Module 1

Ship Types, Structure, Strength, Stability and Corrosion Control Strategies

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Contents

1. Introduction

This module is the first in a series of study towards the IIMS professional qualification in marine corrosion. It covers ship types and aspects of ship structure, strength and stability. In addition, details of corrosion prevention strategies including the use of corrosion protective paints, antifouling coatings, inhibitors and cathodic protection methods are discussed. These are all extensive study areas and consequently not every aspect of the topics can be given complete attention, nevertheless, a broad range of the more important areas are discussed and underlying basic principles described. The ideas covered are further complemented in the slide sections and in some cases, these provide more specific details.

The module begins with a general description of some common ship types including passenger ships, oil tankers, bulk cargo carriers and RoRo vessels. This presents a useful vehicle for insights into other important topics such as the specific arrangements for crew, passengers, machinery and cargo, basic architecture and the important role that organization's such as International Convention for the Prevention of Pollution from Ships (MARPOL), Maritime Safety Committee (MSC) and International Convention for the Safety of Life at Sea (SOLAS) have on marine engineering.

A discussion of ship types is followed by a section on basic ship terminology and this is expanded still further in the first slide section. An appreciation of ship terminology provides a useful foundation for considering ship stability both statical – response in still water and dynamical – response in waves, in more analytical detail. Stability is a prerequisite to understanding the movements that occur in ships and underpins important areas relating to ship strength such as the longitudinal distribution of bending moments and shearing forces. Knowledge of stability and in particular the forces that ships are subjected to is critical to appreciating how ship architecture and designs have evolved over the last century.

2. Types of Ships

2.1 Passenger Ships

During the first half of the twentieth century the passenger ship was the only way to transport large numbers of people about the world reliably. However, the development of air transport took over this role, and the passenger ship market changed almost overnight. The vast majority of ships in this sector are now cruise ships and ferries. Most are of a conventional design, but the fast ferry is very popular for short service routes.

Ferries operating in a limited area or on a short regular route are increasingly being designed using liquefied natural gas (LNG) or 'hybrid' technology as the energy source for vessel propulsion.

Universal agreement has the passenger ship defined as 'a vessel that is designed to carry more than 12 passengers on an international voyage'. These vessels must comply with the relevant International Maritime Organization (IMO) regulations included in the Safety of Life At Sea (SOLAS) and the Load Line Conventions for passenger ships. Cargo ships can still carry up to 12 passengers without being reclassed as a passenger ship.

The only departure from this requirement is in the superyacht sector, where the UK's Maritime Coastguard Agency (MCA) has developed the 13-36 Passenger Yacht Code. This code is for use by the Red Ensign Group to register large passenger yachts that carry up to 36 passengers. These types of vessels find it very difficult to comply with the full requirements of the IMO regulations for passenger ships, and this led the UK administration to develop the regulations for this sector.

Passenger ships, in general, range from small river ferries to large ocean-going vessels. Cruise ships can now carry up to 4000 passengers and are designed to provide maximum comfort for all guests on board, see Figure 1. These ships include in their services large dining rooms, luxury restaurants, theatres, cinemas, swimming pools with water slides, gymnasia, open deck spaces and shops. They usually cater to guests with a range of purchasing power and are being designed increasingly to provide the majority of rooms with a balcony and a 'sea view'.

Ferries are also being designed after listening to customers' needs. For example, ferries carrying large numbers of trucks might provide a specific place where the drivers can rest and have a meal in a restaurant that has been designed with them in mind. Ro-Ro ferries are now 'double decked' and arranged so that both decks can be loaded at the same time. This is important as the time in port for any vessel is 'non-revenue' earning and therefore needs to be reduced to a minimum.

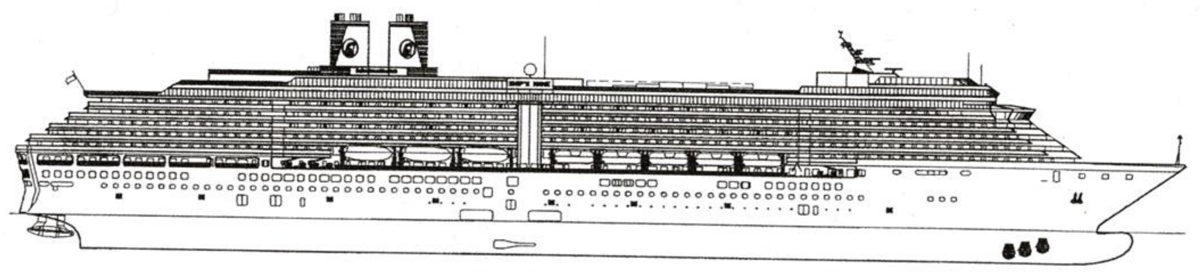


Figure 1. Cruise Liner Schematic[1]

Small 'passenger vessels' are now on the increase, some supplying the ever-growing needs of the 'offshore' renewable energy sector. Passenger vessels restricted to 'inland waterways' are starting to use 'hybrid' technology to meet their propulsion needs. There is an advantage for passenger comfort if electric engines can be used. However, there will have to be a significant development in battery technology before the diesel engine can be removed from the system completely.

Invariably new standards are applied to passenger ships slightly ahead of cargo ships. It is also usually the case that the rules are more stringent for passenger ships, and during the 1990s there was increasing concern about the safety of very large passenger ships and new regulations appeared focusing on their construction and on the training of the crew for such vessels.

Minimum standards for crew accommodation are now required under the International Labour Organisation's (ILO) Maritime Labour Convention 2006 (MLC 2006).

A sign of the times is that most people look to manage risk as they go about their daily work. The IMO is no different and during the 1990s and into the early twentieth century they worked on developing a risk-based approach to the operation and construction of ships.

In 2006, the 82nd sitting of the IMO's Maritime Safety Committee 82 (MSC 82) adopted comprehensive amendments to SOLAS chapter 11-1; this section of SOLAS relates to the subdivision and damage stability requirements for passenger and cargo ships.

Also, in 2006 came the plans to improve the safety of passenger ships based around the Safe Return to Port (SRtP) concept for these ships. SRtP centres around the notion that 'your ship is your best lifeboat', and therefore if the ship can be constructed with maximum 'survivability', then there will be less of a need to resort to the much smaller and more vulnerable 'lifeboats' in the event of an accident.

The IMO amended regulations to improve the safety of passenger ships by placing more emphasis on the prevention of casualties and improving the survivability of the ship in the event of an incident, and thus allowing the passengers to stay safely onboard while the vessel returns to the nearest safe haven.

A further development for the very large passenger ship is the 'diesel electric' (power station) concept. This is where the main engines are large diesel alternators producing high voltage electricity that is used to either power the ship or run large electrical loads servicing the passengers, such as the air conditioning compressors, ventilation fans or galley and laundry equipment.

Two significant marine manufacturers are now making large electric motors that are arranged in their own containers (pods) and hang below the hull of the ship.

2.2 Container Ships

Ships travelling between allocated ports and having specific departure and arrival dates are considered to be running on a liner trade. Both passenger ships and cargo ships can be 'liner ships', however the role of carrying and delivering goods and services has now moved mostly to the domain of the cargo ship with the container vessel being the modern version.

Cargo liners are vessels designed to carry a variety of cargoes between specific ports and, as stated, the modern configuration of this type of vessel is the container ship and most of the non-liquid cargos and some liquid cargos are now carried around the world by this type of ship.

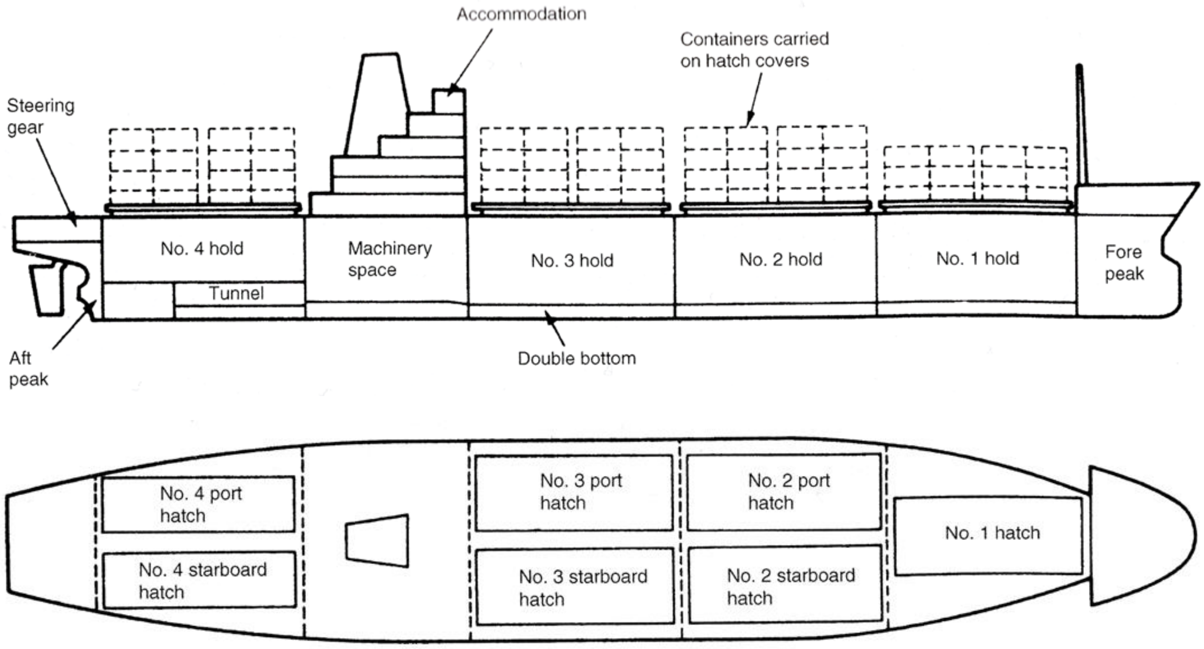


Figure 2. Typical Container Ship Layout[2]

The standardisation of cargo carrying 'units' (containers) has transformed the efficiency of moving cargo from place to place. Anything that will fit into a standard (8 ft x 8 ft 6 in x 20 ft or 40 ft) sized container can be moved via an intermodal transportation system in which the container ship plays a central role in the waterborne part of that system.

The reusable containers can be insulated and refrigerated and are capable of carrying perishable cargoes such as meat, fruit and fish. They are mostly standard steel boxes with doors at one end and are used to transport goods that are packed in boxes, drums, bags and cases or stacked on pallets. More details about containers can be found in Chapter 12 of this book.

Figure 2 shows the layout of a modern container ship, the size of which can be measured by the number of containers it can carry. The sizing is in the form of twenty-foot equivalent (TEU) units. This means that a medium sized container ship could be described as having a size of 9000 TEU or as having the ability to carry 9000 twenty-foot containers. The actual containers carried could be a mixture of twenty foot and forty foot.

The global system is arranged so that there are large 'deep water' ports, known as 'hub ports', that are distributed about the world. Large container ships up to 18 000 TEU travel between these ports. Smaller vessels known as 'feeder' vessels move the cargo from the large ports to smaller ports, close to the hub port.

As with many ships, at the extreme forward end is a tank known as the fore peak which may be used to carry water ballast or fresh water. Above this tank is an area called the chain locker and also a storage space. At the aft end is a tank known as the aft peak which generally encloses the stern tube in a watertight compartment. At the bottom of the vessel and between the two peak bulkheads is a continuous tank top forming a double bottom space which is further subdivided into smaller tanks suitable for carrying oil fuel, fresh water and water ballast.

The machinery space consists of heavy equipment and as such will place considerable local' stresses on the structure of the ship. If placed at the aft end, then the 'light ship' bending moment and hull stress will be reduced. The latest diesel electric propulsion systems enable the designer to place the main diesels in the best possible place for the benefit of the hull thereby maximising the cargo carrying capacity.

The reason for this is that the positions of the engines are not determined by the propeller shafting and gearboxes. The connection to the inboard electric motor or podded drive will be via electric cables and not by mechanical equipment.

Currently, in 2016, most ships use some form of oil as their major energy source. The general term for this fuel is bunkers which is a legacy from the early days of shipping when coal was the main source of fuel and the coal was loaded into coal bunkers. The oil fuel bunkers are taken on board when required and loaded into designated tanks called bunker tanks.

Due to the possibility of the presence of water, the fuel is transferred into settling tanks where any water in the mix will settle to the bottom of the tank. The water can then be drained off prior to the fuel being further treated on board with centrifugal purifiers before being used in the engines. In order to help the stability of a ship, it is generally a good idea to have the bunker tanks as low in the ship as practical, and therefore the tanks used as bunker tanks are usually the double bottom tanks.

It is also advantageous to have the bunkers arranged as close to the machinery space as possible. Fuel oil storage has become a significant issue in the design of ships. This is due to the requirement to have several different types or grades of fuel stored separate from each other.

In the past this has meant that the bunker tanks could be very close to or in contact with the outer hull of the ship. This ensured that any breach of the hull in way of the tank would release oil into the sea. The new MARPOL (International Convention for the Prevention of Pollution for Ships) regulation developed in 2006 and brought into force during 2010 required new builds to have 'protected' fuel oil storage tanks when an individual tank holds more than 60 m^3 of fuel.

When ships have the engine room sighted around the centre part of the vessel, there is a long path for the propeller shaft to take before it exits the hull via the stern tube bearing.

Between the aft engine room bulkhead and the after-peak bulkhead is a watertight shaft tunnel enclosing the shaft and allowing access to the intermediate shaft and bearings directly from the engine room. An exit in the form of a vertical trunk is arranged at the after end of the tunnel in case of emergency. In a twin screw ship, it may be necessary to construct two such tunnels, although they may be joined together at the fore and aft ends.

The arrangement of the machinery space on many modern ships is further aft and therefore the propeller shafting and intermediate bearings are sighted in the machinery space. Invariably a walkway and guard rail are placed close to the rotating shaft so that the watch keeping engineer can safely inspect the drive train for correct operation at any time.

The Maritime Safety Committee (MSC), at its 87th session in May 2010, adopted a new SOLAS regulation 11-1/3-10 on goal-based ship construction standards for bulk carriers and oil tankers (resolution MSC.290(87)).

These rules require that vessels have a design life of at least 25 years and that all the structural and manufacturing rules are consistent with this requirement. The class rules should consider at least:

- Extreme loads
- Design loads
- Fatigue
- Corrosion

2.3 Cargo Ships

General cargo (tramp) ships used to be those ships which are designed to carry any specific type of cargo and travel anywhere in the world on an irregular route. They were often hired out on a spot or time charter to carry bulk cargo or general cargo, and are usually slower and smaller than the container 'liner' vessels. The vessels may carry some or all of these cargos in containers.

To assist the safe stowage of cargo the cargo space is divided into lower holds and compartments between the decks, or 'tween decks. Many ships have three decks, thus forming upper and lower’ tween decks. This system allows different cargoes to be carried in different compartments and reduces the possibility of the cargo getting crushed. Access to the cargo compartments is provided by means of large hatchways which are now all closed by hydraulically operated steel hatch covers.

Suitable cargo handling equipment is provided in the form of hydraulic or electrically powered cranes. Heavy lift equipment may be fitted and is usually situated next to one or more hatches. A forecastle is fitted to reduce the amount of water shipped forward and to provide adequate working space for handling ropes and cables.

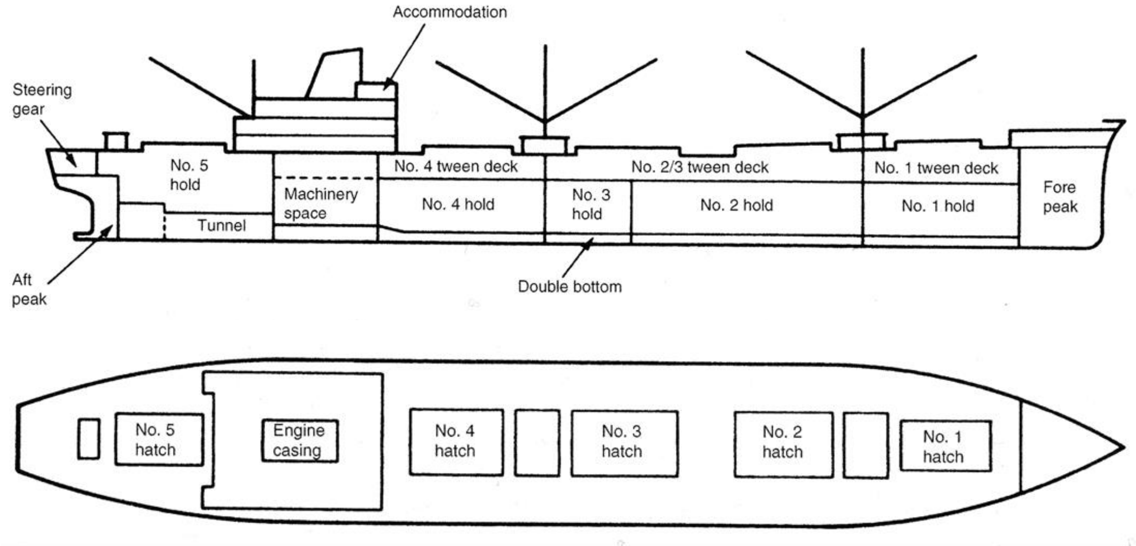


Figure 3. General Cargo Ship[2]

The forecastle also acts very effectively to protect the forward hatches from heavy weather damage. Obviously hatch covers are a prime area to guard against a breach of watertight integrity. The hatch covers are well designed but the forecastle provides a very good first line of defence and deflects the full force away from the hatches.

However, the work of these vessels is now being taken over by bulk carriers and smaller container vessels. Figure 3 shows the layout of a typical cargo tramp. The space immediately forward of the machinery space may be subdivided into lower 'tween decks and hold/deep tank thus improving the ability to even out the stress on the hull and/or give different options for carrying other liquids such as fuel or water.

2.4 RoRo (Roll-On/Roll-Off) Vessels

These vessels are designed with flat decks and have moveable watertight divisions to enable vehicles and tractor-trailer units to be driven into and off the vessel under their own power. Having such a large continuous deck means that any appreciable accumulation of water will have a magnified adverse effect on the vessel's stability. This is due to the 'free surface effect' inherent in such a body of water. The Ro-Ro vessel is particular! susceptible to this feature, and all the staff should be well aware of the dangers of the ship becoming unstable if it is not operated correctly.

A ramp is fitted at one or each of the ends of the ship allowing direct access for car trucks and buses which remain on board in their laden state. These ramps lead to large outer doors which have in the past been a source of leakage due to damage and or incorrect operation. Any ingress of water will come straight onto the Ro-Ro deck leading to the possible problem with free surface effect mentioned earlier.

Containers may be loaded 2 or 3 high by means of fork-lift trucks. Lifts and inter-dec ramps are used to transfer vehicles between decks and the most modern vessels have stern ramps that are angled to allow vehicles to be loaded from a straight quay (Figure 4).

Some specialist Ro-Ro vessels have very large car carrying capacity and are used to move considerable numbers of new cars around the world.

Where the vessel has a combined container/Ro-Ro capacity the term Lo-Lo is sometimes sed. This refers to the lift-on lift-off feature of the containerised cargo.

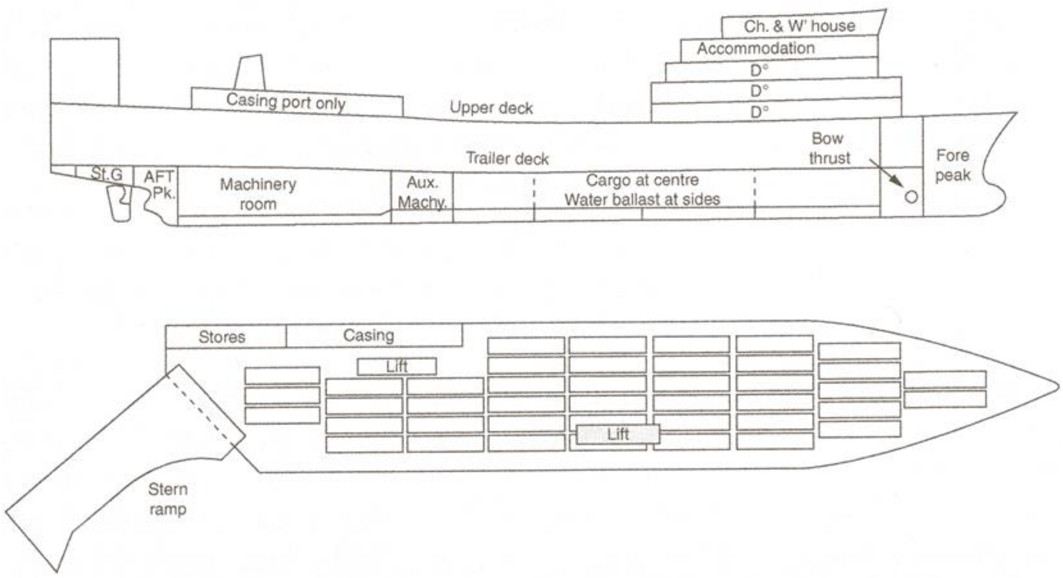


Figure 4. Roll-On, Roll-off Vessel[4]

Accommodation for crew and passengers includes restaurants and fast-food outlets as well as specific areas for long distance lorry drivers where they can complete 'official' rest periods that satisfies the 'drivers' hours' regulations. These vessels tend to work as liner vessels and ferries. The ports of Dover and Calais, either side of the English Channel, are very good examples of ports that are highly specialised in handling the Ro-Ro ferry operation.

2.5 Oil Tankers

Tankers are used to carry oil in bulk, and they can be divided into two different basic types. One type carries unrefined 'crude' oil while the other type, known as a product carrier, carries different types of 'refined' oils such as lubricating oil, naphtha, petrol or diesel oil.

The crude oil carriers are termed very large crude carriers (VLCC; 200 000-300 000 gt) or ultra large crude carriers (ULCC; 300 000+ gt). They are usually larger than the product carriers and can be as much as 300 000 gt. Students will appreciate the fact that if the crude oil is unrefined, then it will contain all the different types of oil all in one. This makes the crude oil quite volatile, and in the past there have been some significant explosions due to the mixture of hydrocarbons in a cargo tank.

Modern tankers (Figure 5.) are now fitted with fixed inert gas systems (all tankers over 8000 gt as of 1 January 2016). This means that when the oil is pumped from a tank during a discharge, the space above is filled with a gas that will not support a fire or explosion. Conversely as the oil is loaded the inert gas is released.

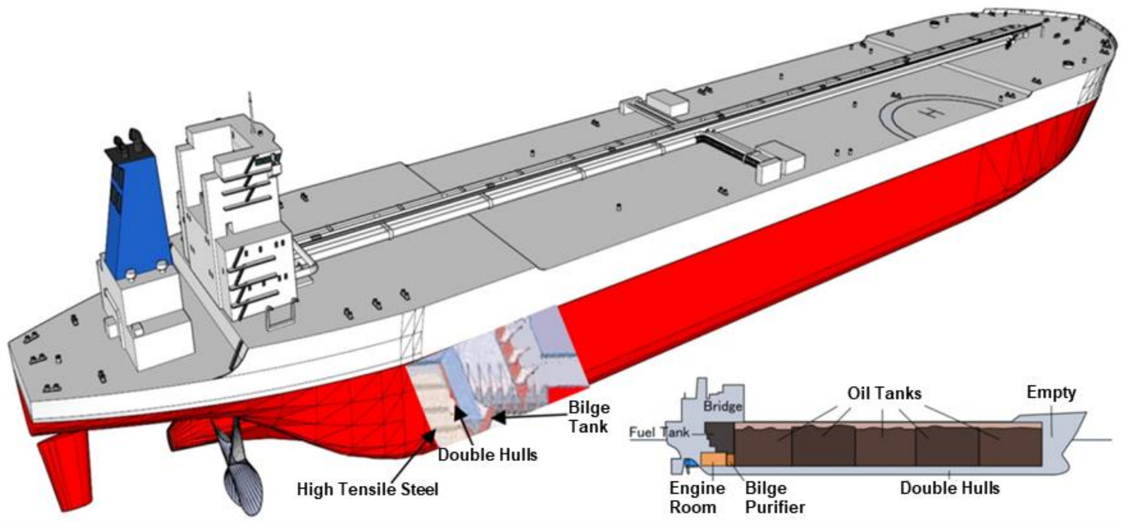


Figure 5. Schematic of an Oil Tanker[3]

The machinery space and accommodation on oil tankers is situated aft. This means that the designers can provide an unbroken cargo space forward of these features. The cargo tanks are subdivided by longitudinal and transverse bulkheads, and the tanks are separated from the machinery space by an empty compartment known as a cofferdam. A pump room may also be provided at the after end of the cargo space just forward of the engine room and may form part of the cofferdam. It is then possible to have the cargo pumps situated in the pump room and the prime mover (diesel engines, steam turbines or electric motors) situated in the machinery space. A gas tight seal is maintained around any rotating drive shaft penetrating the bulkhead between the machinery space and the pump room.

