlantic ships, figuring around 20.000 m2 or 3 soccer fields, or even more. All the loads above have a transient behavior, varying in time and inducing the fatigue.

3.5 Types of ship structural failures

3.5.1 Corrosion

As the sea environment is rich in Oxygen, with salt and dirty, in some cases, the corrosion process is present to all metal structures of a ship. This feature makes corrosion a constant preoccupation in the shipping industry to prevent stresses beyond the design. As a general guideline, the ship structures have over dimensioned thicknesses to consider lifespans of 30 years or more, even with careful painting and maintenance. Make note that the corrosion product must be taken away, using abrasive methods, which decreases the ship plate thickness. Figure 15 shows a typical corrosion profile present in ship hulls. The reddish spots represent the corrosion at high stage or degradation. The dark lane closer to the water line has marine life accumulation on the hull, also a contributing factor for the corrosion. The vertical black items near the bow are the ship anchors, also experimenting corrosion with middle stage pattern approximately.

Figure 15: typical hull corrosion stages [25]

3.5.2 Fretting

This kind of failure links between rough surfaces and wear/ corrosion. The wear phenomenon requires a relative motion between surfaces under contact, originating then high levels of roughness, which is one of the sources for cracks, specially at high speeds.

Thus, fatigue can be present under fretting situations too when the fatigue cracks appear at fretting zones. In ships, it is possible to have this failure in rotating parts, such as axles and bearings, due to poor lubrication or maintenance.

As these parts are made of steels, fretting can be confirmed by the presence of pits and fine red dust, on the contact surfaces, which are related to oxides formed during the increasing of wear.

Figure 16 shows some of indications of fretting in a ship propulsion shaft, at the joint flange with screws. On the upper right-hand side, there are nuts and bolts attached to the flange. In the middle, there are two empty holes, showing traces of fretting, pits, and red dust.

The ship shaft is a forged component, machined to handle the geometry changes, like the holes and flanges. Note the light line transition from the horizontal position to the vertical one, where the nuts and bolts are shown. This light transition helps to avoid stress concentration near the shaft joint.

Figure 16: example of fretting in a ship shaft [25]

3.2.3 Fatigue

The ship dynamic load profiles seen in different conditions provoke fatigue failures.

There are two major cases: low cycle and high cycle [26], which need to be taken while composing the structural stress, according to different boundary conditions, such as local load profile, stress concentration, temperature conditions, material composition, welding geometries and so on.

The overview also considers the classic form to address fatigue throughout the evaluation of data from the failure stress against the number of operation cycles.

3.5.3.1 Low-cycle / strain-based fatigue

This situation is observed in the ship main hull, mostly closer to special configurations, normally linked to stress concentration, which happens in welded joints. The low cycle range can be set as lower than 10^4 number of cycles.

Depending on the shape and stress profile, low cycle fatigue may set the material into the plastic regime, which requires a special approach to prevent failure and to forecast the material lifespan.

Reference [27] presents a suitable reasoning to address this low cycle condition. The strain indicator takes the elastic and plastic regimes together, by summing up each contribution.

It also focuses the welding joints as the worst case to be studied, due to the HAZ detected, basing on testing and empiric relations for shipbuilding steels. Figure 17 presents some results related to marine structures low-cycle fatigue. The dots on the upper part of the figure come from mechanical testing, and the order of cycle magnitude is closer to 10.000. It is worth noting the dark points were made with welded specimen of the material, with a lower stress strength, in comparison to the base material.

In the figure two other limit lines are also shown: the elastic strain-life, closer to the fatigue curve, converging to the same stress limit, for higher cycles, and the plastic strain-life, straight down to the end life limit of 105 cycles approximately. The term 'SSC-346' stands for a ship structural committee nr 346, from the US Government (1990), dealing with fatigue characterization of ship fabricated details.