In the older vessels a double bottom was required only in way of the machinery space and may have been used for the carriage of oil fuel and fresh water. Modern vessels must now have a 'double hull' covering the length of the ship. A forecastle is sometimes required and is used as a storage space, although on larger tankers this area is usually a continuation of the deck rather than a step change in the line of the ship. As the accommodation and navigation bridges are provided at the after end, the deck space may be left unbroken by superstructure and all the services and living arrangements, including catering equipment and facilities, are concentrated in one area.

In the smaller tankers much of the deck space is taken up by pipes and hatches. Therefore it is usual to provide a longitudinal platform or pathway to allow easy access to the forecastle and bow sections. The walkway is situated above the pipes and is known as the 'flying bridge'. On the VLCCs and ULCCs there is sufficient space to walk easily around the pipework. However the distance is so great that sometimes bicycles are provided for the crew. An alternative arrangement is for the ship to have a pump allocated to each cargo tank. Known as 'deep well' pumps they have the prime mover sited on-deck and the pump at the bottom of each tank driven by a long drive shaft.

Another feature required by modern tankers is the ability to moor up to Single Buoy Moorings (SBMs). These are typically arrangements where the output from an oil production field is fed along a pipe line, resting on the sea/river bed and leading to a mooring buoy that could be several miles away.

Readers can see that this single point, situated on the surface of the water, would warrant a special arrangement for securing the vessel. The Oil Companies International Marine Forum (OCIMF) produces guidelines for the design strength of systems for mooring to SBMs.

The method is to use the anchor chain; however the angle of the pull on the securing equipment will have moved from the sea/river floor to the surface. Therefore, the weight on the equipment will be at a much shallower angle.

The midship section is often split longitudinally with a centre tank often about half the width of the ship. However perhaps the most significant developments in tanker design is that of the inclusion of 'double hulls'. Following a series of mandates, during and just after the 1990s, regulation 19 in Annex 1 of MARPOL now requires that tankers over 5000 dwt be fitted with 'double hulls' or an alternative design approved by the IMO.

The harmonised Common Structural Rules (CSR) for Bulk Carriers and Tankers were introduced on 1 July 2015.This set of rules, developed by the International Association of Classification Societies (IACS), replaced the rules set independently for bulk carriers and for double hull oil tankers.

The first and common part covers the minimum requirements for the strength of the hull, such as expected wave loads, hull girder strength as well as minimum buckling and fatigue characteristics. A design life of 25 years is assumed and forms the base for the size of the scantlings and so on. The second part includes information specifically about the construction of the two different types of vessels.

Tankers, five years old or more, are subject to a 'special' survey. This survey will cover all the items in the 'annual' survey but will also examine all cargo tanks, ballast tanks, double bottom tanks, pump rooms, any pipe tunnels, cofferdams and void spaces. The aim is to ensure that the vessel is structurally sound for the next five years. The survey inspection will be backed up by hull thickness data and surveyors will look for corrosion, damage, fractures, deformation or set and any other structural deterioration.

The vessel will need to be dry-docked and all the crude oil washing and ballasting systems need to be in good working order. The tank coatings also need to be in good condition. The first special survey will require a spot check of the double hull but subsequent surveys will require a more rigorous inspection.

In addition to these inspections most respectable charters will insist on conducting a 'tanker vetting' process to ensure that the vessel is in a satisfactory condition to complete its charter and that it conforms to all the necessary requirements.

Tanker vetting will cover the condition of the vessel as well as inspect all the necessary records and documents to ensure that the tanker has been operated and maintained to the level required by the flag administration, by the classification society and by the insurers.

2.6 Bulk Carriers

Bulk carriers are vessels built to carry such cargoes as ore, coal, grain and sugar in large quantities, see Figure 6. They are designed for ease of loading and discharging with the machinery space aft, allowing continuous, unbroken cargo space forward of the accommodation. They are single deck vessels having long, wide hatches, closed by steel covers. The double bottom runs from stem to stern.

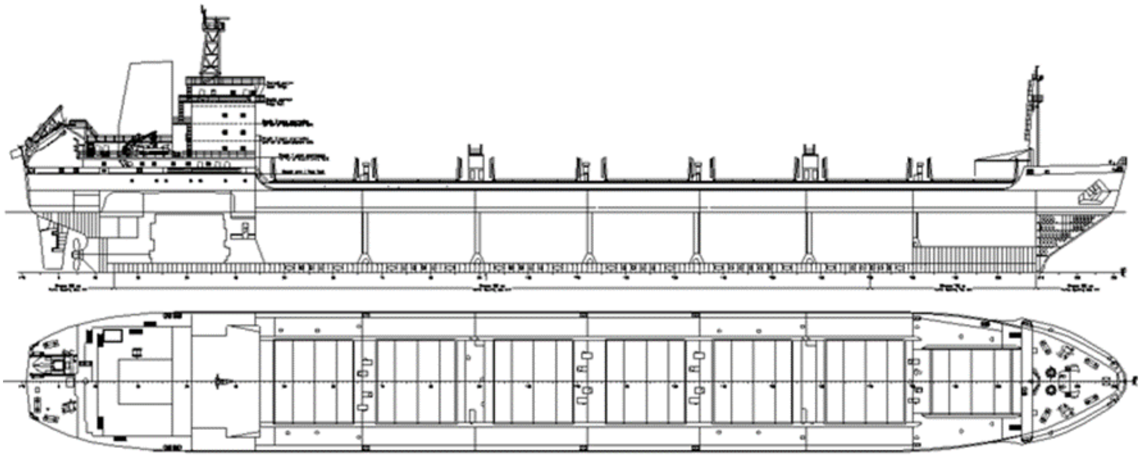


Figure 6. Schematic of a Bulk Carrier[4]

In ships designed for heavy cargoes such as iron ore the double bottom is very deep and longitudinal bulkheads are fitted to restrict the cargo space (Figure 7). This system also raises the centre of gravity of the ore, resulting in a more comfortable ship. The double bottom and the wing compartments may be used as ballast tanks for the return voyage.

Some vessels, however, were designed to carry an alternative cargo of oil in these tanks. With lighter cargoes such as grain, the restriction of the cargo spaces is not necessary although deep hopper sides may be fitted to facilitate the discharge of cargo, either by suction or by grabs. The spaces at the sides of the hatches are plated in as shown in Figure 8 to give self-trimming properties. In the past many bulk carriers had a tunnel is fitted below the deck from the midship superstructure to the accommodation at the after end. The remainder of the wing space was used for water ballast. Some bulk carriers are built with alternate long and short compartments. Thus if a heavy cargo such as iron ore is carried, it is loaded into the short holds.

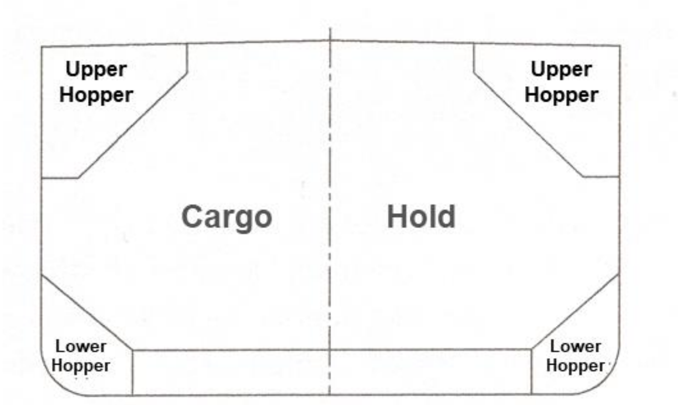


Figure 7. Transverse Section of Bulk Carrier with Heavy Cargo Design[4]

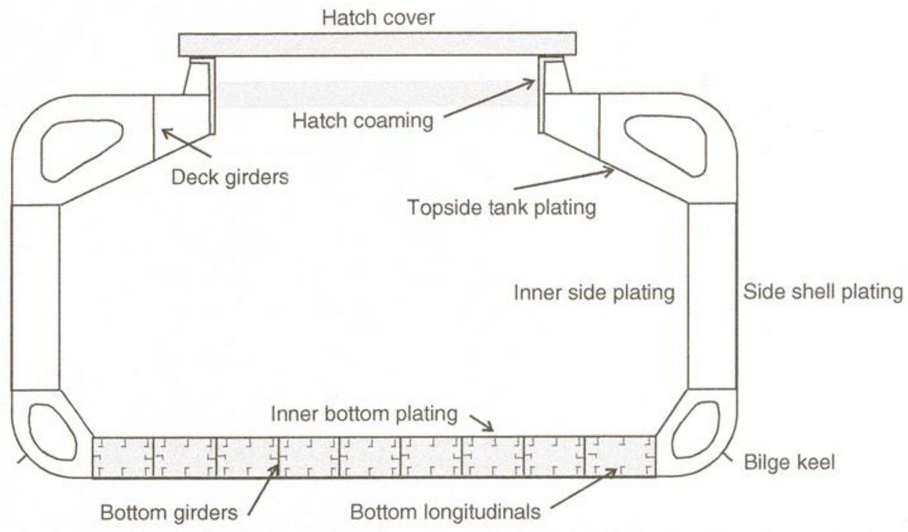


Figure 8. General Arrangement of a Double Skinned Bulk Carrier[4]

A cargo such as bauxite would be carried in the long holds, while a light cargo such as grain or timber would occupy the whole hold space.

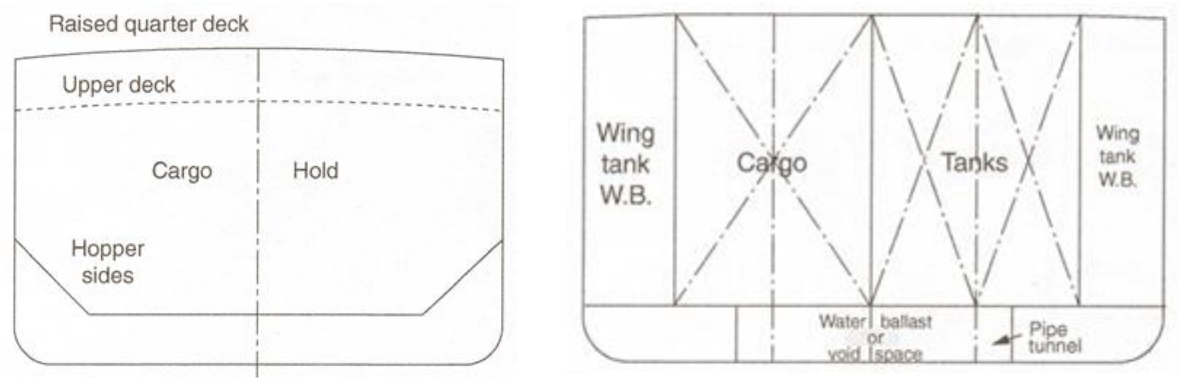
The double bottom is continuous in the cargo space, and it is raised at the sides to form hopper sides which improve the rate of discharge of cargo. Wide hatches are fitted for ease of loading, while in some ships small wing tanks are fitted to give self-trimming properties.

2.6.1 Chemical Carriers

A considerable variety of chemical cargoes are required to be carried in bulk, Figure 9. Many of these cargoes are highly corrosive and incompatible with each other while others require close control of temperature and pressure. Special chemical carriers have been designed and built, in which safety and avoidance of contamination are of prime importance.

To avoid corrosion of the structure, stainless steel is used extensively for the tanks, while in some cases coatings of zinc silicate or polyurethane are acceptable.

Figure 9. Bulk Chemical Carrier[5]



(a) (b)

Figure 10. Chemical Carrier Tank Designs (a) Raised Quarter Deck, (b) Design with Wing Tanks[4]

Protection for the tanks is provided by double bottom tanks and wing compartments which are usually about one-fifth of the midship beam from the ship side, Figure 10.

2.6.2 Liquid Gas Carriers

Over the past 40 years the LNG and the liquefied petroleum gas (LPG) carriers have carved out their own class of vessel, see Figure 11. The natural gas is mostly methane which may be liquefied by reducing the temperature to between -82°C and -162°C in association with pressures of 4.6 MN/m^2 to atmospheric pressure. The 'heavier' petroleum gas on the other hand consists of propane and butane and will be liquefied at a much higher temperature (-7°C).

Figure 11. Liquid Natural Gas (LNG) Carrier[6]

Since low carbon steel becomes extremely brittle at low temperatures, separate containers must be built within the hull and insulated from the hull. Several different systems are available, one of which is shown in Figures 12 and 13. The cargo space consists of three large tanks set at about 1 m from the ship's side. Access is provided around the sides and ends of the tanks, allowing the internal structure to be inspected.

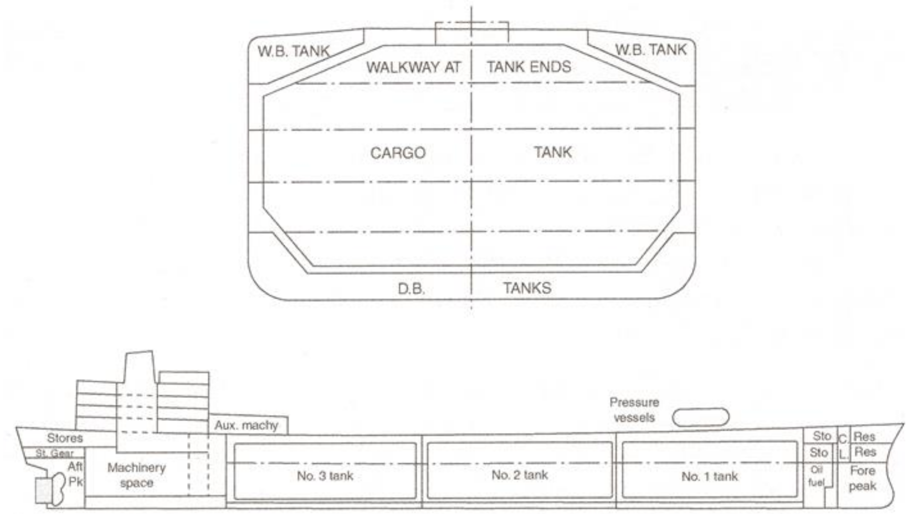


Figure 12. Liquified Natural Gas Carrier Layout[4]

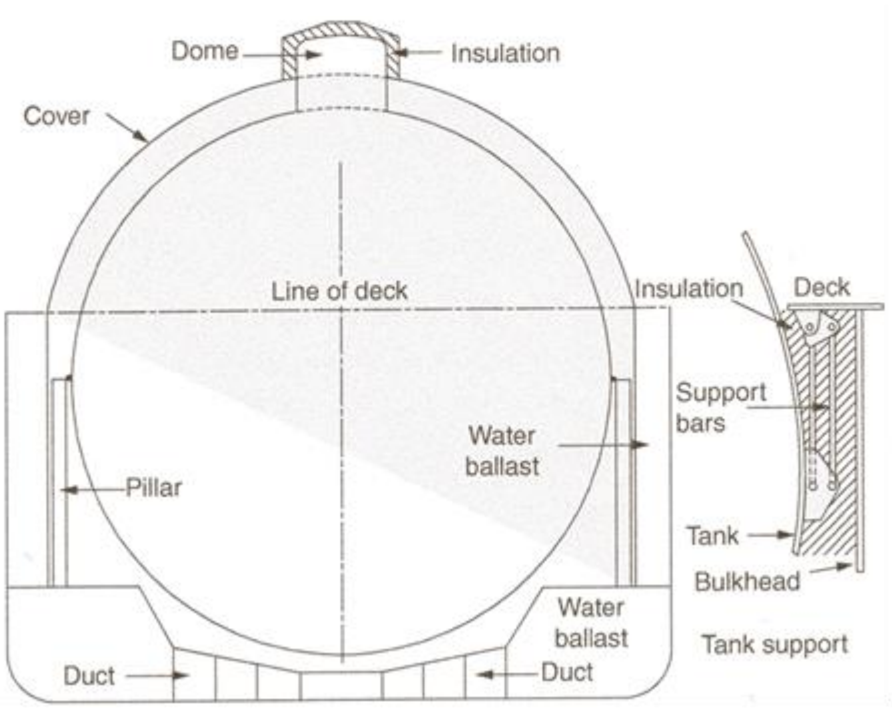


Figure 13. LNG Spherical Tank Design[4]

2.7 Super Yachts

This area of the industry is one that is expanding and developing fast. The demand for larger vessels has brought with it an increase in interest from regulators.

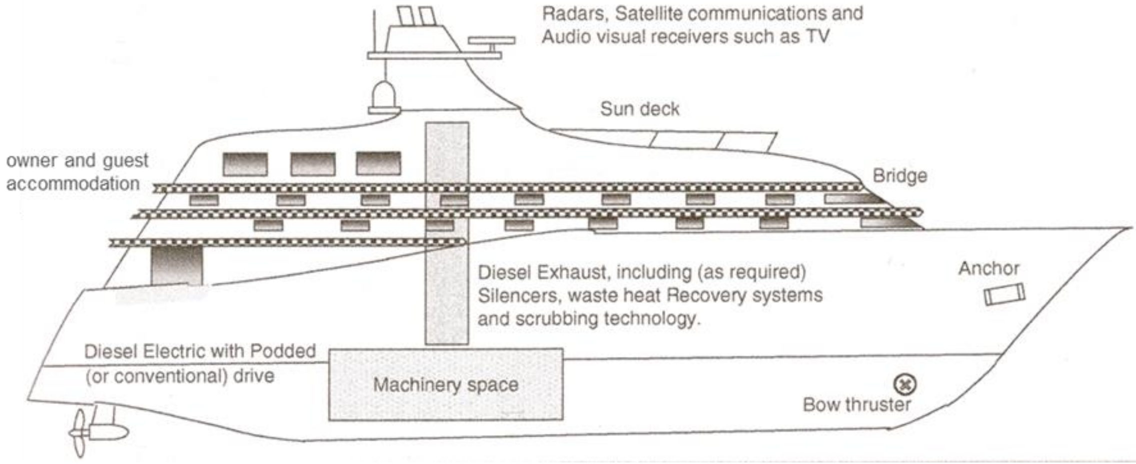


Figure 14. Super Yacht – General Arrangement[4]

Until recent years superyachts were built to a fairly modest size and tonnage and were operated by professional officers and crew on behalf of the owners. At that time the most important authority, IMO, did not have the time of resources to develop rules and guidelines for this area of the industry.

However during the end of the 1980s and through the 1990s the UK's MCA became increasingly concerned about the growing number and size of the vessels that make up this sector.

To offset the rising operating costs owners were also starting to turn to the practice of 'chartering' their yachts. This meant that there was a commercial undertone starting to take hold, and therefore the MCA felt the need to act without the blessing of the IMO. Twenty years on and flag administrations started to understand the wisdom of the MCA, but by then the third generation of the MCA's Large Yacht Code was being published. Version LY3 came about during 2015 and includes yachts carrying up to 12 passengers, see Figure 14.

The Large Yacht Code and the Code of Practice for Yachts carrying 13-36 passengers (the Passenger Yacht Code). The second edition introduced in 2012 sets out the requirements for yachts registered under the Red Ensign Group of flag administrations.

The rules cover all the usual items, such as the strength and standard of design of a yacht's structure, as well as things such as the use of helicopters and tenders/survival craft that are specific to yachts. The regulations also cover the requirements for the qualifications of the officers and crew that operate the yachts.

3. Ship Structure, Stresses and Strength

Ships were originally constructed with single bottoms, liquid fuels and fresh water being contained within separately constructed tanks. The double-bottom structure, which provides increased safety in the event of bottom shell damage, and also provides liquid tank space low down in the ship, evolved during the early part of the twentieth century. Today, only small vessels such as tugs, ferries, and cargo ships of less than 500 gross tonnage have a single-bottom construction. Larger ocean-going vessels are fitted with some form of double bottom.

3.1 Keel and Bottom Structure

At the center line of the bottom structure is located the keel, which forms the backbone of the ship. This contributes substantially to the longitudinal strength and effectively distributes local loading caused when docking the ship. The commonest form of keel is that known as the 'flat plate' keel, and this is fitted in the majority of ocean-going and other vessels, see Figure 15a. A form of keel found on smaller vessels is the bar keel, Figure 15b. The bar keel may be fitted in trawlers, tugs, etc. and is also found in smaller ferries.

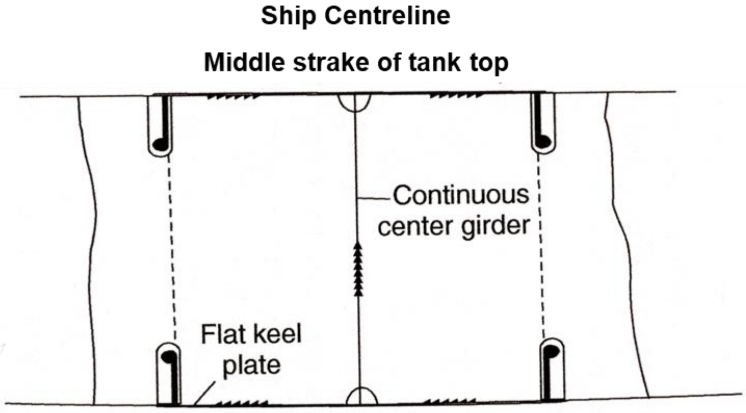


Figure 15a Flat Plate Keel[7]

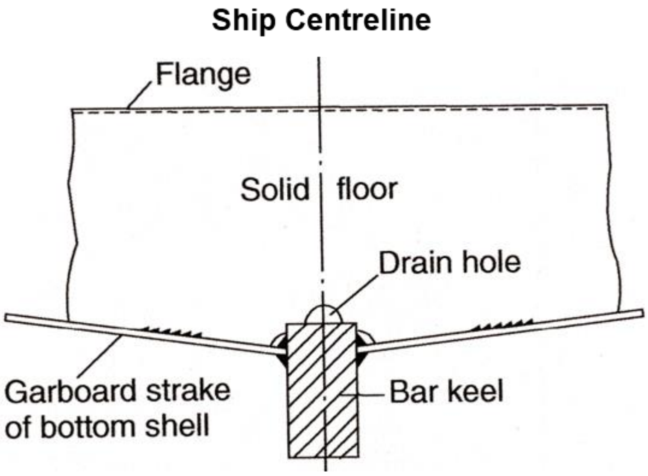


Figure 15b Bar Keel[7]

Where grounding is possible this type of keel is suitable with its massive scantlings, but there is always a problem of the increased draft with no additional cargo capacity. If a double bottom is fitted the keel is almost inevitably of the flat plate type, and bar keels are more often associated with open floors, but a flat plate keel can be fitted in way of open floors.

Duct keels such as that illustrated in Figure 15c are provided in the double bottoms of some vessels. These run from the forward engine room bulkhead to the collision bulkhead and are utilized to carry the double-bottom piping. The piping is then accessible when cargo is loaded, an entrance to the duct being provided at the forward end of the engine room. No duct is required aft of the engine room as the piping may be carried in the shaft tunnel. A width of not more than 2.0 m is allowed for the duct, and strengthening is provided at the tank top and keel plate to maintain continuity of strength of the transverse floors.

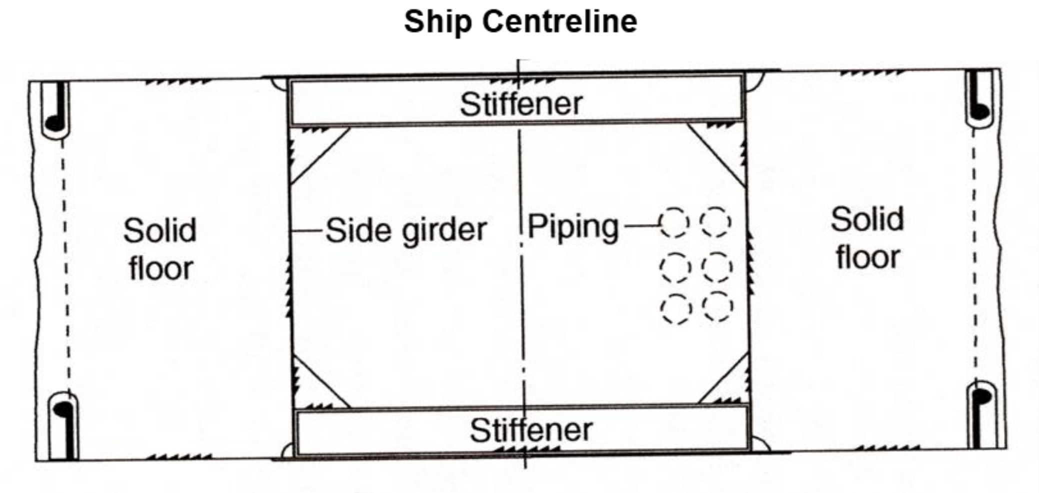


Figure 15c Duct Keel[7]

3.1.1 Bottom Structures

3.1.1.1 Single Bottom

In smaller ships having single bottoms the vertical plate open floors are fitted at every frame space and are stiffened at their upper edge. A center-line girder is fitted and one side girder is fitted each side of the center line where the beam is less than 10 m. Where the beam is between 10 and 17 m, two side girders are fitted and if any bottom shell panel has a width-to-length ratio greater than 4 additional continuous or intercostal stiffeners are fitted. The continuous center and intercostal side girders are stiffened at their upper edge and extend as far forward and aft as possible.