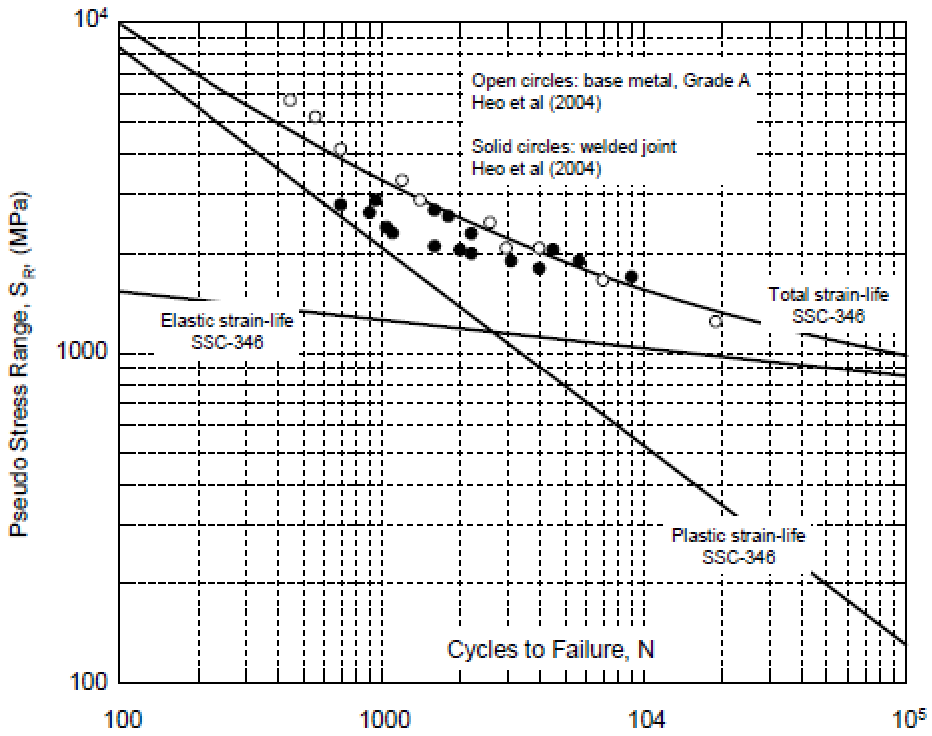

Figure 17: typical strain-based low-cycle fatigue [27]

3.5.3.2 High-cycle / cycle-based fatigue

This case deals with the hardware found in the propulsion systems, like propulsion motors, pumps, air compressors, but it can also be seen in structural items. High cycle fatigue is assumed for work patterns above 10^5 cycles and it is also common to consider a very high cycle fatigue when dealing above 10^7 cycles. Reference [28] covers most of the details related to high cycle fatigue, including the fractography. In a general sense, high cycle fatigue is linked to tough failure mechanisms. Figure 18 shows a comparison of different materials and their behavior under high cycle fatigue, indicating the shipbuilding cases (A36 and other structural steels). Note that the alloy steel 4340 (0.4% of Carbon) exhibits a 100% higher fatigue strength than classical structural steels, and some specimen did not fail at 10^7 cycles or more.

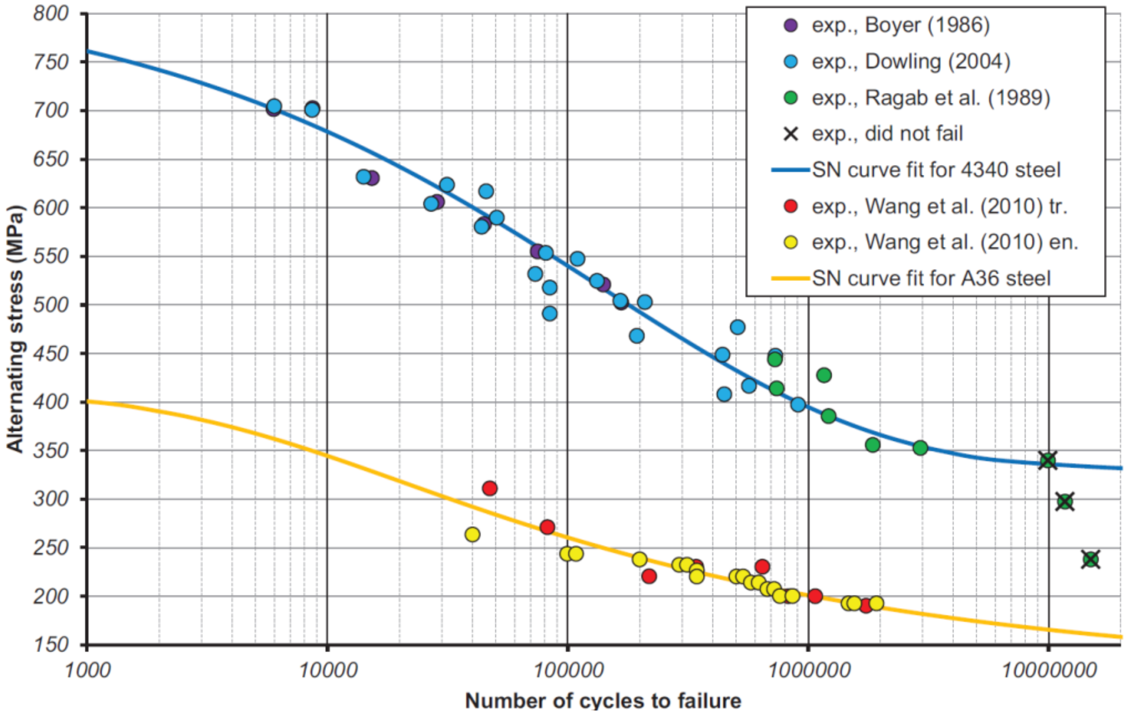

Figure 18: typical high cycle fatigue [28]

3.5.4 Hydrogen embrittlement

Hydrogen is the smallest and lightest atom and thus, as an ion H^+, it can have high mobility throughout crystal planes of metallic materials. Therefore, the diffusion of Hydrogen reveals quite easy when the concentration difference and temperature conditions are present.

As a matter of fact, this diffusion of Hydrogen is reversible consequently and, at room temperatures, it takes order of minutes to happen. In a few words, the presence of Hydrogen produces 'hydrides', which are brittle, inside the crystal lattice (interstitial), inducing the material failure because, when diffused into metallic matrices, this introduces brittle clusters, weakening the material toughness. Three major conditions favor this phenomenon: stress, a Hydrogen source, and the susceptibility of the target material. Note that it is a low temperature phenomenon for steels, which are not affected by Hydrogen embrittlement above of 150^{o}C. All these can be found in ship structures once salt water is a fair source of Hydrogen and other ions.

Figure 19 shows a stress-strain graph (in the middle) and four associated metallography details, regarding the evolution of hydrogen embrittlement, during a effort to use heat treatment as a way to reduce the damage from the phenomenon. In this study, the authors propose to use 'selective laser melting' (SLM) to change the metal structure locally to increase the hydrogen embrittlement resistance. They also propose to carry on a heat treatment (annealing) with the SLM. The idea is to produce materials with the curves in the upper part of the tension test result, rather than the ones in the left lower corner.