The single-bottom structure is shown in Figure 16 and for clarity a three- dimensional representation of the structure is also provided to illustrate those members that are continuous or intercostal. Both single and double bottoms have continuous and intercostal material, and there is often some confusion as to what is implied by these terms.

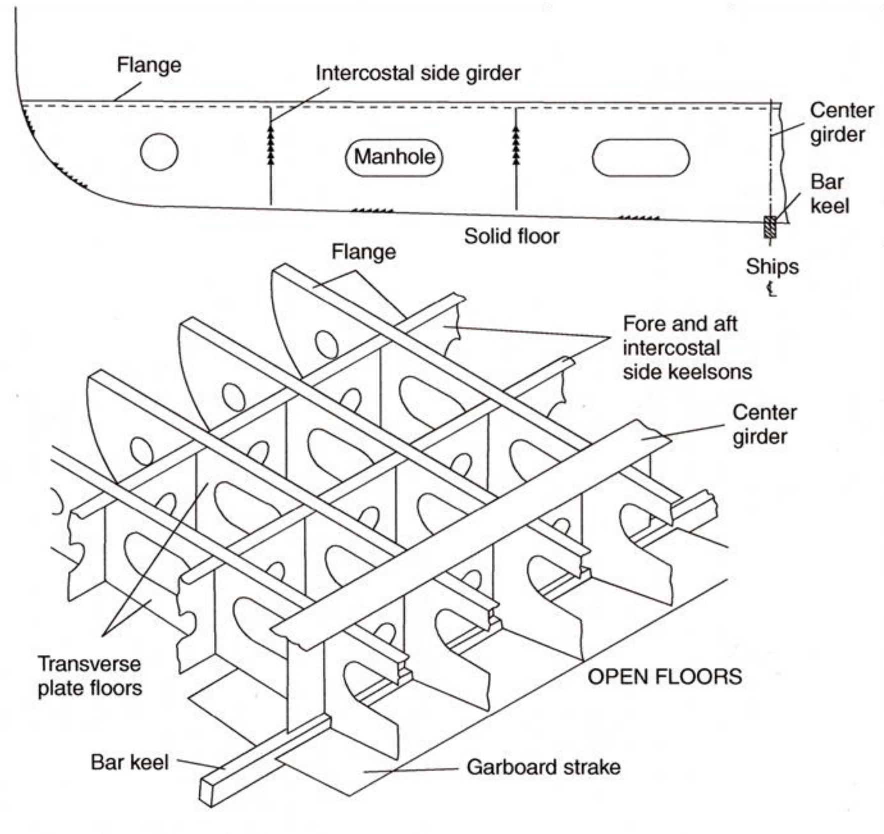


Figure 16. Single-Bottom Construction[7]

A wood ceiling may be fitted across the top of the floors if cargoes are to be carried, but this does not constitute an inner bottom offering any protection if the outer bottom shell is damaged.

3.1.1.2 Double Bottom

An inner bottom (or tank top) may be provided at a minimum height above the bottom shell, and maintained watertight to the bilges. This provides a considerable margin of safety, since in the event of bottom shell damage only the double-bottom space may be flooded, see Figure 17. The space is not wasted but utilized to carry oil fuel and fresh water required for the ship, as well as providing ballast capacity.

The minimum depth of the double bottom in a ship will depend on the classification society's requirement for the depth of center girder. It may be deeper to give the required capacities of oil fuel, fresh water, and water ballast to be carried in the bottom. Water-ballast bottom tanks are commonly provided right forward and aft for trimming purposes and if necessary, the depth of the double bottom may be increased in these regions. In way of the machinery spaces the double-bottom depth is also increased to provide appreciable capacities of lubricating oil and fuel oil. The increase in height of the inner bottom is always by a gradual taper in the longitudinal direction, no sudden discontinuities in the structure being tolerated.

Double bottoms may be framed longitudinally or transversely, but where the ship's length exceeds 120 m it is considered desirable to adopt longitudinal framing. The explanation for this is that on longer ships tests and experience have shown that there is a tendency for the inner bottom and bottom shell to buckle if welded transverse framing is adopted. This buckling occurs as a result of the longitudinal bending of the hull, and may be avoided by having the plating longitudinally stiffened.

Double bottoms in the way of machinery spaces that are adjacent to the after peak are required to be transversely framed.

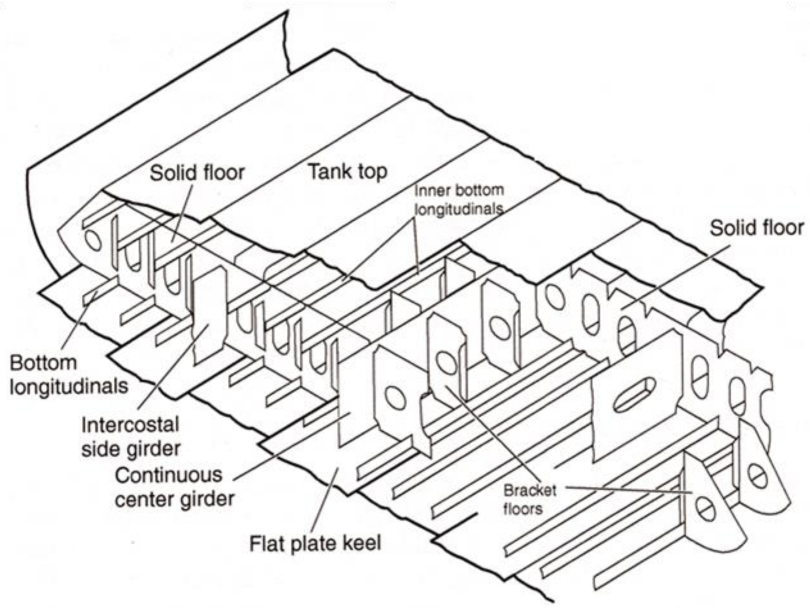


Figure 17. Single-Bottom Construction[7]

3.2 Vertical Shear and Longitudinal Bending

If a homogeneous body of uniform cross-section and weight is floating in still water, at any section the weight and buoyancy forces are equal and opposite. Therefore, there is no resultant force at a section and the body will not be stressed or deformed. A ship floating in still water has an unevenly distributed weight owing to both cargo distribution and structural distribution. The buoyancy distribution is also non-uniform since the underwater sectional area is not constant along the length. Total weight and total buoyancy are of course balanced, but at each section there will be a resultant force or load, either an excess of buoyancy or excess of load. Since the vessel remains intact there are vertical upward and downward forces tending to distort the vessel, see Figure 18, which are referred to as vertical shearing forces, since they tend to shear the vertical material in the hull.

The ship shown in Figure 18 will be loaded in a similar manner to the beam shown below it, and will tend to bend in a similar manner owing to the variation in vertical loading. It can be seen that the upper fibres of the beam will be in tension, as will the material forming the deck of the ship with this loading. Conversely, the lower fibres of the beam, and likewise the material forming the bottom of the ship, will be in compression. A vessel bending in this manner is said to be 'hogging' and if it takes up the reverse form with excess weight amidships is said to be 'sagging'. When sagging the deck will be in compression and the bottom shell in tension. Lying in still water the vessel is subjected to bending moments either hogging and sagging depending on the relative weight and buoyancy forces, and it will also be subjected to vertical shear forces.

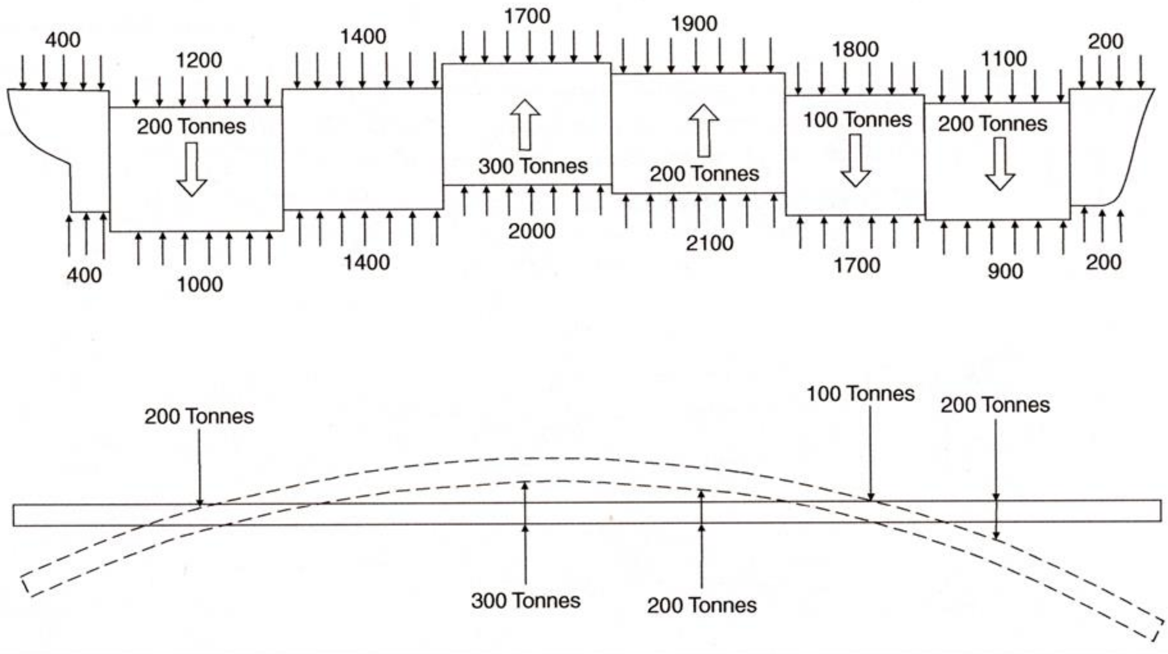


Figure 18. Vertical Shear and Longitudinal Bending in Still Water[7]

3.3 Bending Moments in a Seaway

When a ship is in a seaway the waves with their troughs and crests produce a greater variation in the buoyant forces and therefore can increase the bending moment, vertical shear force, and stresses. Classically the extreme effects can be illustrated with the vessel balanced on a wave of length equal to that of the ship. If the crest of the wave is amidships the buoyancy forces will tend to 'hog' the vessel; if the trough is amidships the buoyancy forces will tend to 'sag' the ship, see Figure 19. In a seaway the overall effect is an increase of bending moment from that in still water when the greater buoyancy variation is taken into account.

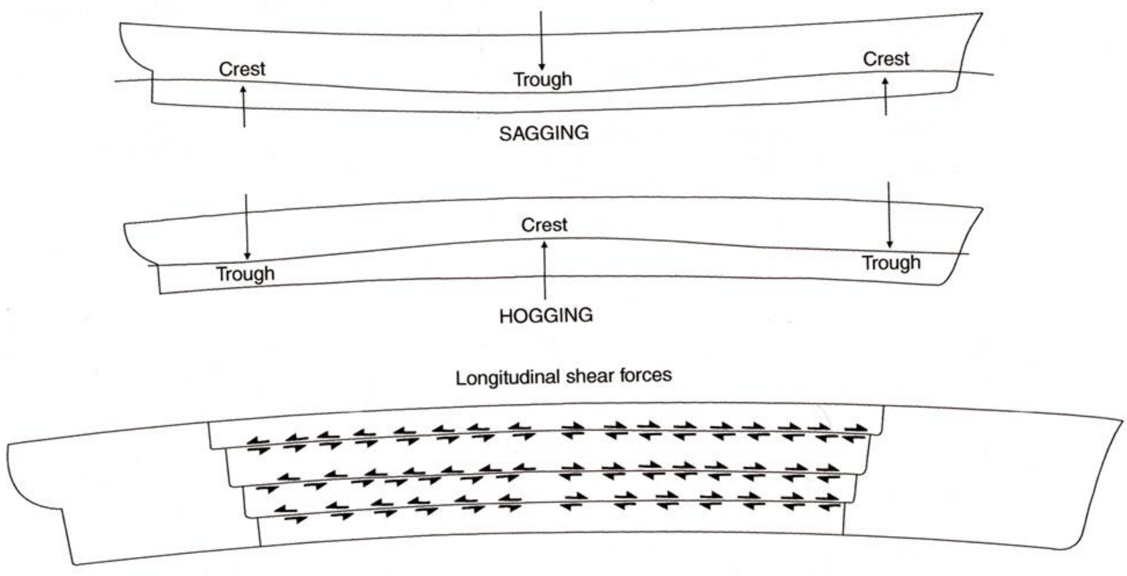


Figure 19. Wave Bending Moments[7]

3.4 Longitudinal Shear Forces

When the vessel hogs and sags in still water and at sea, shear forces similar to the vertical shear forces will be present in the longitudinal plane, see Figure 19. Vertical and longitudinal shear stresses are complementary and exist in conjunction with a change of bending moment between adjacent sections of the hull girder. The magnitude of the longitudinal shear force is greatest at the neutral axis and decreases towards the top and bottom of the girder.

3.5 Bending Stresses

From classic bending theory the bending stress ‘a’ at any point in a beam is given by,

$$\sigma = \frac{M}{I} \times y$$

where *M* = applied bending moment, *y* = distance of point considered from neutral axis, and *I* = second moment of area of cross-section of beam about the neutral axis.

When the beam bends it is seen that the extreme fibers are, say in the case of hogging, in tension at the top and in compression at the bottom. Somewhere between the two there is a position where the fibers are neither in tension nor compression. This position is called the neutral axis, and at the furthest fibers from the neutral axis the greatest stress occurs for plane bending. It should be noted that the neutral axis always contains the center of gravity of the cross-section. In the equation the second moment of area (*I*) of the section is a divisor; therefore, the greater the value of the second moment of area, the less the bending stress will be. This second moment of area of section varies as the depth squared and therefore a small increase in depth of section can be very beneficial in reducing the bending stress. Occasionally reference is made to the sectional modulus (Z) of a beam; this is simply the ratio between the second moment of area and the distance of the point considered from the neutral axis, i.e. $I/y = Z$

The bending stress σ is then given by $\sigma = M/Z$

3.6 The Ship as a Beam

It was noted above that the ship bends like a beam, and in fact the hull can be considered as a box-shaped girder for which the position of the neutral axis and second moment of area may be calculated. The deck and bottom shell form the flanges of the hull girder, and are far more important to longitudinal strength than the sides that form the web of the girder and carry the shear forces. The box-shaped hull girder and a conventional ‘I’ girder are compared in Figure 20.

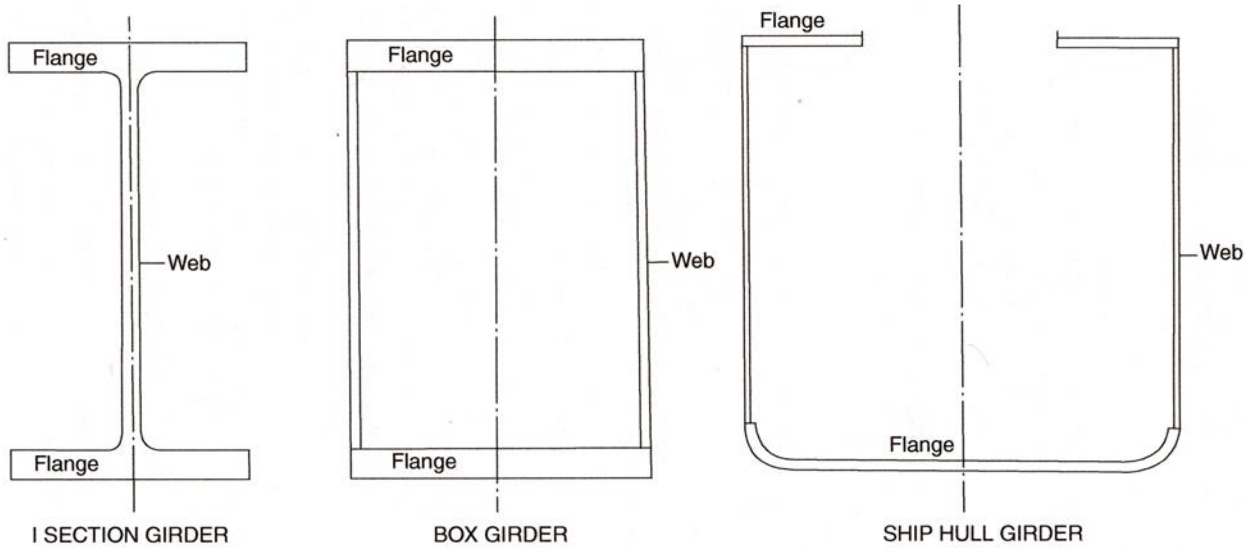


Figure 20. I and Box Girder Sections[7]

In a ship the neutral axis is generally nearer the bottom, since the bottom shell will be heavier than the deck, having to resist water pressure as well as the bending stresses. In calculating the second moment of an area of the cross-section all longitudinal material is of greatest importance and the further the material is from the neutral axis, the greater will be its second moment of area about the neutral axis. However, at greater distances from the neutral axis, the sectional modulus will be reduced and correspondingly higher stress may occur in extreme hull girder plates such as the deck stringer, sheer strake, and bilge. These strakes of plating are generally heavier than other plating.

Bending stresses are greater over the middle portion of the length and it is owing to this variation that Lloyd's give maximum scantlings over 40% of the length amidships. Other scantlings may taper towards the ends of the ship, apart from locally highly stressed regions where other forms of loading are encountered.

3.6.1 Strength Deck

The deck forming the uppermost flange of the main hull girder is often referred to as the strength deck. This is to some extent a misleading term since all continuous decks are in fact strength decks if properly constructed. Along the length of the ship the top flange of the hull girder, i.e., the strength deck, may step from deck to deck where large superstructures are fitted or there is a natural break, for instance in way of a raised quarter deck. Larger superstructures tend to deform with the main hull and stresses of appreciable magnitude will occur in the structure. Early vessels fitted with large superstructures of light construction demonstrated this to their cost. Attempts to avoid fracture have been made by fitting expansion joints, which made the light structure discontinuous. These were not entirely successful and the expansion joint may itself form a stress concentration at the strength deck, which one would wish to avoid. In modern construction the superstructure is usually made continuous and of such strength that its sectional modulus is equivalent to that which the strength deck would have if no superstructure were fitted.

3.7 Transverse Stresses

When a ship experiences transverse forces these tend to change the shape of the vessel's cross-sections and thereby introduce transverse stresses. These forces may be produced by hydrostatic loads and impact of seas or cargo and structural weights, both directly and as the result of reactions due to change of ship motion.

3.7.1 Racking

When a ship is rolling, the deck tends to move laterally relative to the bottom structure, and the shell on one side to move vertically relative to the other side. This type of deformation is referred to as 'racking'. Transverse bulkheads primarily resist such transverse deformation, the side frames' contribution being insignificant provided the transverse bulkheads are at their usual regular spacings. Where transverse bulkheads are widely spaced, deep web frames and beams may be introduced to compensate.

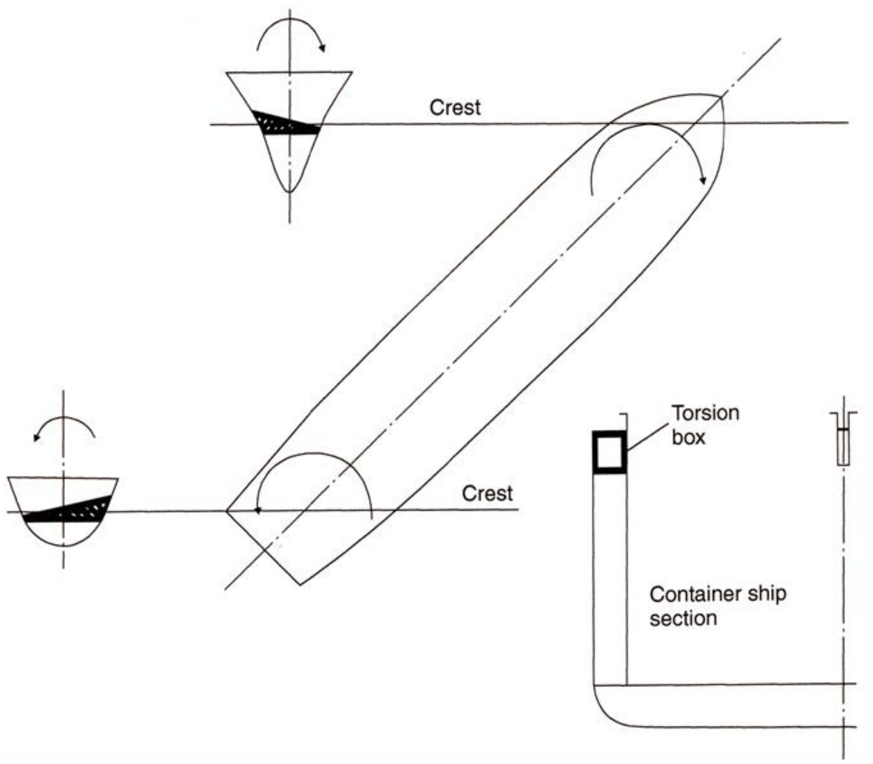


Figure 21. Schematic showing Torsion in a Ship[7]

3.7.2 Torsion

When any body is subject to a twisting moment, which is commonly referred to as torque, that body is said to be in 'torsion'. A ship heading obliquely (45°) to a wave will be subjected to righting moments of opposite direction at its ends, twisting the hull and putting it in 'torsion'. In most ships these torsional moments and stresses are negligible but in ships with extremely wide and long deck openings they are significant. A particular example is the larger container ship, where at the topsides a heavy torsion box girder structure including the upper deck is provided to accommodate the torsional stresses, see Figure 22a-b.