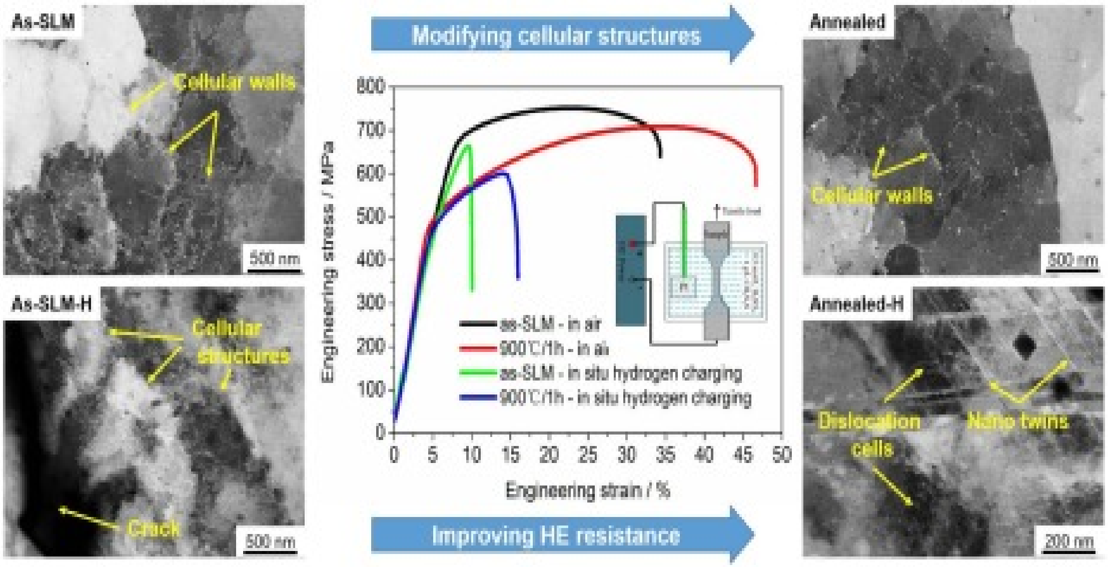

Figure 19: hydrogen embrittlement metallography [29]

During the processing of metal plates at shipyards or factories, the operations of rolling, forming, coating, or cleaning may also introduce Hydrogen as described above, due to poor quality control techniques. The presence of dirty, inadequate, or damp materials in the fabrication line can be a Hydrogen diffusion source, which diffuses due to bad electroplating control. As seen in many industrial applications for high quality welding, the electrodes used in shipyards must have a low Hydrogen content and must be kept at controlled atmosphere (special casing or barns), avoiding moisture or other sources of Hydrogen. Any electric source can also start the Hydrogen diffusion and, therefore, galvanic corrosion needs attention to prevent the phenomenon.

3.5.5 Transition temperature failures

Metallic alloys exhibit a change in their ductility while the operating temperature changes, in direct relation or as the temperature lows so does the ductility. Nonetheless, this modification is not proportion, rather it shows a step profile. The temperature associated to this step start up (down) is called transition temperature. This phenomenon requires attention when dealing with structures facing low operating temperatures, such as cryogenic systems or polar navigation. In short words, above the transition temperature, the metal has a ductile behavior, as the strain follows the load application, as discussed previously. For temperatures below the transition threshold, the failure becomes ‘tough’ or no pre-sign of crack down can be detected, to avoid the total material collapse. Thus, the transition temperature demands special attention to ensure the suitable operating structure envelope.

3.5.5.1 Liberty ships

These ships were constructed in WWII to transport goods and soldiers between North America and Europe and had a cargo capacity of almost 11.000 ton. Based on a British design, they symbolized a classical example of the huge industrial potential of the USA at that time, mobilizing 18 shipyards and a total of 2700 ships, making 4 ships per day as mean rate.

The American design considered welding in the place of rivets, originally designed by the British. Due to poor quality control actions, the employment of non-skilled workers, and other minor causes, some Liberty ships faced fatal cracks, evaluated as brittle failures.

The North Atlantic Ocean has severe conditions in terms of wave and wind loads, besides lower temperatures during the winter. Therefore, the transition temperature mechanism influenced the material behavior, or temperatures lower than the critical ductile-brittle transition zone.

The same phenomenon was already observed in some ships which operated in the Great Lakes, between Canada and the EUA, once the region shows normally very low temperatures in winter normally. Figure 20 shows of the damaged Liberty ships.

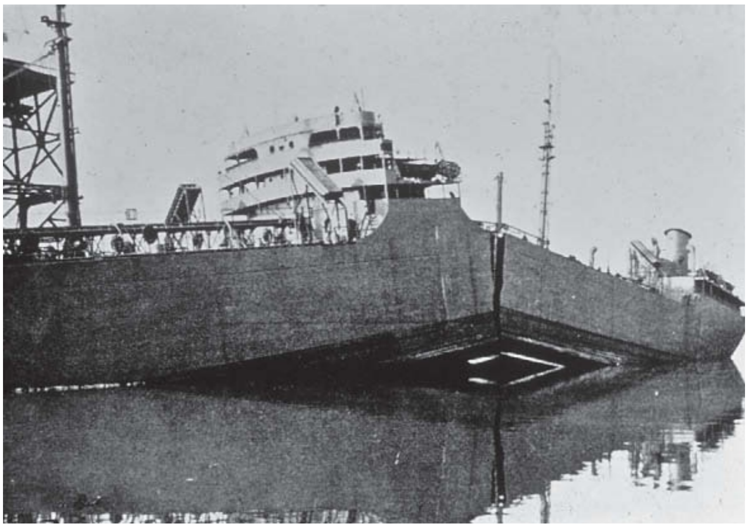

Figure 20: A damaged Liberty ship due to hull cracking [30]

The cracks were originated in regions typically of stress-concentration, such as hatch corners. Additional causes for these failures were overweight and storms beyond the design envelope.

The whole structural design was then redone, widening the space between beams, making the ship less stiff and flexible enough to absorb strain in severe conditions. In addition, the transition temperature of the alloy steel was then dimmed to levels below the North Atlantic harsh conditions.

Figure 21, from the US Naval Research Laboratory [31], shows some technical hints of the importance of the transition temperature on steel alloys, after keeping in mind that above the transition temperature the material will have a ductile behavior, which goes towards a safer way.

U.S. NAVAL RESEARCH LABORATORY

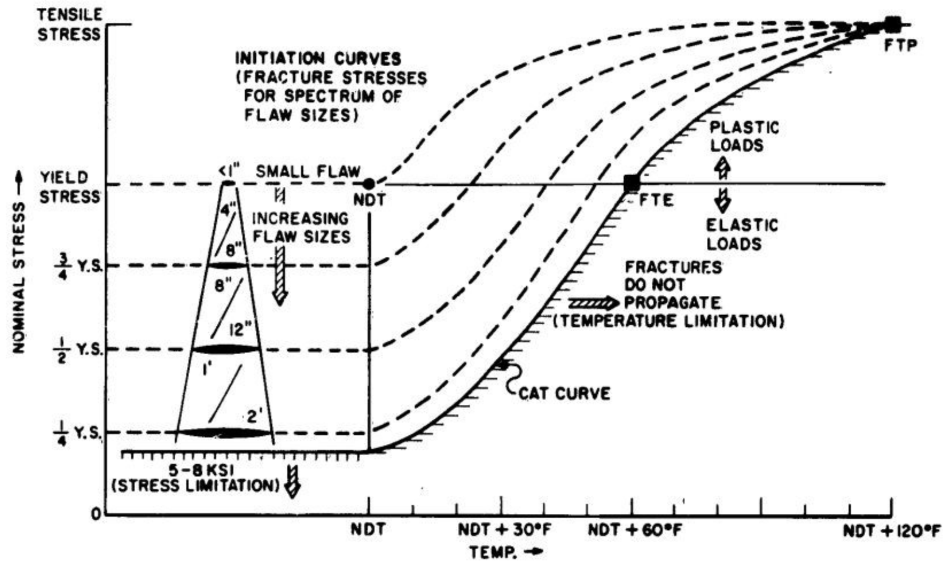

Fig. 9 — Generalized fracture analysis diagram, as referenced by the NDT temperature

Figure 21: the transition temperature curve [31]

The temperatures are represented in the horizontal axis and the nominal tensile testing stresses are shown in the vertical axis. As well known, the Yield stress represents the threshold between the elastic and plastic strain regimes.

Below the transition temperature, the material behavior will close to the tough category, and the higher the tensile load the faster a small crack will propagate (see the upper left corner of the picture), in opposition to a lower the tensile load (lower left corner respectively).

Trends in material selection for ship construction

The herald of an energy transition move indicates the substitution of the fossil fuels in the shipping industry and, consequently, the ship structures and materials already ask for more advance techniques linked to lighter and more reliable structures and systems.

The use of electric power shows to manage a set of advantages when reducing the CO_2 footprint, although further development has been required for the batteries and energy management systems. Nanomaterials have shown a favorable way to be spread into the ship materials sphere, allowing a more precise property build up and selection, mainly to hull paints and covers.

The lighter ship structure will ask for lower propulsion power, for the same payload, and the polymeric materials present an advantage at a large. The development of systems to handle the Hydrogen has its place in the shipping technologies, strengthening the possibilities of the electric ship power. Some ships can burn liquified natural gas (LNG), which is not so environmental aggressive as other fossil fuels, but it requires special safety measures to prevent explosion and fires aboard.

The integration of different power forms, such as screw and modern sails, can save money in time during this transition. For instance, the steel making industry has researched greener ways to operate furnaces and the whole logistic and factory chains, managing the wastes (thermal and material) more carefully (e.g., using more heat recovery techniques). This initiative adds a smaller CO_2 footprint to the shipping industry as well.