3.8 Local Stresses

3.8.1 Panting

Panting refers to a tendency for the shell plating to work 'in' and 'out' in a bellows like fashion, and is caused by the fluctuating pressures on the hull at the ends when the ship is amongst waves. These forces are most severe when the vessel is running into waves and is pitching heavily, the large pressures occurring over a short time cycle. Structural modifications to resist panting is shown in Figures 22a-b

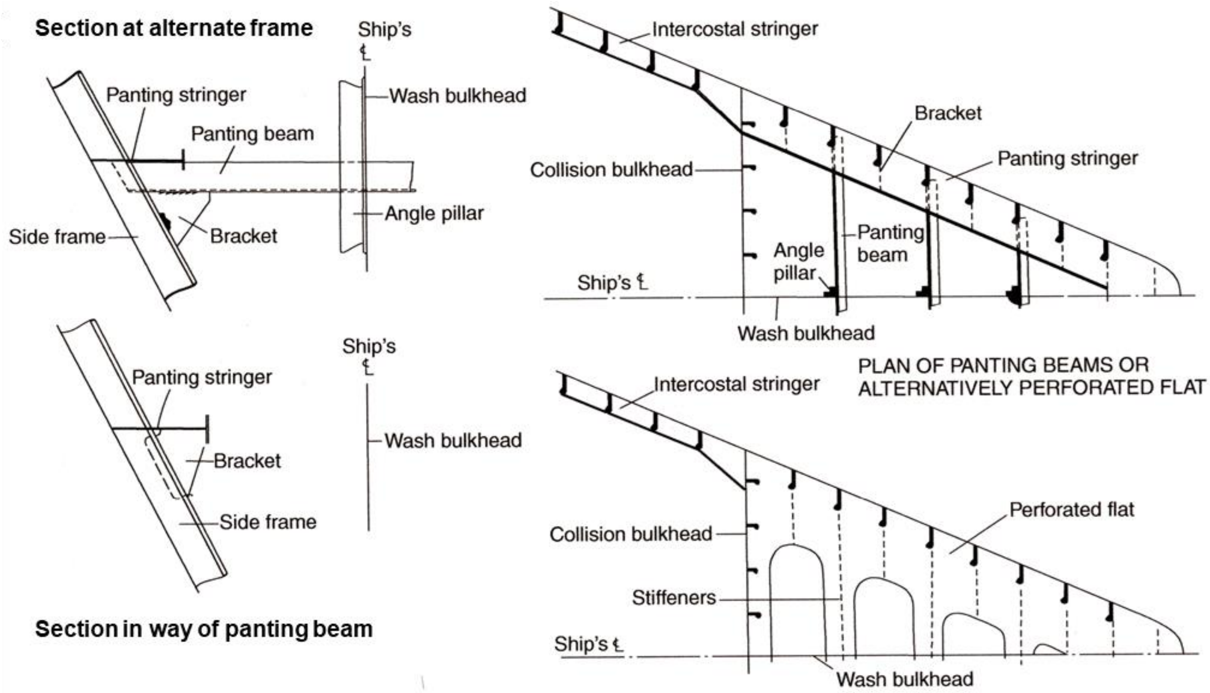


Figure 22a Panting Structural Arrangements[7]

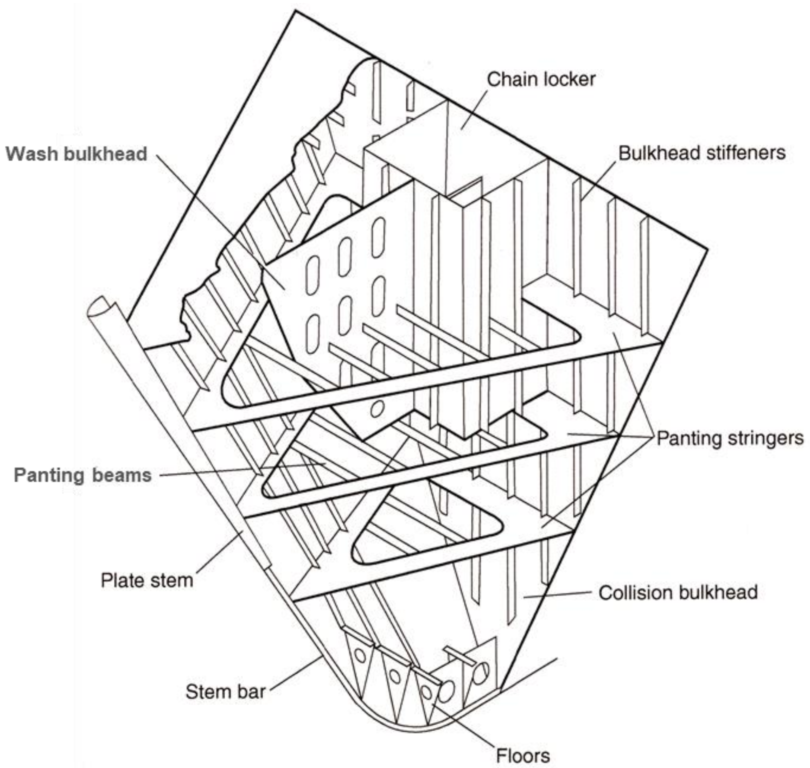


Figure 22b Panting Structural Arrangements[7]

3.8.2 Pounding

Severe local stresses occur in way of the bottom shell and framing forward when a vessel is driven into head seas. These pounding stresses, as they are known, are likely to be most severe in a lightly ballasted condition, and occur over an area of the bottom shell aft of the collision bulkhead.

If the minimum designed draft forward in any ballast or part-loaded condition is less than 4.5% of the ship's length, then the bottom structure for 30% of the ship's length forward in sea-going ships exceeding 65 m in length is to be additionally strengthened for pounding.

Where the double bottom is transversely framed, solid plate floors are fitted at every frame space in the pounding region. Intercostal side girders are fitted at a maximum spacing of three times the transverse floor spacing, and half-height intercostal side girders are provided midway between the full-height side girders.

If the double bottom is longitudinally framed in the pounding region, where the minimum designed draft forward may be less than 4% of the ship's length, solid plate floors are fitted at alternate frame spaces, and intercostal side girders fitted at a maximum spacing of three times the transverse floor spacing. Where the minimum designed draft forward may be more than 4% but less than 4.5% of the ship's length, solid plate floors may be fitted at every third frame space and intercostal side girders may have a maximum spacing of four times the transverse floor spacing. As longitudinals are stiffening the bottom shell longitudinally, it should be noted that fewer side girders need be provided than where the bottom is transversely framed to resist distortion of the bottom with the slamming forces experienced.

Where the ballast draft forward is less than 1% of the ship's length, the additional strengthening of the pounding region is given special consideration.

Greater slamming forces (i.e., pounding) are experienced when the ship is in the lighter ballast condition, and is long and slender, by reason of the increased submersion of the bow in heavy weather with impact also on the bow flare.

3.8.3 Other Stresses

Ship structural members are often subjected to high stresses in localized areas, and great care is required to ensure that these areas are correctly designed. This is particularly the case where various load-carrying members of the ship intersect, examples being where longitudinals meet at transverse bulkheads and at intersections of longitudinal and transverse bulkheads. Another highly stressed area occurs where there is a discontinuity of the hull girder at ends of deck house structures, also at hatch and other opening corners, and where there are sudden breaks in the bulwarks.

4. Stability of Ships

4.1 Flotation Principles

A body floating freely in still water experiences a downward force due to gravity. If the body has a mass *m*, this force will be mg and is known as its *weight*. If the body is in equilibrium there must be a force of the same magnitude and in the same line of action as the weight but opposing it. Otherwise the body would move. This opposing force is generated by the hydrostatic pressures acting on the body Figure 23. These act normal to the body's surface and can be resolved into vertical and horizontal components. The sum of the vertical components is known as the buoyancy force and must equal the body's weight otherwise it would rise or sink.

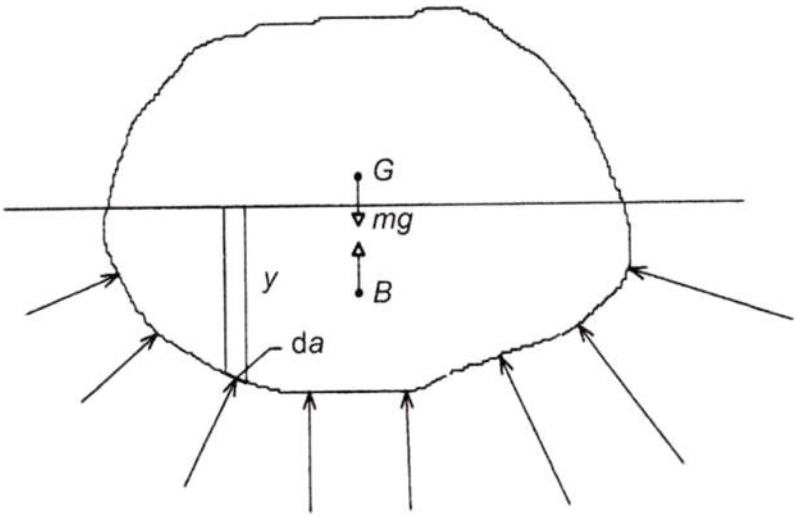


Figure 23. Forces acting on a Floating Body[2]

The horizontal components must cancel out or the body would move sideways. The two forces must act in the same vertical line or the body would be subject to a moment and rotate. The gravitational force m x g can be imagined as concentrated at a point *G* which is the centre of mass, commonly known as the *centre of gravity*. Similarly the opposing force can be imagined to be concentrated at a point *B*, the *centre of buoyancy*.

The pressure acting on a small element of the surface, d*a*, at a depth *y* below the surface is given by,

Pressure = density x gravitational acceleration x depth = ρgy

and the normal force on an element of area d*a* = $\rho gy\, da$

If θ is the angle of inclination of the body's surface to the horizontal then the vertical component of force is:

$(\rho gy\, da)\cos\theta = \rho g$ (volume of vertical element)

Summing over the whole volume, the total vertical force is:

$\rho g\nabla$

where ∇ is the immersed volume of the body.

This is the weight of the displaced water. This vertical force 'buoys up' the body and is known as the buoyancy force or simply buoyancy. The point, B, through which it acts is the centroid of volume of the displaced water and is known as the centre of buoyancy.

Since the buoyancy force is equal to the weight of the body, $m = \rho\nabla$.

In other words the mass of a floating body equals the mass of the water displaced by that body.

If the density of a body is greater than that of the water, the weight of water it can displace is less than its own weight and it will sink to the bottom. If held by a spring balance its apparent weight would be reduced by the weight of water it displaced - due to the water pressures acting upon it. This leads to Archimedes' Principle which states that when a solid is immersed in a fluid it experiences an upthrust equal to the weight of the fluid displaced.

4.1.1 Ship Hull form: Midship Section, Block and Prismatic Coefficients

The hull form of a ship is commonly portrayed graphically by a lines plan or sheer plan, See Figure 24. This shows the various curves of intersection between the hull and the three sets of orthogonal planes. For symmetrical ships, only one half is shown. The curves showing the intersections of vertical fore and aft planes with the hull are grouped in the sheer profile, the waterlines in the half breadth plan, and the sections by transverse planes in the body plan. In merchant ships, the transverse sections are numbered from aft to forward. In warships, they are numbered from forward to aft, although the forward half of the ship is still, by tradition, shown on the right hand side of the body plan. The distances of the various intersection points from the middle line plane are called offsets.

Clearly the three sets of curves making up the lines plan are interrelated as they represent the same three-dimensional body. This interdependency is used in manually fairing the hull form, each set being faired in turn and the changes in the other two noted. At the end of an iterative process, the three sets will be mutually compatible. Fairing is now achieved by computer using mathematical fairing techniques, such as the use of curved surface patches, to define the hull. It is often generated directly from the early design processes in the computer. The old manual process is easier to describe and illustrates the intent. Manual fairing was done first in the design office on a reduced scale drawing. To aid production, the lines were then laid off full scale on the floor of a building known as the mould loft. That is, they were scribed on the floor. They were then re-faired. Some shipyards used a reduced scale, say one-tenth, for use in the building process. Nowadays, data are passed to a shipyard in digital form where it is then fed into a computer-aided manufacturing system.

In some ships, particularly large carriers of bulk cargo, the transverse cross section is constant for some fore and aft distance near amidships. This portion is known as the parallel middle body.

Appendages of the main hull, such as shaft bossing's, or sonar domes, are faired separately.

4.1.1.1 Hull Characteristics

It is possible to derive a number of characteristics for a ship hull which have significance in determining the general performance of the ship. As a floating body, a ship in equilibrium will displace its own weight of water, as explained later. Thus the volume of the hull below the design load waterline must represent a weight of water equal to the weight of the ship at its designed load. This displacement, as it is called, can be defined as:

$$\Delta = \rho g \nabla$$

where ρ is the density of the water in which the ship is floating

g is the acceleration due to gravity

∇ is the underwater volume

For flotation, stability and hydrodynamic performance generally, it is this displacement, expressed either as a volume or a force that is of interest.

For rule purposes Classification Societies may use a moulded displacement which is the displacement within the moulded lines of the ship between perpendiculars.

It is useful to have a feel for the fineness of the hull form. This is provided by a number of form coefficients or coefficients of fineness. These are defined as follows, where ∇ is the volume of displacement:

i) Block coefficient (C_B), Figure 24

$$C_B = \frac{\nabla}{L_{PP}BT}$$

where:

L_{PP} is length between perpendiculars,

B is the extreme breadth underwater

T is the mean draught

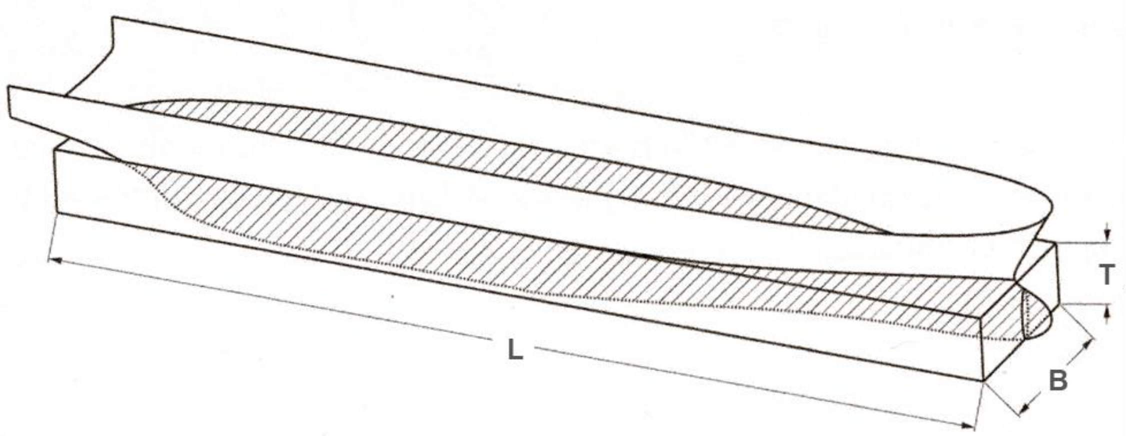


Figure 24. Schematic Showing Parameters used to Determine the Block Coefficient[8]

ii) Waterplane area coefficient (C_{WP}), Figure 25

$$C_{WP} = \frac{A_W}{L_{WL}B}$$

where:

A_w is waterplane area,

L_{WL} is the waterline length

B is the extreme breadth of the waterline

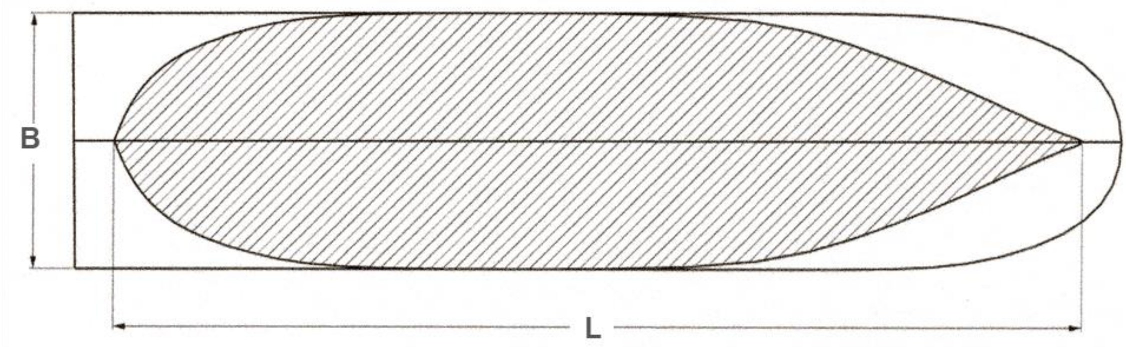


Figure 25. Schematic Showing Parameters used to Determine the Waterplane Area Coefficient[8]

iii) Midship section area coefficient (C_M), Figure 26

$$C_m = \frac{A_M}{T \times B}$$

where:

A_M is the midship section area,

T is the mean draught

B is the extreme underwater depth amidships

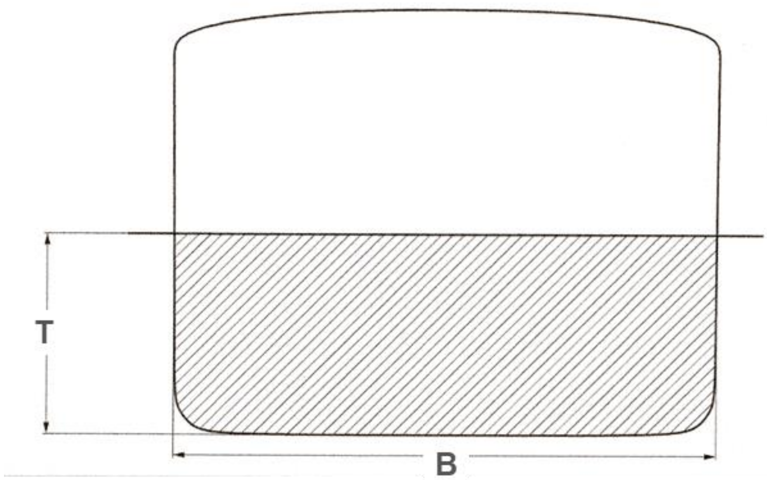


Figure 26. Schematic Showing Parameters used to Determine the Midship Section Area Coefficient[8]

iii) Longitudinal prismatic coefficient (C_P), Figure 27

$$C_P = \frac{\nabla}{A_M L_{PP}}$$

where:

A_M is the midship section area,

L_{PP} is length between perpendiculars

∇ is the volume of displacement

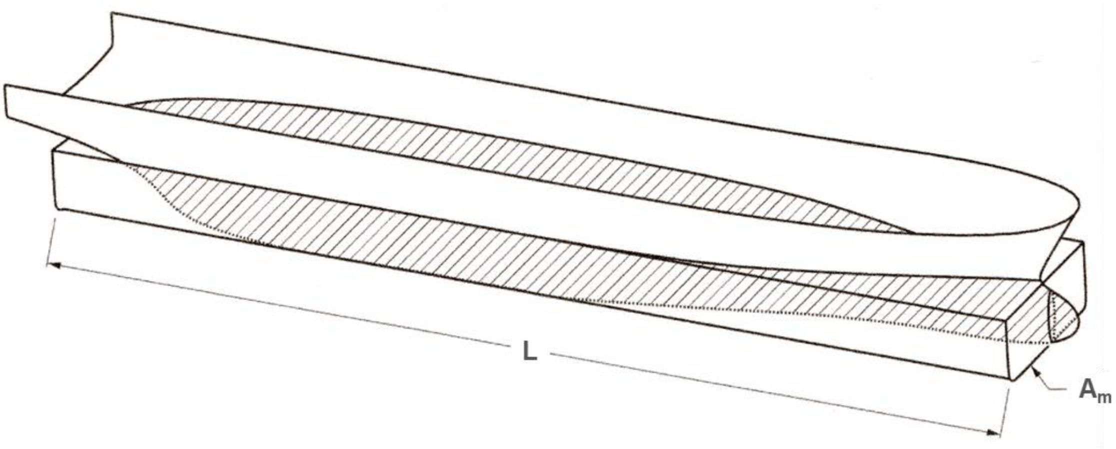


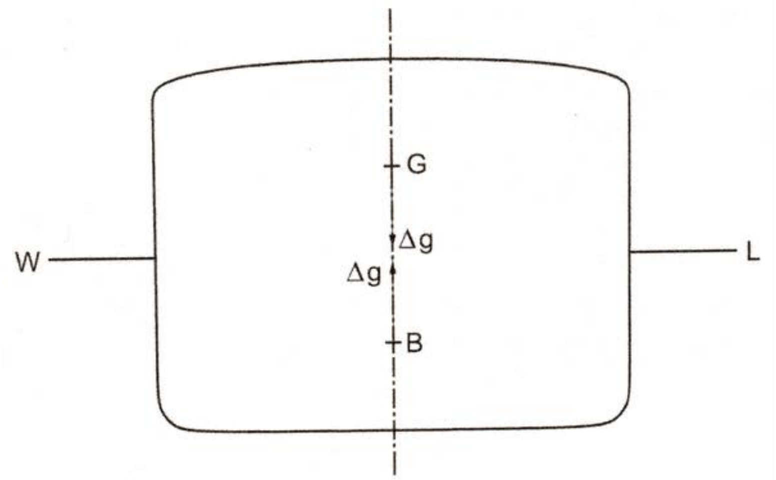
Figure 27. Schematic Showing Parameters used to Determine the Longitudinal Prismatic Coefficient[8]

These coefficients are ratios of the volume of displacement to various circumscribing rectangular or prismatic blocks, or of an area to the circum-scribing rectangle. Use has been made of displacement and not the moulded dimensions because the coefficients are used in the early design stages and are more directly related to most aspects of ship performance. Practice varies, however, and moulded dimensions may be needed in applying some classification societies' rules.

The values of these coefficients can provide useful information about the ship form. For instance, the low values of block coefficient for cargo liners would be used for high-speed refrigerated ships. The low block coefficient value for icebreakers reflects the hull form forward which is shaped to help the ship drive itself up on to the ice and break it. The great variation in size

4.1.2 Introduction to Stability

The term 'stability' can be applied to a number of different types of behaviour that a ship can exhibit, but in general it is used as a term to refer to the transverse static stability of a ship. This is the ship's ability to return to the upright (level heel) condition when external loads or forces are applied.



WL: waterline
B: centre of buoyancy
G: centre of gravity
Δg: weight of ship = to weight of water displaced

Figure 28. Ship in Equilibrium[8]

In the upright position, figure 28, the weight of the ship acts vertically down through the centre of gravity G, while the upthrust acts through the centre of buoyancy B. Since the weight is equal to the upthrust, and the centre of gravity and the centre of buoyancy are in the same vertical line, the ship is in equilibrium.

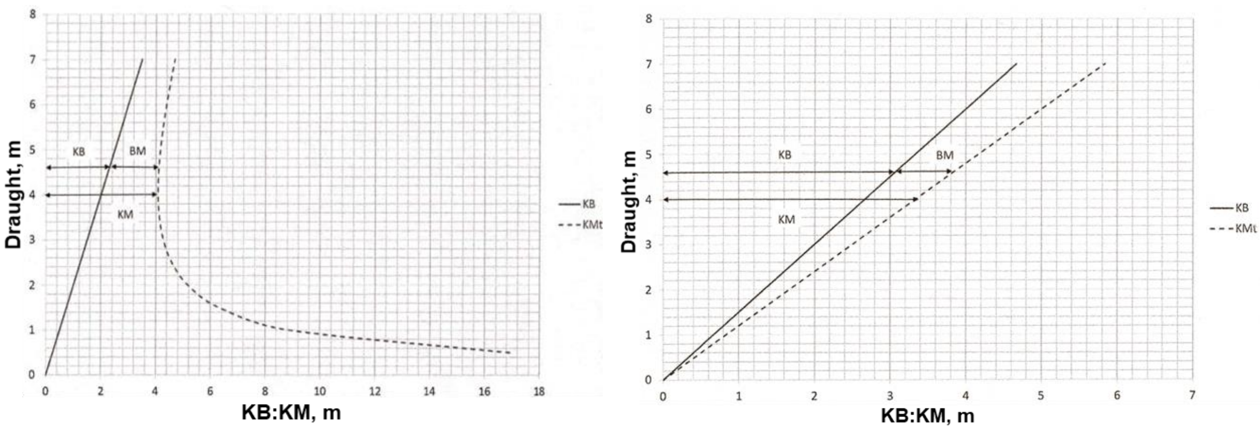
When the ship is heeled, the centre of buoyancy moves off the centreline and a perpendicular drawn from the new centre of buoyancy intersects the centreline at an imaginary point known as the metacentre. In the stable condition a ship's metacentre is always above the centre of gravity and the relative positions of the centre of gravity and the metacentre are critical to the stability of a ship.

4.1.3 Metacentric Diagrams

To ascertain the GM for any condition of loading it is necessary also to calculate the KB and BM (i.e., KM) for any draft.

Since both KB and BM depend upon draught, their values for any ship may be calculated fora number of different draughts, and plotted to form the metacentric diagram for the ship. The height of the transverse metacentre above the keel may then be found at any intermediate draught.

The metacentric diagram for a box barge is similar to that for a ship (figure 29a), while the diagram for a vessel of constant triangular cross section is formed by two straight lines starting from the origin (figure 29b).



(a) (b)

Figure 29. Metacentric Diagrams for (a) Box Barge and (b) Triangular Cross Section Vessels[8]

When loading a ship the officer responsible should aim to complete the loading with a GM which is neither too large nor too small. See table below as a guide. A metacentric diagram is a graph from which the KB, BM and thus the KM can be found for any draft by inspection.

Table 1. Typical Working GM Values for Different Ship Types

Ship Type	GM (fully loaded condition), m
General Cargo	0.30 – 0.50
Oil Tankers	0.50 – 2.00
Double-Hull Super Tankers	2.00 – 2.50
Container Ships	1.50 – 2.50
Ro-Ro Vessels	~1.50
Bulk Ore Carriers	2.0 – 3.0

If the KG is known and the KM is found from the diagram, the difference will give the GM. Also, if a final GM be decided upon, the KM can be taken from the graph and the difference will give the required final KG.

4.2 Stability at Small and Large Heel Angles

4.2.1 Small Heel Angles

When a ship is inclined by an external force to an angle θ, the centre of gravity remains in the same position but the centre of buoyancy moves from B to B_1, see Figure 30.