3.5.6 Structural reliability

In modern structural design, the use of probability models has increased to save resources, lives and to a better environmental protection, because the data management has improved with the use of larger digital computing engineering. Therefore, the structural reliability has better profiles and continues to be expressed as the complement of the failure probability, or structure reliability equals to (1 – structure failure probability). As a result, structural reliability becomes more and more a design philosophy taking the place of the deterministic methods, being also applicable to the structural maintenance.

The core of the ship structural reliability is to handle the set of uncertainties found in the ship construction, operation, and maintenance. These uncertainties lie on the variability of the material composition, processing (where welding has a main contribution) and degradation (here oxidation/corrosion leads). Due to the large number of factors, it has been a place to use statistic models to predict the material failure, in different orders of math complexity.

As an example, the combination of two different materials, such as steel and Aluminum, or the impact of ice into ships not designed for it put together different approaches when dealing with ship structural reliability. Also worth noting, the use of accelerometers with wireless digital networks grabs data from hot spots to feed up statistical methods, and the Machine Learning and Artificial Intelligence tools to provide a quick overview of the hull reliability.

Another example of material reliability assessment comes from the nuclear material selection aiming the primary circuit conditions, or the materials closer to the nuclear core. To cool down the nuclear fuel elements and to extract the heat produced by the fission reaction chain, light water is used in most of the reactors.

Therefore, the materials will face a water medium under nuclear fluence, measured in terms of number of neutrons per square centimeters (n/cm^2). This last characteristic comes from the integration of the neutron flux ($n/cm^2.s$) over time, where one core can last for say 30 months or more, depending on the nuclear materials selected and actual power profile. During the fission, high energy particles are released from the core and produce heavy impact in the structural materials. The operational and economic performance of a reactor comes from the reactor core performance and its interaction with all the surrounding materials.

Stress corrosion cracking has presented problems in reactor materials reliability, when dealing with alloys such as the 600 and 152, they have a high corrosion resistance tough. These alloys also have a thermal expansion coefficient like the carbon steel, which is the main material of the reactor pressure vessel, and it is advisable to use materials with the same expansion coefficient, to prevent strain or dissimilar deformations due to the temperature.

In the last forty years, these alloys have been used but shown early cracks impeding the reactor economics. The Electric Power Institute (EPRI/USA) has conducted a series of laboratory testing regarding the stress corrosion cracking in pressurized water reactors, mainly to assess what metallic alloys will improve the material reliability.

Even today, the causes of this stress cracking phenomenon have not been understood fully, and the prediction when and where it may occur has been a challenge, although studies have been carried out in weld parts. The most key chemical components have been identified as Carbon and Chromium, both present in the alloys, but also their manufacturing details, residual stresses, and the operational envelope have a significant contribution. To improve the material reactor reliability, the solution was the change for the alloy 690, which is now set for the new designs and replacements.

3.5.7 Risk management

Since its beginning, the shipping industry operates along the insurance market, due to the amount of money involved. The prediction of how things may go wrong takes part of the mathematic techniques used by the insurance companies. They are based on data collected from different sources and time, and generate the probability of an event to happen, which is then linked to the consequences of this event, in terms of money figures.

The multiplication of the probability to happen and the money consequences is called ‘risk’ in a straight manner. Therefore, different math techniques have been developed to calculate the probability and to assess the consequences, shaping up what is called ‘risk management’. The Bayes theorem is instrumental within this whole procedure because it handles the conditional probability, or the probability of something to happen, knowing that another event has already occurred.

In the shipping industry, the risk management has different levels, and it starts a way before the ship operation per se. While studying the shipping routes, based on forecast market requirements, to link ports and cargo terminals, weather data is analyzed as a time series to identify seasonal components, which may be set in terms of wave loads or storms intensity. This analysis will make part of the probability to have a damage hull and all the consequences, in other words to figure out the risk associated to the route.

Another risk involved deals to run aground while entering or exiting some terminals and ports. Shallow waters require constant chart update because sand or bottom obstacles vary in position quite often. Even using port pilots, the probability to run aground exists and, in some cases, can damage the hull drastically. In this case, even with a certain damage extension, a ship may sail under restraint envelopes till to reach a shipyard for repair.