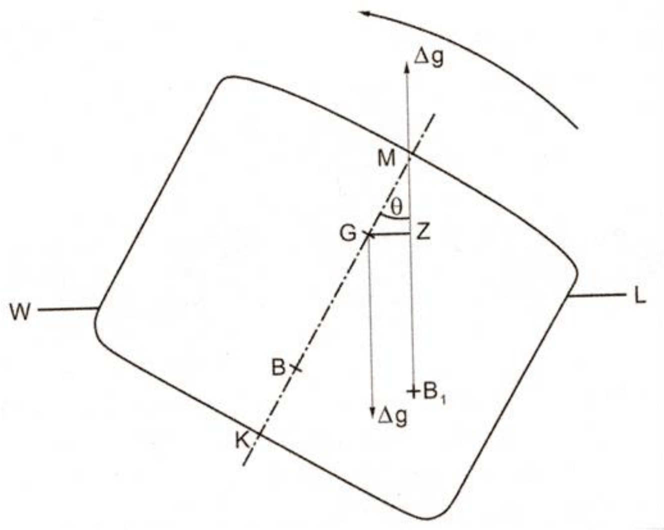


Figure 30. Stable Ship at Small (<10^o) Heel Angle (positive correcting righting lever)[8]

The buoyancy, therefore, acts up through B1 while the weight still acts down through G, creating a moment of Δg x GZ, which tends to return the ship to the upright. A Δg x GZ is known as the righting moment and GZ the righting lever. Since this moment tends to right the ship, the vessel is said to be stable.

For small angles of heel, up to about 10°, the vertical through a new centre of buoyancy B_1 intersects the centreline at M, the transverse metacentre. It can be seen from figure 30 that,

$$GZ = GM \sin\theta$$

Thus, for small angles of heel, GZ is a function of GM, and since GM is independent of θ while GZ depends upon θ, it is useful to express the initial stability of a ship in terms of GM, the metacentric height. GM is said to be positive when G lies below M and the vessel is stable.

A ship with a small metacentric height will have a small righting lever at any angle and will roll easily; its roll will be a slow lollop. The ship is then said to be tender. A ship with a large metacentric height will have a large righting lever at any angle and will have a considerable resistance to rolling. The ship is then said to be stiff. A stiff ship will be very uncomfortable, having a very small rolling period, which produces a short and snappy roll. In extreme cases, this may cause structural damage.

If the centre of gravity lies above the transverse metacentre, the moment acts in the opposite direction, increasing the angle of heel. The vessel is then unstable and will not return to the upright, the metacentric height being regarded as negative.

4.2.2 Large Heel Angles

When a ship heels to an angle greater than about 10°, the principles on which the initial stability above is based are no longer true. The proof of the formula for BM was based on the assumption that the two waterplanes intersect at the centreline and that the wedges are right-angled triangles. Neither of these assumptions can be made for large angles of heel, and the stability of the ship must be determined from first principles. In practice, this is calculated by computer programs for the ship by the naval architect, but the principles that stability software uses are as described below.

As a ship loads and unloads cargo, or burns fuel, the possible combinations of displacement and centre of gravity are infinite. Any method for calculating the stability of the vessel must take this into account.

The righting lever, GZ, is the perpendicular distance from a vertical axis through the centre of gravity G to the centre of buoyancy B_1. As G could have any number of locations, it is easier to calculate the perpendicular distance of the line of action for B_1 from the keel, for a range of displacements. This distance is called KN.

From figure 31 it can is apparent that:

$$KN = KG\sin\theta + GZ$$

Which can be rearranged to give,

$$GZ = KN - KG\sin\theta$$

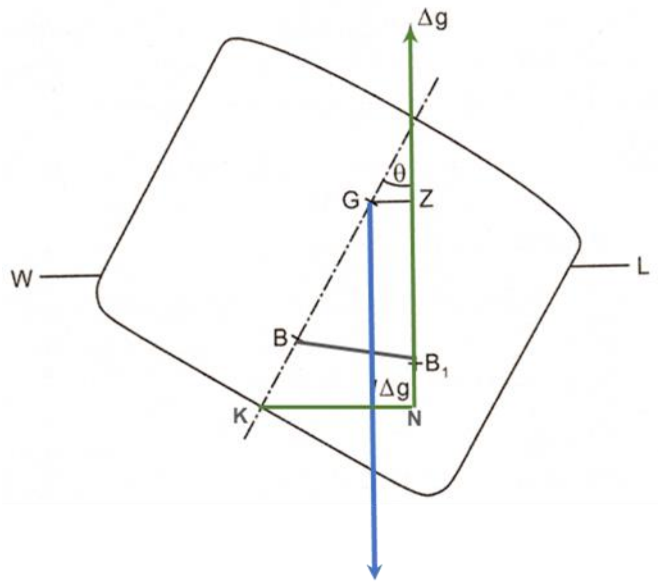


Figure 31. Cross Section of Heeled Ship

Therefore, if KG and KN are known, GZ can be calculated. KN is calculated by a computer program splitting the hull into sections along the ship's length. Each section will be inclined through a range of angles, say 15°, 30°, 45°, 60°, 75° and 90° for different displacements. The overall values of KN for the hull are then calculated from the values at each of the sections, and summated using Simpson's Rule.

Section 4.4.2 below describes how cross curves can be used to determine the stability curve for any ship displacement.

4.3 Hydrostatic, Cross and Bonjean Curves

4.3.1 Hydrostatic Curves

Earlier it was shown how the displacement, position of B, M and F can be determined. It is usual to obtain these quantities for a range of waterplanes parallel to the design waterplane and plot them against draught, draught being measured vertically. Such a set of curves are called hydrostatic curves, see Figure 32.

Hydrostatic curves are useful for working out the draughts and the initial stability, as represented by GM, in various conditions of loading. This is done for all normal working conditions of the ship and the data supplied to the master.

The curves in the figure show moulded and extreme displacement and the latter is normally shown simply as the displacement curve and which allows for displacement to outside of plating and outside the perpendiculars, bossings, bulbous bows, etc., which is relevant to the discussion of flotation and stability. Clearly the additions to the moulded figure can have a measurable effect upon displacement and the position of B.

It should be noted that the curves include one for the increase in displacement for unit increase in draught. If a waterplane has an area A, then the increase in displaced volume for unit increase in draught at that waterplane is 1 × A. The increase in displacement will be pgA. For p = 1025kg/m^3 and g = 9.81 m/s^2 increase in displacement per metre increase in draught is:

$$1025 \times 9.81 \times 1 \times A = 10{,}055A \text{ newtons.}$$

The increase in displacement per unit increase in draught is useful in approximate calculations when weights are added to a ship. Since its value varies with draught it should be applied with care.

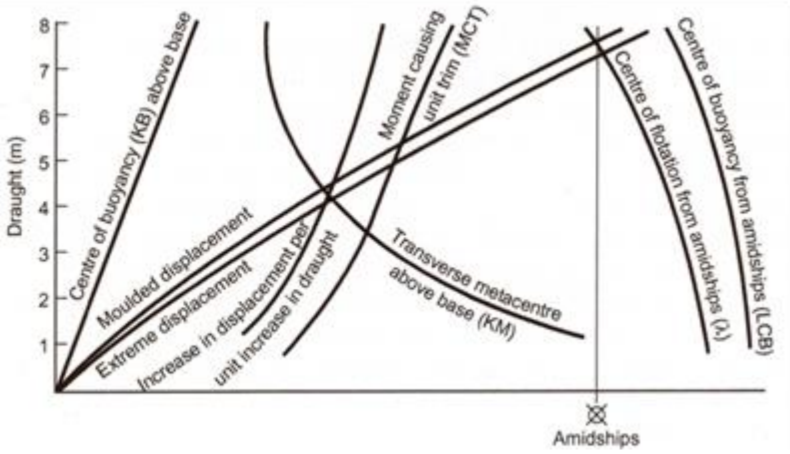


Figure 32. Hydrostatic Curves[2]

4.3.1.1 Tonnes per Unit Immersion

It is apparent that the hydrostatic curves include one for the increase in displacement for unit increase in draught. If a waterplane has an area A, then the increase in displaced volume for unit increase in draught at that waterplane is I × A. The increase in displacement will be pgA.

For p = 1025 kg/m^3 and g = 9.81 m/s^2 increase in displacement per metre increase in draught is:

$$1025 \times 9.81 \times 1 \times A = 10{,}055A \text{ newtons}$$

It is usual to quote the increase in displacement in terms of the extra tonnes per unit immersion. As with MCT, it is necessary to know the unit of immersion used. It may be 1 m or 1 cm. The latter is to be preferred if the area of the waterplane changes appreciably over 1 m. It is often, then, abbreviated to TPC. The increase in displacement per unit increase in draught is useful in calculations where weights are added to a ship provided the change in draught is small.

Hydrostatic curves are useful for working out the draughts and the value of GM, in various conditions of loading. This is done for all normal working conditions of the ship and the results supplied to the master.

4.3.2 Cross Curves

The vertical position of centre of gravity (G) of the ship is not always fixed. It changes with every voyage, depending on the loading conditions and the amount of ballast. The CG of the ship also changes when the ship is in transit. This varying nature of CG makes it difficult for the designer to assume the loading conditions at which GZ curves should be obtained, because different values of KG (vertical centre of gravity) would result in different metacentric heights (GM), and since the righting lever (GZ) is directly related to GM, the stability curves for each of the loading condition would be different. So how is this problem circumvented?

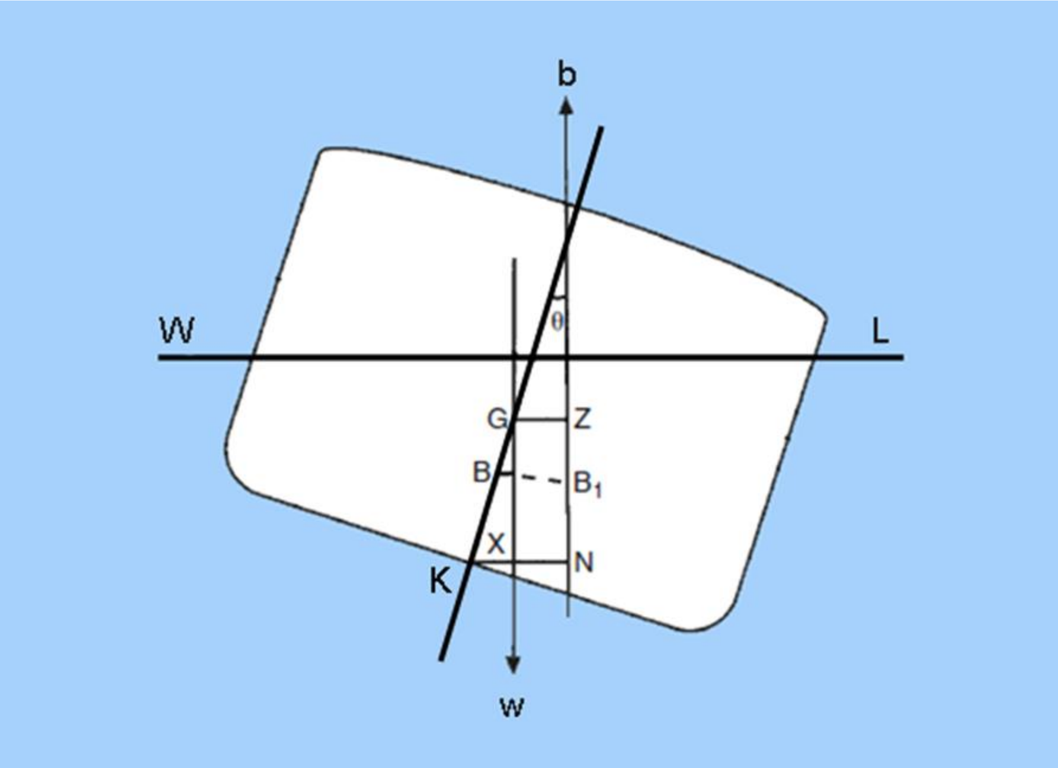


Figure 33. Heeling Vessel and Associated Geometry

In order to make things easier, a few known facts were considered before developing the concept of cross curves of stability:

KG will vary according to the loading condition.

The KG of the ship is always known to the designer, and also the ship's captain, for every loading condition.

The angle of heel at any condition is also known to the designer and the ship's captain.

The cross curves of stability were developed, so that, for any loading condition (where KG is already known), values of righting lever (GZ) can be obtained for all angles of heel, see Figure 33.

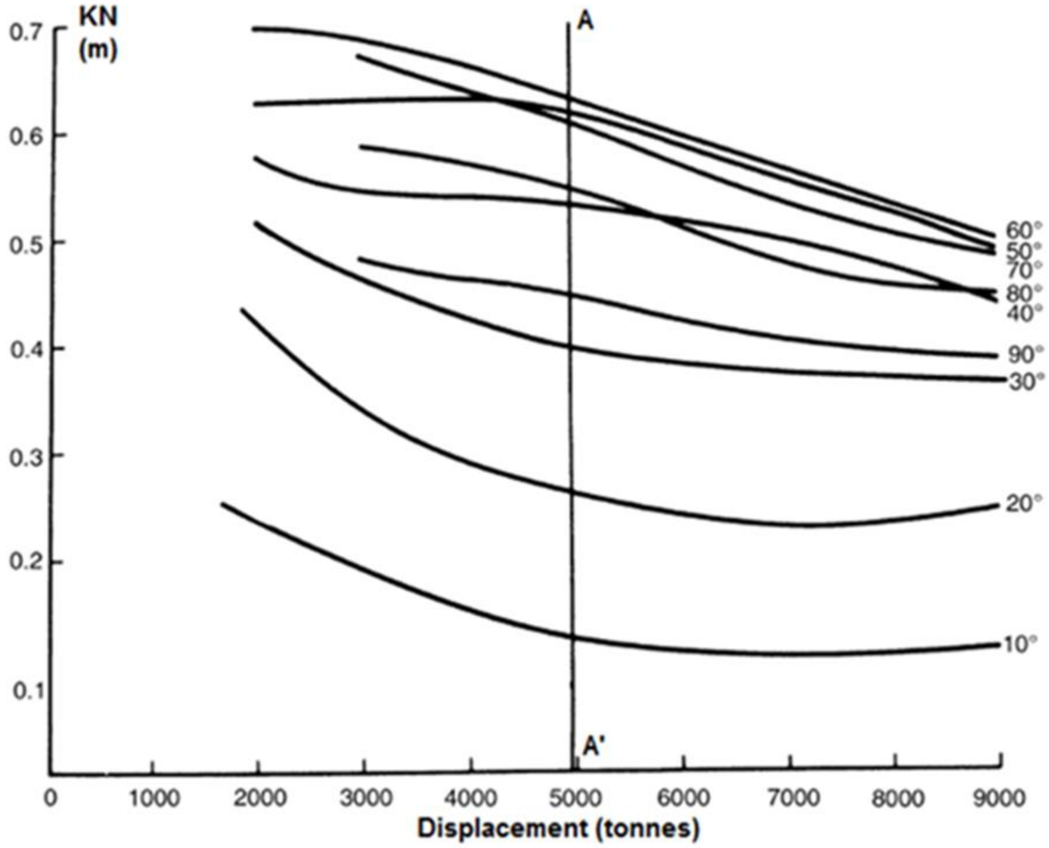


Figure 34. Cross Curves Showing How a Stability Curve can be Determined for a Displacement of 5000 Tonnes[9]

Once the KN curves are obtained, it is possible for the designer to obtain the stability curve / GZ curve for any loading condition.

First, the loading condition is set, and the corresponding vertical center of gravity (KG) is obtained. The displacement of the ship for a particular loading condition is also available (from the hydrostatic curves, see above). Once the displacement is fixed, a vertical line is drawn at the corresponding displacement on the KN curve. As an example assume that the displacement for the given loading condition is 5000 tonnes. So, the line AA' is drawn through the KN curves, at 5000 tonnes, see Figure 34. The value of KN at each angle of heel is then replaced in the expression above, to obtain the GZ at each angle of heel. Once done, the designer can obtain the GZ versus angle of heel values, which can be plotted to obtain the stability curve for a particular loading condition, see Figure 34.

Thus, the KN curve enables us to obtain the stability curve at any predetermined, as well as new loading conditions. For this reason, KN curves are provided in the Stability Booklet of a ship, so that, in case the ship is operating in a loading condition it hadn't operated in before, the GZ curve can still be obtained easily to determine the stability of the ship.

4.3.3 Bonjean Curves

The shape and dimensions of a ship hull form are represented by a body plan which together with vertical sections (sheer plan or profile) and horizontal sections (waterlines) make up the lines plan, see Figure 35.

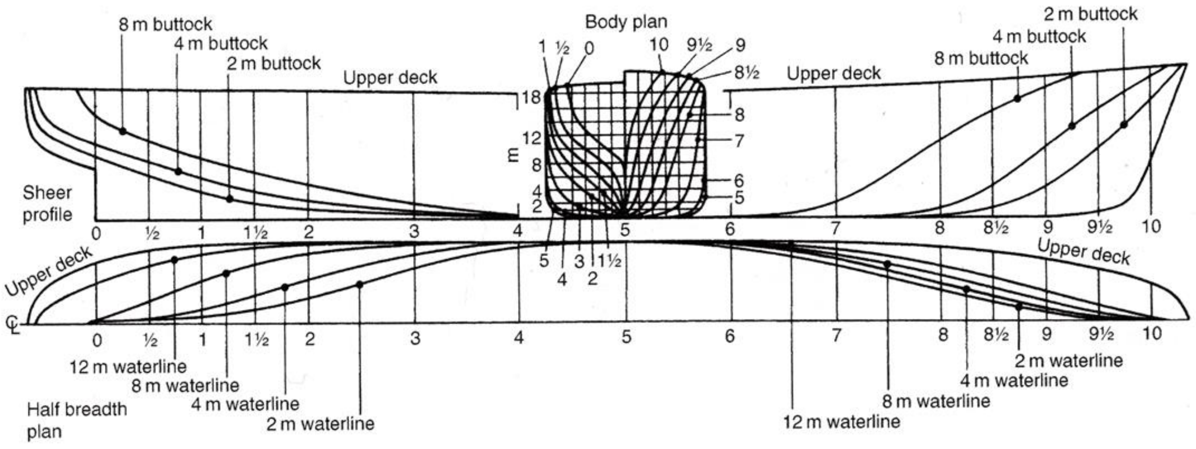


Figure 35. 3D Lines Plan Showing Form of a Vessel[2]

One method of finding the underwater volume is to use Bonjean curves. These are curves of immersed cross-sectional areas plotted against draught for each transverse section. They are usually drawn on the ship profile as in Figure 36. Bonjean curves are drawn to give the immersed area of transverse sections to any draft and may be used to determine the longitudinal distribution of buoyancy.

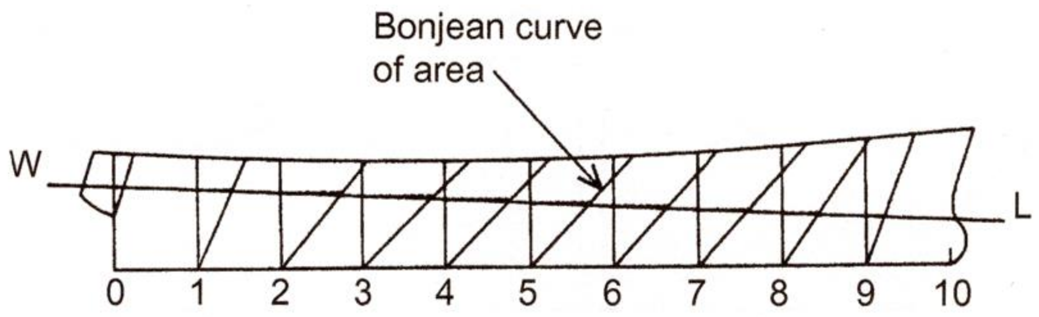


Figure 36. Bonjean Curves[2]

Suppose the ship is floating at waterline WL. The immersed areas for this waterline are obtained by drawing horizontal lines from the intercept of the waterline with the middle line of a section to the Bonjean curve for that section. Having the areas for all the sections, the underwater volume and its longitudinal centre of buoyancy can be calculated.

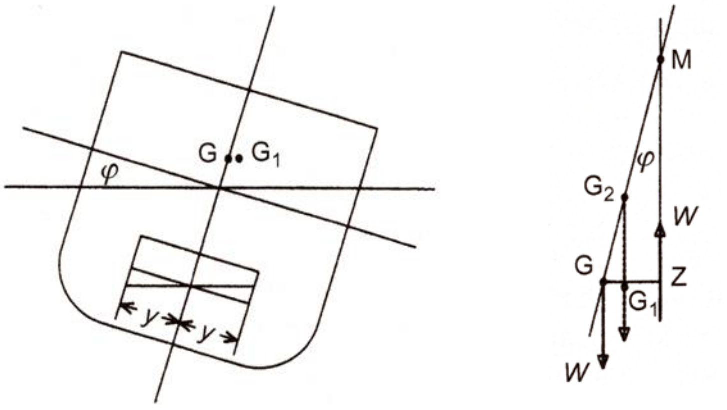
The figure shows the ship divided into 10 elemental strips along its length LOA. In practice the Naval Architect may split the ship into 40 elemental strips in order to obtain greater accuracy of prediction for the weight distribution.

When displacement was calculated manually, it was customary to use a displacement sheet. The displacement up to the design waterline was determined by using Simpson's rules applied to half ordinates measured at water- lines and at sections. The calculations were done in two ways. First the areas of sections were calculated and integrated in the fore and aft direction to give volume. Then areas of waterplanes were calculated and integrated vertically to give volume. The two volume values had to be the same if the arithmetic was correct. The displacement sheet was also used to calculate the vertical and longitudinal positions of the centre of buoyancy. This text has concentrated on calculating the characteristics of a floating body. It is helpful to have these concepts developed in more detail using numerical examples and the calculations lend itself well to the use of Excel spreadsheets.

4.4 Effect of Free Surface

A ship in service will usually have tanks which are partially filled with liquids. These may be the fuel and water tanks the ship is using for its own services or tanks carrying liquid cargoes. When the ship is heeled slowly through a small angle the liquid surface moves so as to remain horizontal. In this discussion a quasi-static condition is considered so that sloshing of the liquid is avoided. Different considerations apply to the dynamic conditions of a ship rolling where ‘sloshing’ forces may be significant to the structural strength of tanks.

For small angles, and assuming the liquid surface does not intersect the top or bottom of the tank, the volume of the wedge that moves is (Figure 37)



(a) (b)

Figure 37. Schematic showing Fluid Free Surface and Change in Centre of Gravity, Reduction in GZ (Righting Moment) and GM[10]

The free surfaces of tanks must be kept to a minimum. One way of reducing them is to subdivide wide tanks into two or more narrow ones. Assuming a tank has a constant section and length, *l*, the second moment of area without division is $lB^3/12$. With a centre division the sum of the second moments of area of the two tanks is $(l/12)(B/2)^3 \times 2 = lB^3/48$. The introduction of a centre division has reduced the free surface effect to a quarter of its original value. Using two bulkheads to divide the tank into three equal width sections reduces the free surface to a ninth of its original value. Thus subdivision is very effective and it is common to subdivide the double bottom of ships. The main tanks of ships carrying liquid cargoes must be designed taking free surface effects into account and their breadths are reduced by providing centreline or wing bulkheads. Some particulate cargoes, such as grain, carried in bulk can move as the ship heels causing a similar effect to a liquid free surface.

4.4.1 Practical Implications of Free Surface

The effect of a free surface of liquid may be most dangerous in a vessel with a small metacentric height and may even cause the vessel to become unstable. In such a ship, tanks that are required to carry liquid should be pressed up tight. If the ship is initially unstable and heeling to port, then any attempt to introduce water ballast will reduce the stability. Before ballasting, therefore, an attempt should be made to lower the centre of gravity of the ship by pressing up existing tanks and lowering masses in the ship. If water is introduced into a double bottom tank on the starboard side, the vessel will flop to starboard and may possibly capsize. A small tank on the port side should therefore be filled completely before filling on the starboard side. The angle of heel will increase due to free surface and the effect of the added mass, but there will be no sudden movement of the ship.

A particularly dangerous condition may occur when a fire breaks out in the upper tween decks of a ship or in the accommodation of a passenger ship. If water is pumped into the space, the stability of the ship will be reduced both by the added mass of water and by the free surface effect. Any accumulation of water should be avoided. Circumstances will dictate the method used to remove the water, and will vary with the ship, cargo and position of fire, but it is likely to be via the use of a portable pump.

It is important to note that the free surface effect depends upon the displacement of the ship and the shape and dimensions of the free surface. It is independent of the total mass of liquid in the tank and of the position of the tank in the ship.

The ship with the greatest free surface effect is, of course, the oil tanker, since space must be left in the tanks for expansion of oil. It is common for tankers to have longitudinal bulkheads, to reduce the free surface effect and give the ships great longitudinal strength. Within the design of dry cargo vessels, it is rarely possible to have longitudinal bulkheads, due to the loading and unloading requirements. Thus, while the free surface effect in a tanker is greater than in a dry cargo ship, it is of more importance in the latter.

The importance of the free surface effect should never be underestimated. It was a contributory factor to the capsize of the Herald of Free Enterprise in 1987, which resulted in the loss of 193 lives.