The hull structure and related systems (e.g., ballast control, fire control etc.) must be monitored to evaluate the probabilities involved. For instance, the hull structure is checked in terms of strain evolution (longitudinal and transversally) of the different kind of structural components. This strain evolution makes part of probabilistic models to assess the hull safety, or how close the actual load condition is to the design or licensing limit. As mentioned before, accelerometers and wireless networks also work in data gathering to fill up math algorithms used for risk management.

Unfortunately, fire aboard has a not neglected frequency, as an initiation event for an accident, and thus, the probability of fire and its progression aboard is taken during the risk management. The consequences of a fire while in a port or terminal are different from those in the middle of an ocean.

The risk management takes care to quantify this set of conditions, which impacts the operational costs. Maintenance conditions are also taken by the risk management because some spare parts change may occur on route, depending on the difficult or importance level. Moreover, some repairs are not allowed while on sailing and must be done at a skilled shipyard.

One of the forms to assess the maritime risk is to build up a matrix, considering the levels of severity (impacts) and the probabilities. The impacts may be from ‘minor’ to ‘catastrophic’, and the probabilities may be linked to a frequency of occurrence in terms of years.

For instance, an event that has a probability to occur at every 10 million years is less probable than the one to occur at every 100 years. Thus, a matrix can be colored in terms of the acceptance of the risk. Figure 22 shows an example of the risk matrix. The figures shown may vary depending on the accumulated data and operational experience, among other factors. Grounding and collision are the main accidents on the scene, but others exist such as fire and hull failures. The main consequence also regarded is the presence of ‘leak’, which may or not occur, with odd environmental aftermaths. As a general point of view, the ship must set sail with ‘negligible risk’ area. The acronym ‘ALARP´ stands for as low as reasonably practical.

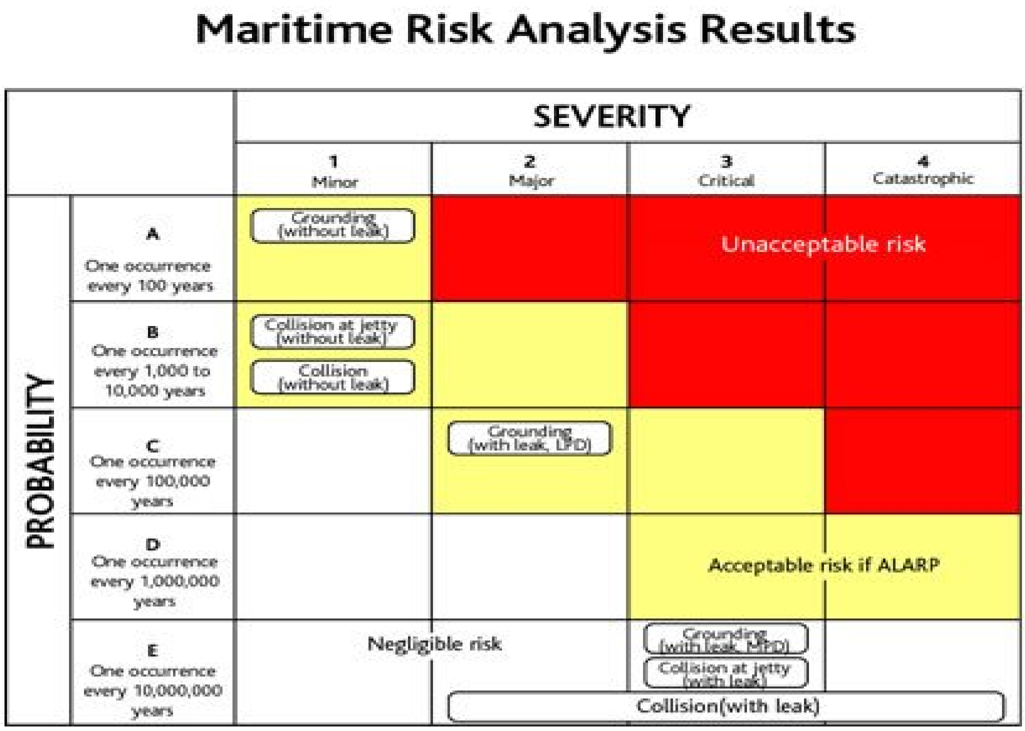

Figure 22: example of ship accident risk matrix [32]

3.5.7.1 Hazard analysis

The nuclear and petrochemical industries provide good examples of hazard analysis, which are also taken by the shipping case. The handle of dangerous materials, such as acids, fuels, explosive gases, and others demand a chain of safety measures to cope with the risk which is accepted by national safety authorities. For instance, some ships operate with aviation fuel, such as the aircraft carriers. The hazard analysis demands to consider the same provisions set for airports added with those from the naval culture or requirements, to protect people, hardware, and the environment. Normally, aviation fuel vaporizes in conditions different from the crude oil burned in some ship power systems and then it requires different kind of stopping valves, instrumentation, and storage tanks (e.g., due to corrosion).

The hazard analysis classifies the ship areas/conditions into categories linked to the safety measures need to follow the legal framework where the ship is registered or operates. For instance, while in ports, nuclear propulsion ships are required to maintain their nuclear reactors in a hot shutdown condition, which means there is no propulsion power, but only the power necessary to operate their safety systems accordingly. In addition, some auxiliary systems may be required, external to the ship, to provide heat removal from the ship nuclear systems, which is the case of the heating and cooling ventilation systems. Another example of hazard analysis focuses the need to maintain tanks almost full, rather than operating with intermediate levels. In ships, the half level condition normally worsens the ship stability, due to a phenomenon called 'free water' oscillation. Furthermore, depending on the fluid and its temperature, the half level may set an easier vaporization condition, increasing the fire probability.

4 Concluding Remarks

In this chapter, a general view of the ship design was presented, covering its phases and relevant technical issues. The characterization of the ship dimensions and systems, along design drawings and materials application, was described in a progressive way. As the sections of the chapter were presented, the engineering materials field had been expanded in terms of technical figures and details. The focus was to provide a spark to the reader about the variety of topics around the ship materials selection and its evolution, without the pretense explore all the fields in deep. The data presented came from open sources, intending to provide a order of magnitude of the reasoning discussed along the text, and they may be seem as mean values. All topics here shown are under continuous development, mainly the nuclear examples, and more recently the application of Machine Learning and Artificial Intelligence. As a high potential subject for technical improvement, the environmental impact reduction with new fuels and propulsion systems has its place to catch the general attention.

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Suggested Reading

A - https://www.academia.edu/41835546/Materials_Selection_in_Mechanical_Design_Fourth_Edition, which is a book on materials selection from Prof. Michael F. Ashby, with several technical charts guiding the selection of different engineering material for real applications.

B - https://www.materials.unsw.edu.au/study-us/high-school-students-and-teachers/materials-shaped-history, which provides an overview of the history evolution of materials processing and its consequences in normal life.A. H. Cheng and D. T. Cheng. Heritage and early history of the boundary element method. Eng. Anal. Bound. Elem., 2005. ISSN 09557997. doi: 10.1016/j.enganabound.2004.12.001.

C - https://lps.library.cmu.edu/ETHOS/article/id/40/, dedicated to the material science history, focusing the technology transitions and its aftermaths.A. H. Cheng and D. T. Cheng. Heritage and early history of the boundary element method. Eng. Anal. Bound. Elem., 2005. ISSN 09557997. doi: 10.1016/j.enganabound.2004.12.001.

D - https://www.nrl.navy.mil/Our-Work/Areas-of-Research/Material-Science-Technology/, where examples of laboratory campaigns are shown to develop defense hardware related to naval affairs.A. H. Cheng and D. T. Cheng. Heritage and early history of the boundary element method. Eng. Anal. Bound. Elem., 2005. ISSN 09557997. doi: 10.1016/j.enganabound.2004.12.001.

E - https://www.sname.org/, a broad site covering manifold shipbuilding and design issues.A. H. Cheng and D. T. Cheng. Heritage and early history of the boundary element method. Eng. Anal. Bound. Elem., 2005. ISSN 09557997. doi: 10.1016/j.enganabound.2004.12.001.