4.5 Longitudinal Stability - Trim

Consider a ship, floating at waterline W_0L_0, see Figure ???, is caused to move through a small angle, θ, at constant displacement (by moving a weight longitudinally, say), to a new waterline W_1L_1 intersecting the original waterplane in a transverse axis through F. Trim is the difference between the ship forward and aft draughts.

The volumes of the immersed and emerged wedges must be equal so, for small θ,

$$\int 2y_f\left(x_f\theta\right) dx = \int 2y_a\,(x_a\theta) dx$$

where y_f and y_a are the waterplane half breadths at distances x_f and $\mathbf{x_a}$ from F.

This is the condition that F is the centroid of the waterplane and F is known as the centre of flotation. For small trims at constant displacement a ship trims about a transverse axis through the centre of flotation. For most ships F is somewhat aft of amidships.

If a small weight is added to a ship it will sink and trim until the extra buoyancy generated equals the weight and the centre of buoyancy of the added buoyancy is vertically below the centre of gravity of the added weight.

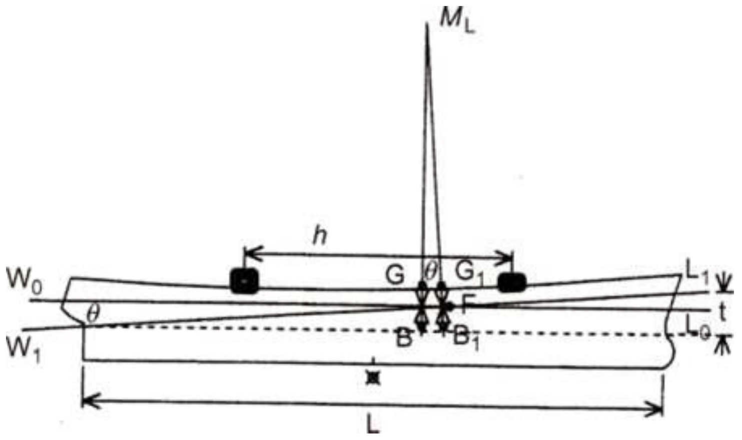


Figure 38. Trim Changes[2]

If the weight is added in the vertical line of the centre of flotation then the ship sinks bodily with no trim as the centre of buoyancy of the added layer will be above F. Generalising, this a small weight placed anywhere along the length can be regarded as being initially placed at F to cause sinkage and then moved to its actual position, causing trim. In other words, it can be regarded as a weight acting at F and a trimming moment about F.

4.5.1 Moment to Change Trim

If the ship in Figure 38 is trimmed by moving a weight, w, from its initial position to a new position h forward, the trimming moment will be wh. This will cause the centre of gravity of the ship to move from G to G_1 and the ship will trim causing B to move to B_1 such that:

$$GG_1 = wh/W$$

and B_1 is vertically below G_1.

The trim is the difference in draughts forward and aft. The change in trim angle can be taken as the change in that difference divided by the longitudinal distance between the points at which the draughts are measured. From Figure 38,

$$\tan\theta = t/L = GG_1/GM_L = wh/WGM_L$$

from which:

$$wh = t \times W \times GM_L/L$$

This is the moment that causes a trim t, so the moment to cause unit change of trim is,

$$WGM_L/L$$

The moment to change trim (MCT) 1 m is a convenient figure to quote to show how easy a ship is to trim. It should be noted that whilst most authorities use a meter as the unit change, some use the MCT by 1cm. It is recommended, therefore, that the full title is given, e.g. MCT 1 m.

The value of MCT is very useful in calculating the draughts at which a ship will float for a given condition of loading. Suppose it has been ascertained that the weight of the ship is W

and the centre of gravity is x forward of amidships and that at that weight with a waterline parallel to the design waterline it would float at a draught T with the centre of buoyancy y forward of amidships. There will be a moment $W(y - x)$ taking it away from a waterline parallel to the design one. The ship trims about the centre of flotation by an amount equal to the moment divided by the MCT for the waterplane. The draughts at any point along the ship length can then be found by simple ratios.

5. Corrosion Control Strategies

The control of corrosion may be broadly considered in two forms, cathodic protection and the application of protective coatings, i.e., paints.

5.1 Cathodic Protection

Only where metals are immersed in an electrolyte can the possible onset of corrosion be prevented by cathodic protection. The fundamental principle of cathodic protection is that the anodic corrosion reactions are suppressed by the application of an opposing current. This superimposed direct electric current enters the metal at every point, lowering the potential of the anode metal of the local corrosion cells so that they become cathodes.

There are two main types of cathodic protection installation, sacrificial anode systems and impressed current systems.

5.1.1 Sacrificial Anode Systems

Sacrificial anodes are metals or alloys attached to the hull that have a more anodic, i.e., less noble, potential than steel when immersed in sea water. These anodes supply the cathodic protection current, but will be consumed in doing so and therefore require replacement for the protection to be maintained.

This system has been used for many years, the fitting of zinc plates in way of bronze propellers and other immersed fittings being common practice. Initially, results with zinc anodes were not always very effective owing to the use of unsuitable zinc alloys. Modem anodes are based on alloys of zinc, aluminum, or magnesium, which have undergone many tests to examine their suitability; high-purity zinc anodes are also used. The cost, with various other practical considerations, may decide which type is to be fitted.

Sacrificial anodes may be fitted within the hull, and are often fitted in ballast tanks. However, magnesium anodes are not used in the cargo-ballast tanks of oil carriers owing to the ‘spark hazard’. Should any part of the anode fall and strike the tank structure when gaseous conditions exist, an explosion could result. Aluminum anode systems may be employed in tankers provided they are only fitted in locations where the potential energy is less than 28 kgm.

5.1.2 Impressed current Systems

These systems are applicable to the protection of the immersed external hull only. The principle of the systems is that a voltage difference is maintained between the hull and fitted anodes, which will protect the hull against corrosion, but not overprotect it, thus wasting current. For normal operating conditions the potential difference is maintained by means of an externally mounted silver/silver chloride reference cell detecting the voltage difference between itself and the hull. An amplifier controller is used to amplify the micro-range reference cell current, and it compares this with the preset protective potential value that is to be maintained. Using the amplified DC signal from the controller, a saturable reactor controls a larger current from the ship's electrical system that is supplied to the hull anodes. An AC current from the electrical system would be rectified before distribution to the anodes. Figure 39 shows such a system.

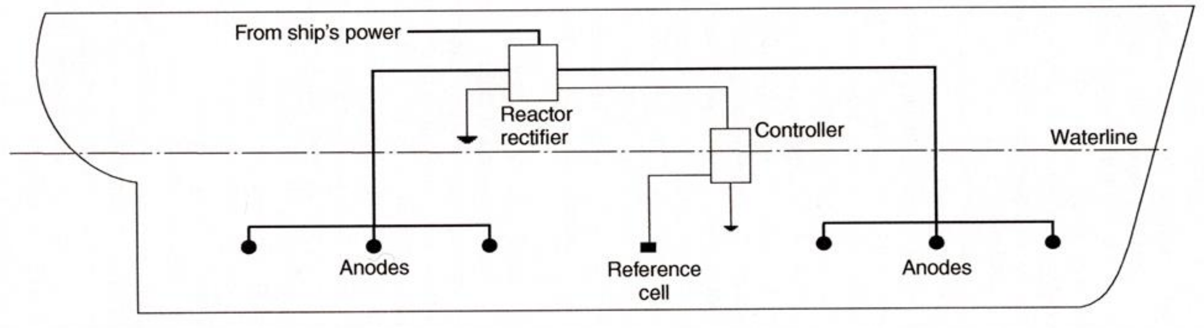


Figure 39. Impressed Current Cathodic Protection System[11]

Originally consumable anodes were employed, but in recent systems nonconsumable relatively noble metals are used; these include lead/silver and platinum/palladium alloys, and platinized titanium anodes are also used.

A similar impressed current system employs a consumable anode in the form of an aluminum wire up to 45 meters long that is trailed behind the ship whilst at sea. No protection is provided in port.

Although the initial cost is high, these systems are claimed to be more flexible, to have a longer life, to reduce significantly hull maintenance, and to weigh less than the sacrificial anode systems.

Care is required in their use in port alongside ships or other unprotected steel structures.

5.2 Protective Coatings

Paints intended to protect against corrosion consist of pigment dispersed in a liquid referred to as the 'vehicle'. When spread out thinly the vehicle changes in time to an adherent dry film. The drying may take place through one of the following processes:

1. When the vehicle consists of solid resinous material dissolved in a volatile solvent, the latter evaporates after application of the paint, leaving a dry film
2. A liquid like linseed oil as a constituent of the vehicle may produce a dry paint film by reacting chemically with the surrounding air
3. A chemical reaction may occur between the constituents of the vehicle after application, to produce a dry paint film. The reactive ingredients may be separated in two containers ('two-pack paints') and mixed before application. Alternatively, ingredients that only react at higher temperatures may be selected, or the reactants may be diluted with a solvent so that the reaction occurs only slowly in the can

Corrosion-inhibiting paints for application to steel have the following vehicle types:

1. Bitumen or pitch. Simple solutions of bitumen or pitch are available in solvent naphtha or white spirit. The bitumen or pitch may also be blended by heat with other materials to form a vehicle

2. Oil based. These consist mainly of vegetable drying oils, such as linseed oil and tung oil. To accelerate the drying by the natural reaction with oxygen, driers are added
3. Oleo-resinous. The vehicle incorporates natural or artificial resins into drying oils. Some of these resins may react with the oil to give a faster-drying vehicle. Other resins do not react with the oil but heat is applied to dissolve the resin and cause the oil to body.
4. Alkyd resin. These vehicles provide a further improvement in the drying time and film-forming properties of drying oils. The name alkyd arises from the ingredients, alcohols and acids. Alkyds need not be made from oil, as an oil-fatty acid or an oil-free acid may be used

   (Note: Vehicle types 2 and 4 are not suitable for underwater service, and only certain kinds of type 3 are suitable for such service.)
5. Chemical resistant. Vehicles of this type show extremely good resistance to severe conditions of exposure. As any number of important vehicle types come under this general heading, these are dealt with individually

a) Epoxy resins. Chemicals that may be produced from petroleum and natural gas are the source of epoxy resins. These paints have very good adhesion, apart from their excellent chemical resistance. They may also have good flexibility and toughness where co-reacting resins are introduced. Epoxy resins are expensive owing to the removal of unwanted side products during their manufacture, and the gloss finish may tend to ‘chalk’, making it unsuitable for many external decorative finishes. These paints often consist of a ‘two-pack’ formulation, a solution of epoxy resin together with a solution of cold curing agent, such as an amine or a polyamide resin, being mixed prior to application. The mixed paint has a relatively slow curing rate at temperatures below 10 °C. Epoxy resin paints should not be confused with epoxy-ester paints, which are unsuitable for underwater use. Epoxy-ester paints can be considered as alkyd equivalents, as they are usually made with epoxy resins and oil-fatty acids.

b) Coal tar/epoxy resin. This vehicle type is similar to the epoxy resin vehicle except that, as a two-pack product, a grade of coal tar pitch is blended with the resin. A formulation of this type combines to some extent the chemical resistance of the epoxy resin with the impermeability of coal tar.

c) Chlorinated rubber and isomerized rubber. The vehicle in this case consists of a solution of plasticized chlorinated rubber, or isomerized rubber. Isomerized rubber is produced chemically from natural rubber, and it has the same chemical composition but a different molecular structure. Both these derivatives of natural rubber have a wide range of solubility in organic solvents, and so allow a vehicle of higher solid content. On drying, the film thickness is greater than would be obtained if natural rubber were used. High build coatings of this type are available, thickening or thixotropic agents being added to produce a paint that can be applied in much thicker coats. Coats of this type are particularly resistant to attack from acids and alkalis.

d) Polyurethane resins. A reaction between isocyanates and hydroxyl-containing compounds produces ‘urethane’ and this reaction has been adapted to produce polymeric compounds from which paint film, fibers, and adhesives may be obtained. Paint films so produced have received considerable attention in recent years, and since there is a variety of isocyanate reactions, both one- and two-pack polyurethane paints are available. These paints have many good properties: toughness, hardness, gloss, abrasion resistance, as well as chemical and weather resistance. Polyurethanes are not used underwater on steel ships, only on superstructures etc., but they are very popular on yachts, where their good gloss is appreciated.

Vinyl resins. Vinyl resins are obtained by the polymerization of organic compounds containing the vinyl group. The solids content of these paints is low; therefore, the dry film is thin and more coats are required than for most paints. As vinyl resin paints have poor adhesion to bare steel surfaces they are generally applied over a pretreatment primer. Vinyl paint systems are among the most effective for the underwater protection of steel.

6. Zinc-rich paints. Paints containing metallic zinc as a pigment in sufficient quantity to ensure electrical conductivity through the dry paint film to the steel are capable of protecting the steel cathodically. The pigment content of the dry paint film should be greater than 90%, the vehicle being an epoxy resin, chlorinated rubber, or similar medium.

5.2.1 Painting Ships

To obtain the optimum performance from paints it is important that the metal surfaces are properly prepared before application of paints and subsequently maintained as such throughout the fabrication and erection process. Paints tailored for the service conditions of the structure to which they apply, and recommended as such by the manufacturer, only should be applied. It is common, especially for ships undergoing a regular dry-docking, for the coating process to be specified and managed by the coating supplier.

5.2.1.1 Surface Preparation

Good surface preparation is essential to successful painting, the primary cause of many paint failures being the inadequacy of the initial material preparation.

It is particularly important before painting new steel that any millscale should be removed. Millscale is a thin layer of iron oxides that forms on the steel surface during hot rolling of the plates and sections. Not only does the non-uniform millscale set up corrosion cells, as illustrated previously, but it may also come away from the surface removing any paint film applied over it. Any corrosion from storage of the steel outdoors in a stockyard must also be removed.

It is also important to create a good surface for coating. Swedish standards are often quoted, SA 3 being white metal and SA 2.5 being near white metal. SA 2.5 is common as a reasonably achievable standard for shipyards. The surface is clean and the blasting process also provides a ‘key’ with very small indentations to which the coating adheres well.

The most common methods employed to prepare steel surfaces for painting are:

- Blast cleaning
- Pickling
- Flame cleaning

- Preparation by hand
- High-pressure water blasting

Blast cleaning is the most efficient method for preparing the surface and is in common use in all large shipyards. Smaller shipyards, where the quantity of steel processed does not justify the capital investment in the preparation equipment, usually buy steel already prepared from a steel mill or stockist.

Following the blast cleaning it is desirable to brush the surface and apply a coat of priming paint as soon as possible, since the metal is liable to rust rapidly.

There are two main types of blasting equipment available, an impeller wheel plant where the abrasive is thrown at high velocity against the metal surface, and a nozzle type where a jet of abrasive impinges on the metal surface. The latter type should preferably be fitted with vacuum recovery equipment, rather than allow the spent abrasive and dust to be discharged to atmosphere, as is often the case in ship repair work. Impeller wheel plants that are self-contained and collect the dust and recirculate the clean abrasive are generally fitted within the shipbuilding shops.

Steel shot is the preferred blast medium for preparation of steel plates and profiles for new construction. As the process proceeds the shot is recovered and reused. The shot breaks down during the blasting and a mix of new and broken shot provides good surface preparation. Dust and other debris are filtered out of the recovery system for disposal.

Cast iron and steel grit may be used for the abrasive, also copper slag, but nonmetallic abrasives are also available. Grit has been used in ship repair but is becoming much less popular because of environmental issues associated with disposal of the waste material. The use of sand is prohibited in most countries because the fine dust produced may cause silicosis.

Pickling involves the immersion of the metal in an acid solution, usually hydro-chloric or sulfuric acid, in order to remove the millscale and rust from the surface. After immersion in these acids the metal will require a thorough hot water rinse. It is preferable that the treatment is followed by application of a priming coat. Pickling is no longer found in most of the ship construction industry.

Using an oxyacetylene flame the millscale and rust may be removed from a steel surface. The process does not entirely remove the millscale and rust, but it can be quite useful for cleaning plates under inclement weather conditions, the flame drying out the plate. Flame, or another heating process, is used as part of an automated preparation line in a shipyard, to preheat the steel, which assists the cleaning and drying of the primer paint coating.

Hand cleaning by various forms of wire brush is often not very satisfactory, and would only be used where the millscale has been loosened by weathering, i.e., exposure to atmosphere over a long period. For ships in service hand cleaning may be used for very small corroded areas.

High-pressure water blasting is superseding grit blasting for ship repair. It is capable of restoring a steel surface to SA 2.5, provided any corrosion has not been allowed to develop. Disposal of the waste material, in this case mainly water, is a main reason for the adoption of water blasting.

Blast cleaning using shot or grit is preferred for best results and economy in shipbuilding, it is essential prior to application of high-performance paint systems used today. Pickling, which also gives good results, can be expensive and less applicable to production schemes; flame cleaning is much less effective; and hand cleaning gives the worst results. Water blasting is mainly a ship repair process.

5.2.1.2 Temporary Protection During Building

After the steel is blast cleaned it may be several months before it is built into the ship and finally painted. It is desirable to protect the material against rusting in this period as the final paint will offer the best protection when applied over perfectly clean steel.

The formulation of a prefabrication primer for immediate application after blasting must meet a number of requirements. It should dry rapidly to permit handling of the plates within a few minutes and working the plates within a day or so. It should be nontoxic, and it should not produce harmful porosity in welds nor give off obnoxious fumes during welding or cutting. For some high-speed welding processes it is necessary to remove the primer in way of the welds to avoid porosity. After cutting and welding, areas of damaged primer are usually strip coated by hand to cover the affected steel and retain the primer protection against corrosion.

The primer must also be compatible with any subsequent paint finishes to be applied. Satisfactory formulations are available, for example a primer consisting of zinc dust in an epoxy resin.

Some shipyards where work is entirely undercover and where the steel is used quickly may dispense with primer.

Given the sophistication and cost of modem, long-life coatings, their application is critical to performance. It is common for shipyards to take complete units and blocks, once all the hot work is completed, for final coating in a controlled environment. So-called ‘paint cells’ are temperature- and humidity-controlled buildings. The units are driven into the cells using self-elevating transporters. The units are then blasted, if no primer has been used or the primer is degraded and unsuitable for overcoating. Once cleaned the coatings can be applied in near ideal conditions. Hull and internal coatings are applied.

Where the units are to be joined in the building dock, unpainted areas are left. These are completed after the hull welding, using localized protection from unsuitable weather conditions.

5.2.1.3 Paint Systems on Ships

The paint system applied to any part of a ship will be dictated by the environment to which that part of the structure is exposed. Traditionally, the painting of the external ship structure was divided into three regions:

i) Below the waterline, where the plates are continually immersed in sea water.

ii) The waterline or boot topping region, where immersion is intermittent and lot of abrasion occurs.

iii) The topsides and superstructure exposed to an atmosphere laden with salt spray, and subject to damage through cargo handling.

However, now that tougher paints are used for the ship’s bottom the distinction between regions need not be so well defined, one scheme covering the bottom and waterline regions.

(i) Below the Waterline

The ship's bottom has priming coats of corrosion-inhibiting paint applied that are followed by an antifouling paint. Paints used for steels immersed in sea water are required to resist alkaline conditions. The reason for this is that an iron alloy immersed in a sodium chloride solution having the necessary supply of dissolved oxygen gives rise to corrosion cells with caustic soda produced at the cathodes. Further, the paint should have a good electrical resistance so that the flow of corrosion currents between the steel and sea water is limited. These requirements make the standard nonmarine structural steel primer red lead in linseed oil unsuitable for ship use below the waterline. Suitable corrosion-inhibiting paints for ships' bottoms are pitch or bitumen types, chlorinated rubber, coal tar/epoxy resin, or vinyl resin paints. The antifouling paints may be applied after the corrosion-inhibiting coatings and should not come into direct contact with the steel hull, since the toxic compounds present may cause corrosion.

(ii) Waterline or Boot Topping Region

Generally, modem practice requires a complete paint system for the hull above the waterline. This may be based on vinyl and alkyd resins or on polyurethane resin paints.

(iii) Superstructures

Red lead- or zinc chromate-based primers are commonly used. White finishing paints are then used extensively for superstructures. These are usually oleo-resinous or alkyd paints that may be based on 'nonyellowing' oils, linseed oil-based paints that yellow on exposure being avoided on modem ships.

Where aluminum alloy superstructures are fitted, under no circumstance should lead-based paints be applied; zinc chromate paints are generally supplied for application to aluminum.

5.2.1.4 Cargo and Ballast Tanks

Severe corrosion may occur in a ship's cargo tanks as the combined result of carrying liquid cargoes and sea water ballast, with warm or cold sea water cleaning between voyages. This is particularly true of oil tankers. Tankers carrying 'white oil' cargoes suffer more general corrosion than those carrying crude oils, which deposit a film on the tank surface, providing some protection against corrosion. The latter type may, however, experience severe local pitting corrosion due to the non-uniformity of the deposited film, and subsequent corrosion of any bare plate when sea water ballast is carried. Epoxy resin paints are used extensively within these tanks, and vinyl resins and zinc-rich coatings may also be used.

5.3 Antifouling Systems

The immersed hull and fittings of a ship at sea, particularly in coastal waters, are subject to algae, barnacle, mussel, and other shellfish growth that can impair its hydrodynamic performance and adversely affect the service of the immersed fittings.

Fittings such as cooling water intake systems are often protected by impressed current antifouling systems, and immersed hulls today are finished with very effective self-polishing antifouling paints.

5.3.1 Impressed Current Antifouling Systems

The functional principle of these systems is the establishment of an artificially triggered voltage difference between copper anodes and the integrated steel plate cathodes. This causes a minor electrical current to flow from the copper anodes, so that they are dissolved to a certain degree. A control unit makes sure that the anodes add the required minimum amount of copper particles to the sea water, thus ensuring the formation of copper oxide that creates ambient conditions precluding local fouling. A control unit can be connected to the management system of the vessel. Using information from the management system, the impressed current antifouling system can determine the amount of copper that needs to be dissolved to give optimum performance with minimum wastage of the anodes.

5.3.2 Antifouling Paints

Antifouling paints consist of a vehicle with pigments that give body and color together with materials toxic to marine vegetable and animal growth. Copper is the best known toxin used in traditional antifouling paints.

To prolong the useful life of the paint the toxic compounds must dissolve slowly in sea water. Once the release rate falls below a level necessary to prevent settlement of marine organisms, the antifouling composition is no longer effective. On merchant ships the effective period for traditional compositions was about 12 months. Demands in particular from large tanker owners wishing to reduce very high docking costs led to specially developed antifouling compositions with an effective life up to 24 months in the early 1970s. Subsequent developments of constant emission organic toxin antifoulings having a leaching rate independent of exposure time saw the paint technologists by chance discover coatings that also tended to become smoother in service. These so-called self-polishing antifoulings, with a lifetime that is proportional to applied thickness and therefore theoretically unlimited, smooth rather than roughen with time and result in reduced friction drag. Though more expensive than their traditional counterparts, given the claim that each 10-micron (10-3 mm) increase in hull roughness can result in a 1% increase in fuel consumption, their selfpolishing characteristic as well as their longer effective life, up to 5 years' protection between dry dockings, made them attractive to the shipowner.

The benefits of the first widely used self-polishing copolymer (SPC) antifouling paints could be traced to the properties of their prime ingredients, the tributyltin compounds or TBTs. TBTs were extremely active against a wide range of fouling organisms and they were able to be chemically bonded to the acrylic backbone of the paint system. When immersed in sea water a specific chemical reaction took place that cleaved the TBT from the paint backbone, resulting in both controlled release of the TBT and controlled disappearance or polishing of the paint film. Unfortunately, it was found that the small concentrations of TBTs released, particularly in enclosed coastal waters, had a harmful effect on certain marine organisms. This led to the banning of TBT antifouling paints for pleasure boats and smaller commercial ships in many developed countries and the introduction of regulations limiting the release rate of TBT for antifouling paints on larger ships. The International Convention on the Control of Harmful Antifouling on Ships, 2001 subsequently required that:

1. Ships shall not apply or reapply organotin compounds that act as biocides in antifouling systems on or after 1 January 2003; and

2. No ship shall have organotin compounds that act as biocides in antifouling systems (except floating platforms, FSUs, and FPSOs built before 2003 and not docked since before 2003).

The final phase-out of TBT paints was in 2008. In theory, ships could retain the paint if it was sealed under another coating but in practice TBTs are no longer at sea.

(Note: Organotin means an organic compound with one or more tin atoms in its molecules used as a pesticide, hitherto considered to decompose safely, now found to be toxic in the food chain. A biocide is a chemical capable of killing living organisms.)

Antifouling paints subsequently applied have generally focused on either the use of copper-based self-polishing antifouling products, which operate in a similar manner to the banned TBT products, or the use of the so-called low-surface-energy coatings. The latter coatings do not polish or contain booster biocides, instead they offer a very smooth, low-surface-energy surface to which it is difficult for fouling to adhere. When the vessel is at rest some fouling may occur but once it is underway and reaches a critical speed the fouling is released.

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Part 2: Corrosion control and prevention for metals used in the marine environment

Section a **Ship Terminology, Types and Structural Aspects**

Section b **Ship Hydrodynamics, Stability and Strength Aspects**

Section c **Corrosion Control Strategies**

Professional Qualification

in Marine Corrosion

Presented by **Mike Lewus**

Module 1

(section a)

Ship Terminology, Types and Structural Aspects

Module 1 (section a)

Summary

- **Ship Building**
  - Brief introduction; history
  - Regulatory Organisations
  - Ship Terminology and Designations
- **Ship Types: Characteristics and Regulations**
  - Container and cargo Ships
  - Bulk Carriers
  - Chemical and liquefied gas carriers
  - Oil tankers
  - RO-RO vessels
  - Passenger liners
- **Ship Types: Structural Aspects**
  - Contrast structure between ship types
  - Strength aspects

Module 1 (section a)

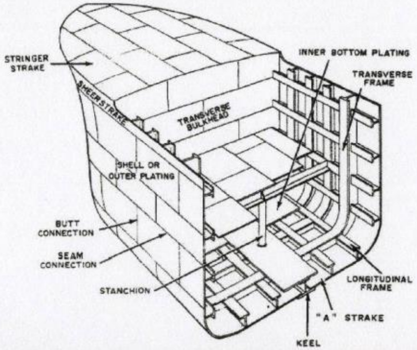
Brief History

- **Ship strength and structure**
  - Prior to the last 150 years construction of sea going vessels (usually in wood) was based on a cut-and-try, experiment-and-discard, test-and-retest approach
  - This taught us how to build vessels that generally held together most of the time
  - In the last century and a half, building vessels that are strong enough as needed have been formalized
  - The most reliable and practical rules-of-thumb are formalized *scantling rules* based on engineering analysis cross-checked against a database of successful vessels
  - Such rules define the construction materials and dimensions based on a few easily obtainable numbers such as length, overall displacement and design speed

Module 1 (section a)

Scantling Regulations

- Scantling refers to the collective dimensions of the framing (apart from the keel) to which planks/beams or plates are attached to form the hull. Scantlings include transverse and longitudinal framing sections, shell plating, bulkheads etc. etc.
- Regulations covering strength requirements for scantlings including are specified by Lloyds, ABS and others
- Nowadays more scientific methods including FE, fluid dynamics, aerodynamics etc. are used



Module 1 (section a)

Regulatory Organisations

- International Maritime Organisation (IMO)
  - Under the United Nations
  - Prime function to regulate shipping i.e. harmonise national rules based on international conventions
  - No power to enforce the international safety regulations, this role is for 'Flag States'
- Classification Societies e.g. Lloyds Register (oldest)
  - Publish rules and regulations that are principally concerned with the strength and structural integrity of the ship
- International Association of Classification Societies (IACS)
  - Under auspices of IACS classification societies are engaged in developing common rules for ships

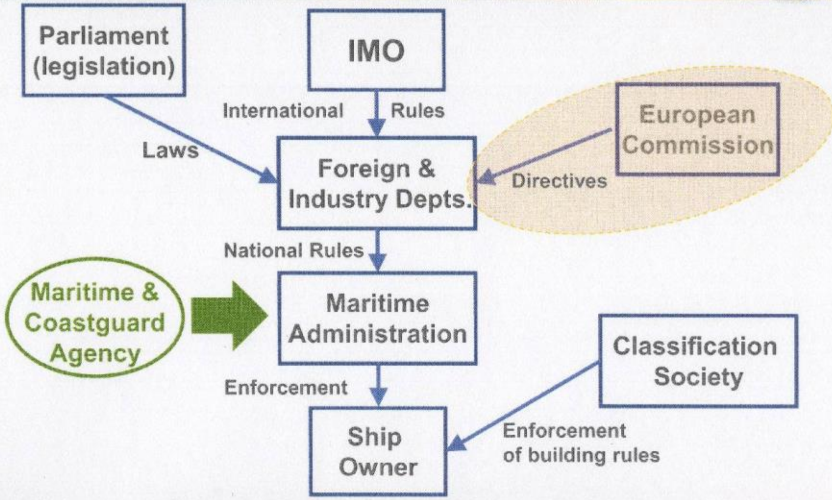
Module 1 (section a)

Regulatory Organisations: IACS Members

Society		Country
American Bureau of Shipping	ABS	USA
Bureau Veritas	BV	France
China Classification Society	CCS	China
Croatian Register of Shipping		Croatia
Det Norske Veritas (DNV)	DNV	Norway
Germanische Lloys	GL	Germany
Indian Register of Shipping		India
Korean Register	KR	Korea
Lloyd's Register	LR	UK
Nippon Kaiji Kyotai (Class NK)	NK	Japan
Polish Register of Shipping		Poland
Registro Italiano Navale (RINA)	RINA	Italy
Russian Maritime Register of Shipping	RS	

Module 1 (section a)

Regulatory Organisations: Heirarchy



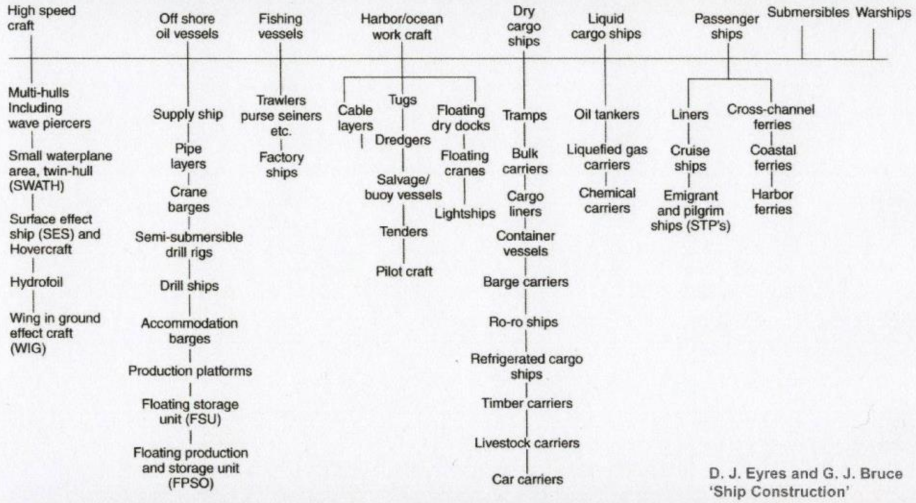
Module 1 (section a)

Ship Types: A and B

- Ships are divided into two types, Type A and B
- Type 'A' ships are designed to carry only liquid cargoes in bulk and cargo tanks are only have small access openings closed by watertight gasketed covers of steel or materials with equivalent properties
  - These vessels benefit from the minimum assignable freeboard (see later slides)
- Type 'B' ships are all other ships that do not have type 'A' provisions
  - As a considerable variety of ships are type 'B' a reduction or increase from the basic 'tabled' Type 'B' freeboard is made in a number of cases (see later slides)

Module 1 (section a)

Ship Types

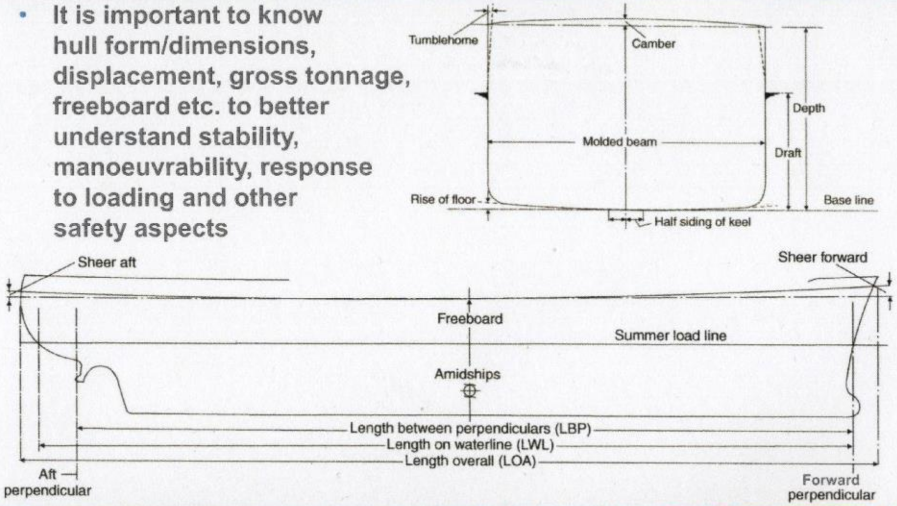


D. J. Eyres and G. J. Bruce 'Ship Construction'

Module 1 (section a)

Ship Terminology

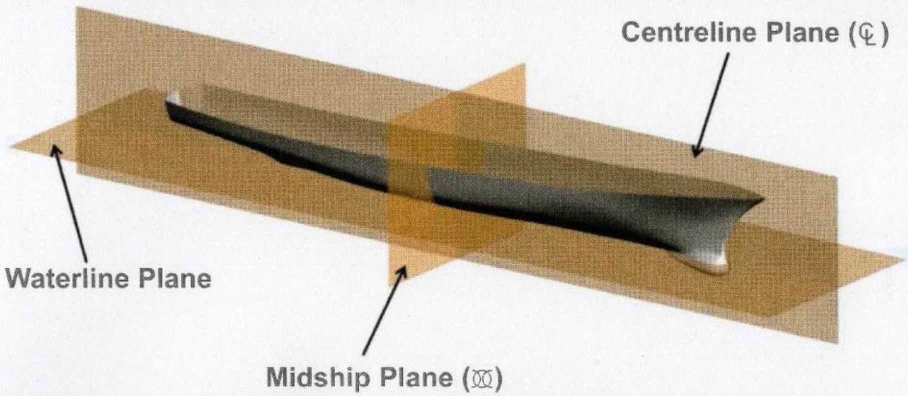
- It is important to know hull form/dimensions, displacement, gross tonnage, freeboard etc. to better understand stability, manoeuvrability, response to loading and other safety aspects



Module 1 (section a)

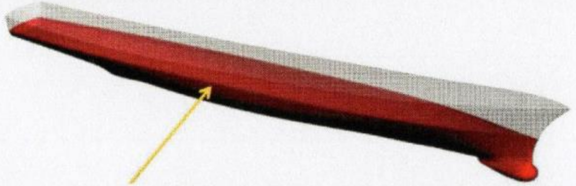
Ship Terminology: Reference Planes

- Important Reference Planes
  - Horizontal, transverse and longitudinal

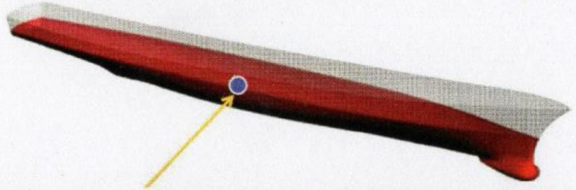


Module 1 (section a) — Ship Terminology: Displacement and Buoyancy

- Volume of Displacement, ∇

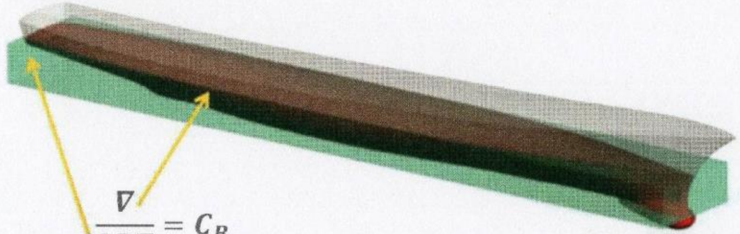


- Centre of Buoyancy, B



Module 1 (section a) — Ship Terminology: Block Coefficient

- Block Coefficient, C_B
  - Describes the overall fullness of the hull

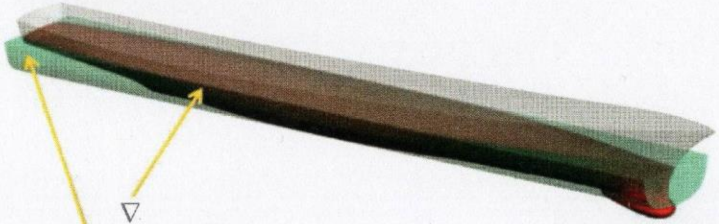


$$\frac{\nabla}{LBT} = C_B$$

- L usually equals LWL
  Typical values for CB, 0.45 for a naval destroyer to 0.85 for a very large tanker very large tanker

Module 1 (section a) — Ship Terminology: Prismatic Coefficient

- Prismatic Coefficient, C_P
  - Describes fineness of the bow and stern without influence of midship fullness

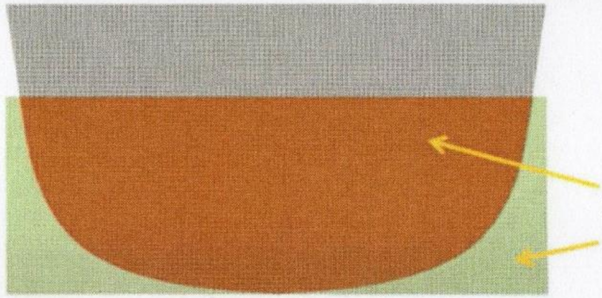


$$\frac{\nabla}{A_M L} = C_P$$

- L usually equals LWL
  Typical values for C_P, 0.57 for a naval destroyer to 0.85 for a very large tanker

Module 1 (section a) — Ship Terminology: Midship Section Coefficient

- Midship Section Coefficient, C_P
  - Describes the fullness of the midship section



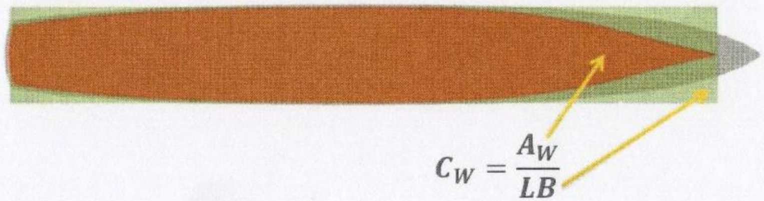
$$\frac{A_M}{BT} = C_M$$

- Note $C_B = C_P C_m$
  Typical values for C_M: 0.75 for a naval destroyer to 0.95 for a very large tanker

Ship Terminology: Waterplane Coefficient

Module 1 (section a)

- Waterplane Coefficient, C_P
  - Describes the fullness or fineness of the waterplane



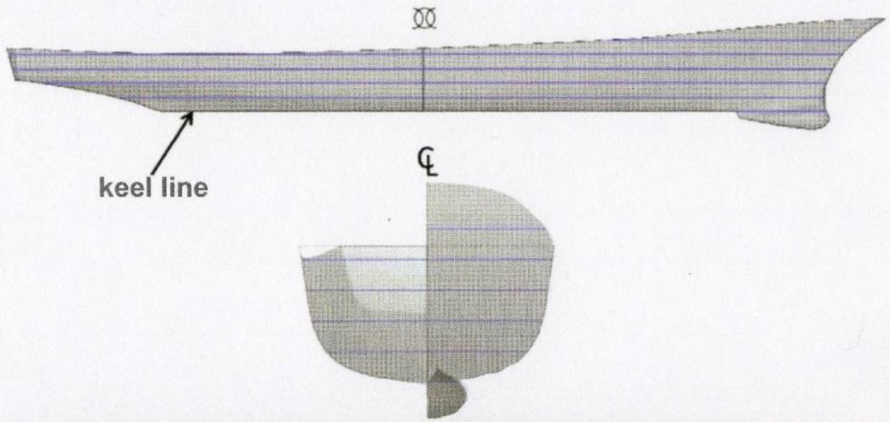
$$C_W = \frac{A_W}{LB}$$

- L usually equals LWL
  Typical values for C_W, at design waterline: 0.67 for a naval destroyer to 0.92 for a very large tanker

Ship Terminology: Waterlines

Module 1 (section a)

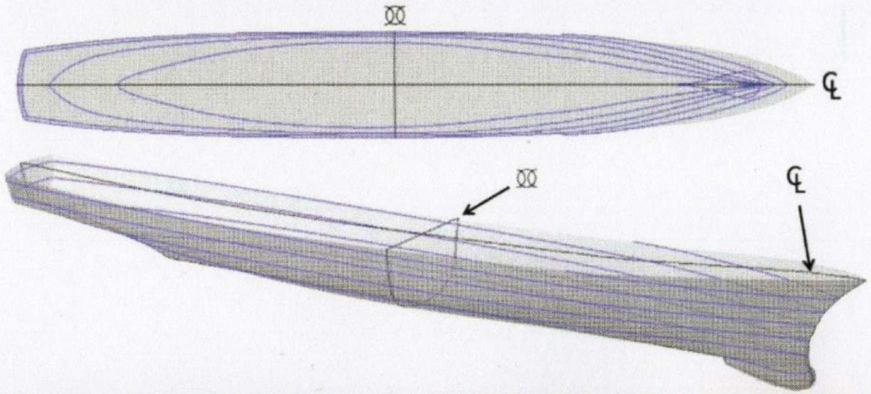
- Waterlines
  - From side and front views, lines are straight



Ship Terminology: Waterlines

Module 1 (section a)

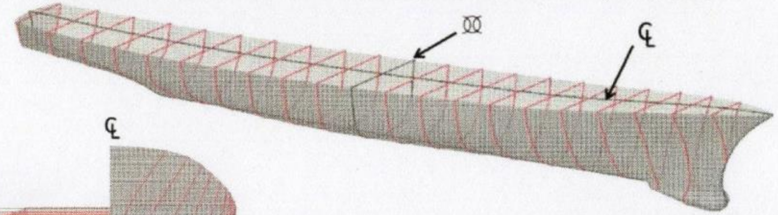
- Waterlines
  - Top, plan or oblique view water lines reveal curvature as line moves from keel to top decks

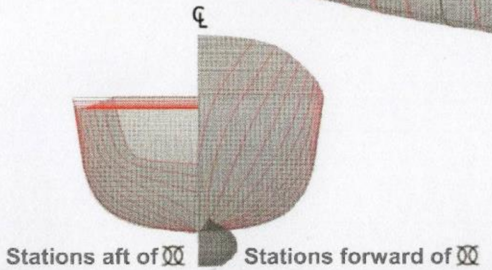


Ship Terminology: Stations

Module 1 (section a)

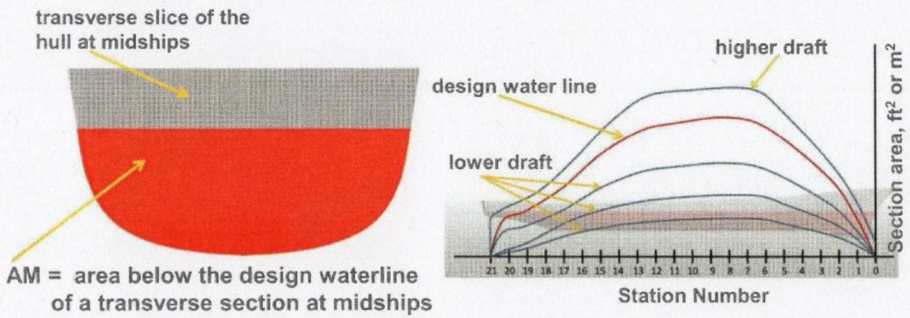
- Stations
  - Top, plan or oblique view water lines reveal curvature as line moves from keel to top decks





Ship Terminology: Sectional Area

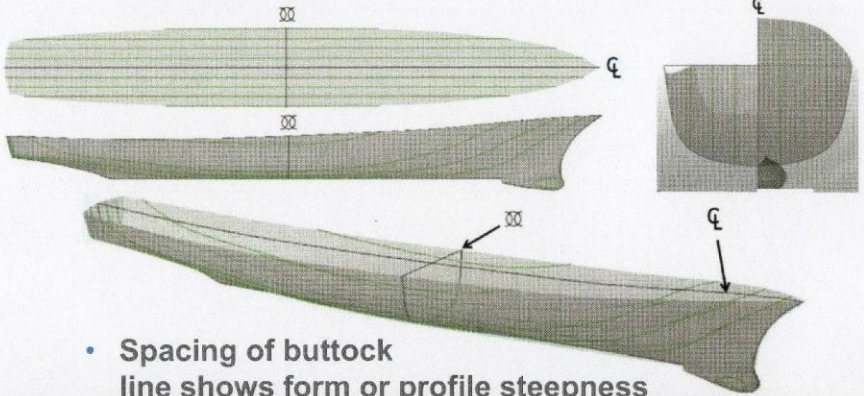
- Midship station area and sectional area curves at different stations



- Lower station area at stern and bow and increasing are moving to midships

Ship Terminology: Buttock Lines

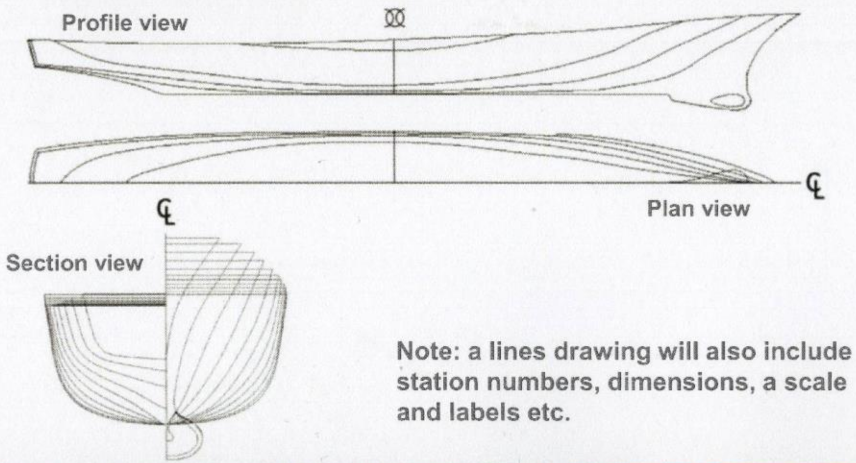
- Buttock Lines
  - Generated by translating centreline plane to port and starboard



  - Spacing of buttock line shows form or profile steepness

Ship Terminology: Lines Drawing

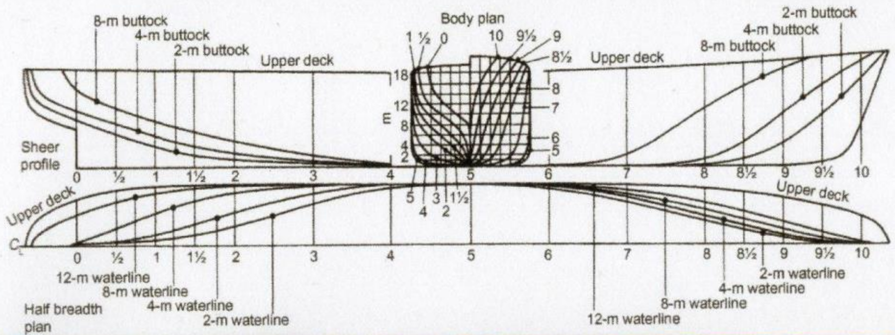
- Lines Drawing



Note: a lines drawing will also include station numbers, dimensions, a scale and labels etc.

Ship Terminology: Lines Drawing

- Hull form
  - A lines plan portrays the ship hull form graphically
  - This shows the various curves of intersection between the hull and 3 sets of orthogonal planes
  - The 3 sets of curves help facilitate fairing the hull form



Module 1 (section a)

Ship Terminology: Important Lengths

- Length between perpendiculars (LPP or L_{PB})
  - Distance measured along the summer load waterplane from the aft to fore perpendiculars
- Length overall (LOA or L_{OA})
  - Distance between the extreme points forward and aft measured parallel to the summer (or design) waterline (the forward point may be on the raked stem or on a bulbous bow
- Length on the waterline (LWL or L_{WL})
  - Length on waterline, at which the ship is floating between the intersections of the bow and aft end with the waterline
- Scantling length
  - Is the LBP, but is not to be less than 96% of LWL
- Subdivision length
  - Length used in damage stability calculations

Module 1 (section a)

Ship Terminology: Gross Tonnage

- Gross Tonnage Definition (GT) - not to be confused with deadweight tonnage or displacement
  - Gross tonnage is calculated based on 'the moulded volume of all enclosed spaces of the ship' and is used to determine a ship's manning regulations, safety rules, registration fees, and port dues
  - Gross tonnage is a measure of the internal capacity of a ship
  - IMO convention (1969) on tonnage measurement of ships led to an 'universally' accepted definition – agreement came into force in July 1982

$$GT = K_1 V$$

$$K_1 = 0.2 + 0.02 Log_{10} V$$

Where V = total volume of all enclosed spaces (m^3)

Module 1 (section a)

Ship Terminology: Compensated Gross Tonnage

- Gross Tonnage (GT)
  - Used to compare the output of shipbuilding countries – never intended as a statistical measure of the work required to build a ship
- Compensated Gross Tonnage (CGT)
  - Is an indicator of the work necessary to build a given ship
  - Calculated by multiplying the tonnage of a ship by a coeff. which is determined according to type and size of a ship

$$CGT = A \times GT^B$$

Ship Type	A	B
Oil Tanker	48	0.57
Bulk Carriers	29	0.61
Full Container	19	0.68
RoRo Vessel	32	0.63
General Cargo	27	0.64
LPG Carrier	62	0.57
LNG Carrier	32	0.68
Ferries	20	0.71
Passenger	49	0.67
Fishing Vessel	24	0.71

Module 1 (section a)

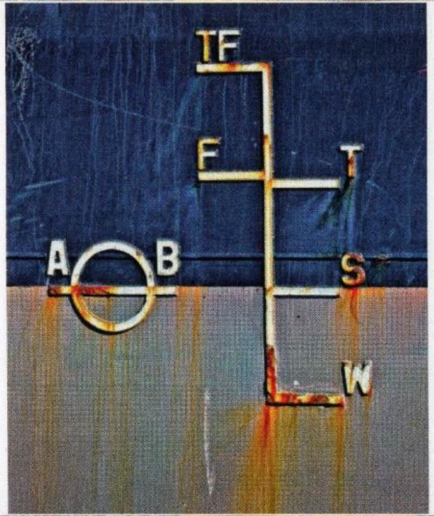
Ship Terminology: Load Lines

- Load Line Definition
  - Load line is a special marking positioned amidships which depicts the draft of the vessel and the maximum permitted limit in distinct types of waters to which the ship can be loaded
  - Last update at International Load Line Convention 2003
- Load Line Purpose
  - Fundamental purpose of a Load Line is to define a maximum legal limit up to which a ship can be loaded by cargo. By prescribing such limits, the risk of having the vessel sailing with inadequate freeboard and buoyancy is minimised

Module 1 (section a)

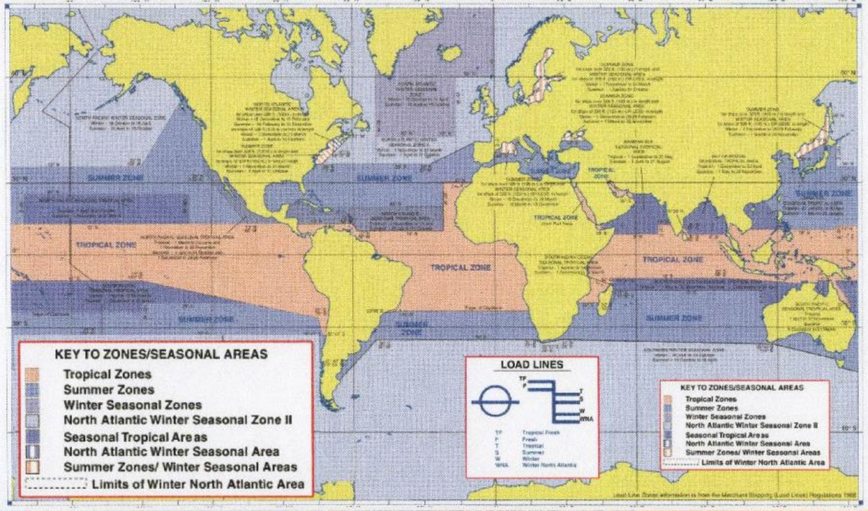
Ship Terminology: Load Lines

- Load Line Definitions
  - A-B: American Bureau of Shipping
  - T: Tropical zones
  - S: Summer
  - W: Winter
  - TF: Tropical freshwater
  - F: Freshwater
- Others
  - WNA: Winter North Atlantic
  - Numbers: draft marks in cm or m



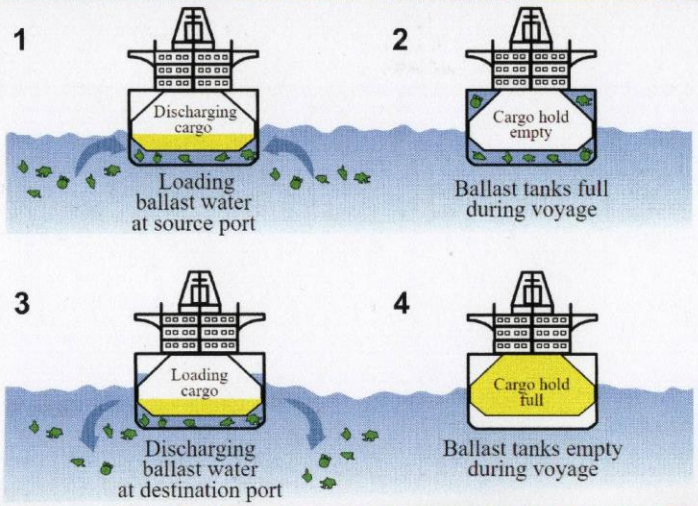
Module 1 (section a)

Ship Terminology: Load Line Zones



Module 1 (section a)

Ship Terminolgy: Bilge and Ballast



Module 1 (section a)

Vessel Type: Passenger Ships

- Definition
  - Vessel certified to carry 12 or more passengers
  - Classification societies issue passenger ship safety certificates
- Passenger ship categories include
  - Ferries: provide link in a transport system and large ocean-going ferries are a combination of roll-on roll-off ships (Ro-Ro) and passenger vessel
  - Cruise ships: A growth area with vessels now capable of carrying 3000-4000 passengers at speeds of 22 knots
  - Liners: Advent of long distance air travel reduced the number of passengers taking sea/ocean voyagers by ship, but in recent years interest has been renewed

Module 1 (section a)

Vessel Type: Cruise Ship Versus Liner

Primary Function	Cruise Ship	Ocean Liner
Primary Function	Leisure	Transportation
Shape	High on Water	Lower on Water – Pointed Bow
Hull Thickness	Standard	Extra Thick
Speed	Standard	Fast
Onboard Conditions	Traditional, Elegant	Varied

Module 1 (section a)

Vessel Type: Passenger Ships

- Structural Aspects
  - For fire protection A, B and C class divisions (bulkheads) are specified
    - A Class: made of steel (or equivalent rated material) capable of preventing the passage of smoke and flame to the end of a 60min. Standard fire test
  - Passenger ships are divided into main vertical zones by A-class divisions, not more than 40m apart
  - These divisions are carried through the main hull, superstructure and deckhouses
  - The remaining bulkheads and decks within the main vertical zones are A, B or C class depending upon the fire potential and relative importance of adjacent compartments

Module 1 (section a)

Vessel Type: Passenger Ships

- Spacing of Watertight Bulkheads – Passenger Ships
  - P208 – ship construction D Eyres et al

Length (L) of Ship, m	No. of Bulkheads	
	Machinery Midships	Machinery Aft
≤ 65	4	3
65 < L ≤ 85	4	4
85 < L ≤ 105	5	5
105 < L ≤ 115	6	5
115 < L ≤ 125	6	6
125 < L ≤ 145	7	6
145 < L ≤ 165	8	7
165 < L ≤ 190	9	8
190	To be considered individually	

Module 1 (section a)

Vessel Type: Container Ships

- Definition and Brief History
  - A container ship is defined as a ship designed exclusively for carriage of containers in holds and on deck
  - Containers in holds are normally stowed within cellular guide systems
  - The development of container ships was closely linked to the development of special container ports and supporting road and rail transport networks
  - Limits are imposed on the ship size by external factors such as geographical features and port facilities
  - Many ships need to use rivers but the three waterways of particular interest are:
    - Suez Canal (Suez Canal Authority) – 25000 ships/yr
    - Panama Canal (Panama Canal Commission) 14000 ships/yr
    - Saint Lawrence Seaway

Module 1 (section a)

Vessel Type: Container Ships

Maersk Line container ships: Typical loads are a mix of 20-foot and 40-foot (2-TEU) ISO-standard containers, with the latter predominant.

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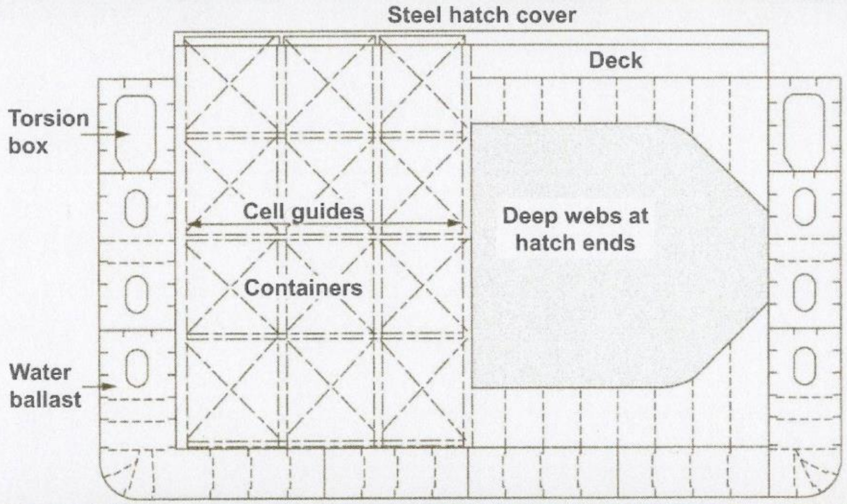
Module 1 (section a)

Vessel Type: Container Ships



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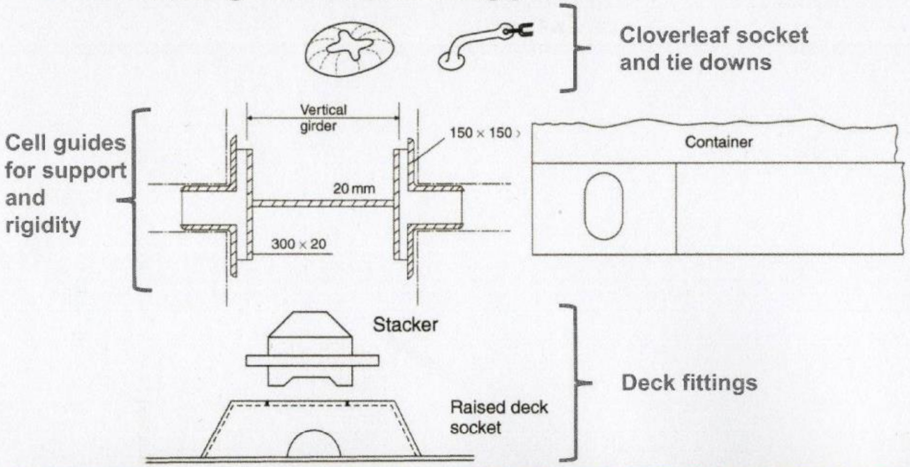
Module 1 (section a)

Vessel Type: Container Ships

- Container guides and lashing points



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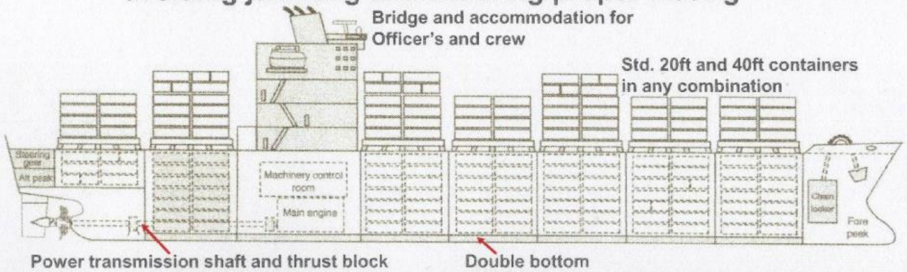
Module 1 (section a)

Vessel Type: Container Ships

- Container stacking arrangement
  - Below decks containers are restrained in vertical cell guides, which are typically 150 x 150 x 12 angles
  - The cell guides are not a part of the ship's structure, they are designed so they do not carry the main hull stresses
  - Clearance between cell guide and containers is critical for avoiding jamming and ensuring proper mating



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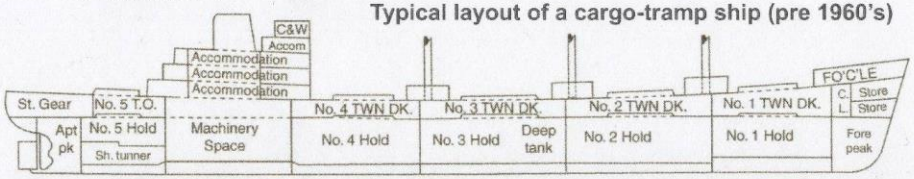
Module 1 (section a) — Vessel Type: Dry Cargo (Tramp) Ships

- General cargo or 'tramp' ships used to be ships that were designed to carry any specific type of cargo and travel anywhere on the world on irregular routes.
- They were hired out on a spot or a time charter to carry bulk cargo or general cargo
- Such ships are usually slower and smaller than the 'container' liner vessels
- Cargo vessels may now carry some or all cargoes in containers

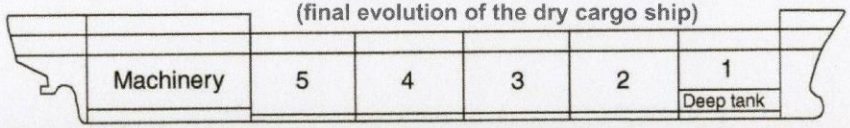
Typical layout of a cargo-tramp ship (pre 1960's)



Module 1 (section a) — Vessel Type: Dry Cargo (Tramp) Ships

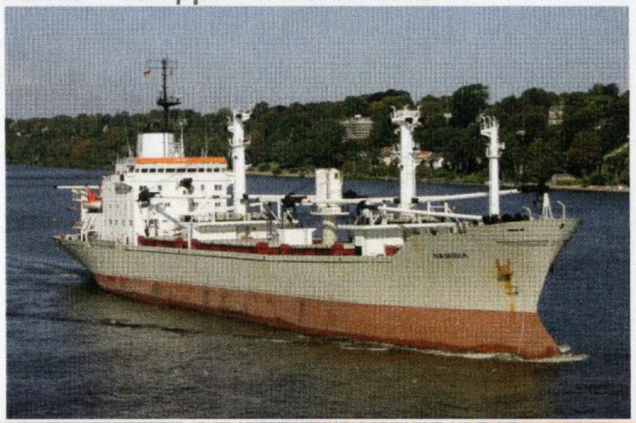
- Dry cargo ship evolution
  - Originally the machinery position was amidships with paddle wheel propulsion. Coal fuel was favourably placed amidships for trim purposes
  - With use of oil fuel this problem was overcome and machinery was moved further aft, but right aft could produce excessive trim by the stern in light conditions
  - With screw propulsion definite advantages were gained by having machinery right aft and the vessel is then provided with deep tanks forward

All-aft cargo liners typical of mid 1960's (final evolution of the dry cargo ship)



Module 1 (section a) — Vessel Type: Cargo (Tramp) Ships

- General cargo vessel Namibia arriving at Hamburg (2007), built in 1977 by Van der Giessen-de Noord, Krimpen a/d Ijssel, Netherlands – scrapped in March 2010



Module 1 (section a) — Vessel Type: Dry Cargo (Tramp) Ships

- Characteristics of a cargo (tramp) vessel
  - Suitable cargo handling equipment is provided in the form of hydraulic or electrically powered cranes
  - A *forecastle* is fitted to reduce the amount of water shipped forward and to provide adequate working space for handling ropes and cables
  - The forecastle also prevents forward hatches from heavy weather damage
  - The space immediately forward of the machinery space may be subdivided into lower 'tween decks and *hold/deep tank* to improve the ability to even out the stress on the hull and/or give different options for carrying other liquids such as fuel or water
  - The work of these vessels has largely been taken over by bulk carriers and smaller container vessels

Vessel Type: Oil Tankers

- Oil Tankers

'Live Position' 16/08/21 16:09

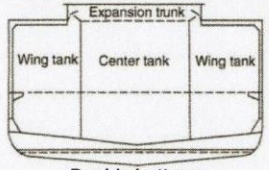
Supertanker: AbQaiq
Built 2002, LOA 338m Width 58m
Draught 11.2m Ave Speed 11kn
Carrying Capacity, 302,986 t DWT
Position – Persian Gulf

Module 1 (section a)

Vessel Type: Oil Tankers

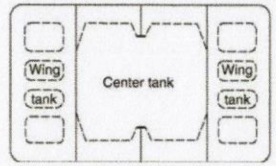
- Oil Tanker: Notable Points

Length 77.6m Deadweight 1680 t
Beam 10.4m
Depth 5.8m Speed 10kn

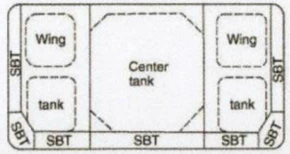


Double bottom

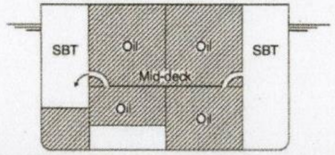
Length B.P. 330m Deadweight 332,000 t
Beam 53.3m
Depth 32 m Speed 14.5kn



Double-hull tanker



Mid-deck tanker principle



Module 1 (section a)

Vessel Type: Oil Tankers

- Oil Tanker: Notable Points
  - Growth of vessels from 1880 to end of WW2 was gradual, average deadweight rising from 1500 to ~12000 tonnes
  - Post WW1 deadweight increased rapidly to 30,000 tonne by 1959
  - Today tankers range from 100,000 to 500,000 and service speeds since the late 1940s increased from 14 to 17knots
  - Tanker fleet grew dramatically until 1973/74 to meet expanding demand
  - MARPOL protocols
    - 1978: provision of clean water ballast tank capacity; primarily to reduce pollution risk, though segregated water ballast tanks in midship reason aids the reduction of still water bending moments when tanker is fully loaded

Module 1 (section a)

Vessel Type: Container Ships

- Oil tanker size categories

AFRA Scale		Flexible Market Scale	
Class	Size in DWT, $x10^3$ Ton	Class	Size in DWT, $x10^3$ Ton
General purpose tanker	10 to < 25	Product tanker	10 to < 60
Medium range tanker	25 to <45	Panamax	60 to <80
LR1 (large range)	45 to < 80	Aframax	80 to < 120
LR2 (large range)	80 to < 160	Suezmax	120 to < 200
VLCC (very large crude carrier)	160 to < 320	VLCC	200 to < 320
ULCC (ultra large crude carrier)	320 to < 550	ULCC	320 to < 550

Module 1 (section a) — Vessel Type: Oil Tankers

- Oil Tanker: Notable Points
  - March 1989 the tanker Exxon Valdez, which complied fully with the MARPOL requirements ran aground and discharged 11 million gallons of crude oil in Prince William Sound, Alaska
    - Incident led to the oil pollution act and existing single-hull tankers operating in US waters were to be phased out
  - MARPOL protocols
    - November 1990: USA suggests to MARPOL that convention should be amended to make double hulls compulsory for new oil tankers
    - In 1992 MARPOL stipulate tankers ≥ 5000 tonne must be double hulled or of a design offering equivalent protection
    - Whilst MARPOL provided for alternative tanker designs USA did not and no alternative designs were built
    - Agreement to phase out single hull tankers in 2005

Module 1 (section a) — Vessel Type: Bulk Cargo Carriers

- Bulk carriers: Sabrina I is a typical modern Handymax bulker with 5 holds, 5 hatches and 4 cranes.

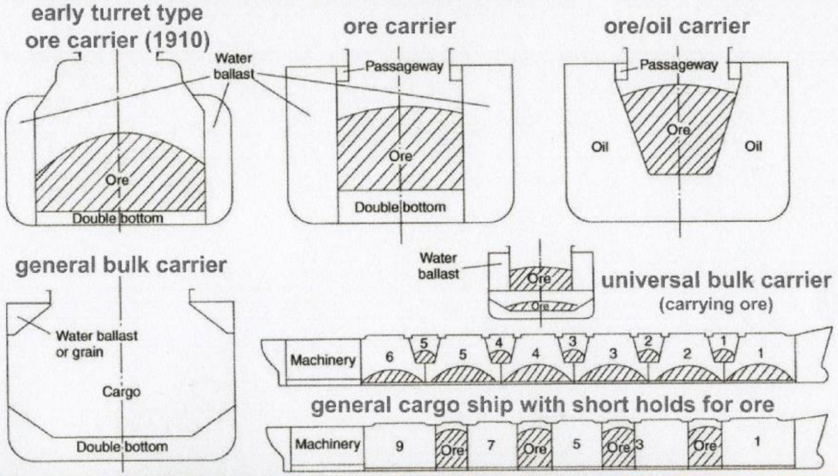
Owned by Portline of Portugal
LOA: 190.00m
beam: 32.26m
(panamax) cranes: 4 x 30 metric tons SWL
cargo hold capacity: ~ 67,500 cubic metres

Module 1 (section a) — Vessel Type: Bulk Cargo Carriers

- Bulk Carrier: Notable Points
  - The volume of cargoes transported by sea increased rapidly in the second half of the 20th century, particularly oil-related products
  - Bulk carriers carry cargoes that don't need packaging and can benefit from the economies of scale
  - Typically subdivided into tankers (previous slides) and dry bulk carriers i.e. coal, grain, cement, alumina, bauxite and other ores, packaged steel, timber etc. etc.
  - Most bulk carriers are single-deck ships, longitudinally framed with a double bottom, with cargo carrying section of the ship divided into holds or tanks – arrangement of holds or tanks vary according to the range of cargoes
    - Typical arrangements - see next slide

Module 1 (section a) — Vessel Type: Bulk Cargo Carriers

- Bulk Carrier: Hold arrangements



Module 1 (section a)

Vessel Type: Liquid Gas Carriers

- Liquid natural gas (LNG) carriers
  - LNG Carrier Galea - at Barcelona

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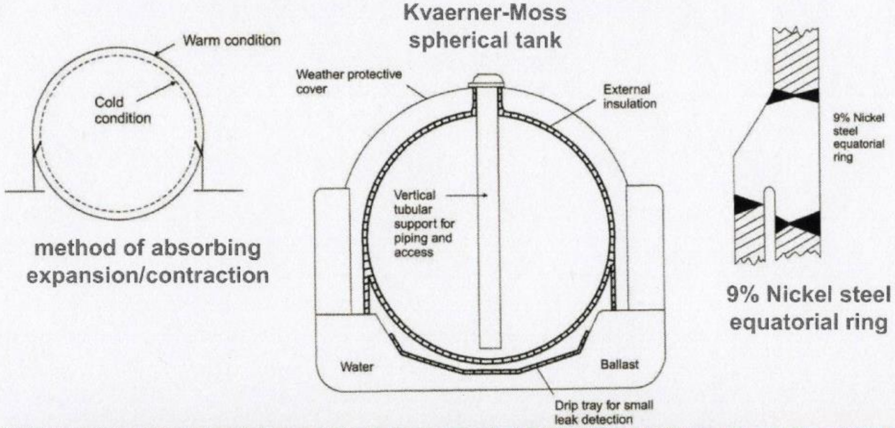
Module 1 (section a)

Vessel Type: Liquid Gas Carriers

- Liquid natural gas (LNG) carriers: Notable points
  - Allowance for expansion and contraction



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Module 1 (section a)

Vessel Type: Liquid Gas Carriers

- Liquid natural gas (LNG) carrier tanks
  - Several independent tank types
    - Type A: designed primarily using standard traditional methods of ship structural analysis
    - Type B: designed using more sophisticated tools and methods to determine stress levels, fatigue life and crack propagation characteristics – design based on the so-called 'crack detection before failure principle'
    - Type C: designed as pressure vessels; normally used for LPG and occasionally ethylene
  - Kvaerner-Moss Type B tank containment system has been widely accepted and installed in many LNG ships
    - Tank consists of either aluminium alloy or 9% nickel steel, sphere is welded to a vertical cylindrical skirt
    - The sphere expands and contracts freely

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Module 1 (section a)

Vessel Type: Liquid Gas Carriers

- LNG and LPG ships: notable points
  - Gas carriers have similar overall arrangements to tankers with machinery and accommodation aft and cargo containment is spread over the rest of the ship length
  - Specific gravity of LPG cargoes varies from 0.58 to 0.97, whilst LNG ships are often designed for a cargo specific gravity of 0.5 so characteristics of LNG ships in particular is their low draft and high freeboards
  - Water ballast cannot be carried in the cargo tanks so provision is made for it in double-hull spaces, double-bottom, bilge tank and upper wing spaces
  - Double-hull feature of LNG carriers and many LPG ships is a safety requirement
  - All gas ships have spaces around the tanks that are monitored for gas leaks

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Module 1 (section a)

Vessel Type: Roll-On Roll-Off

- Ro-Ro Vessels, Notable Points
  - These vessels are designed with flat decks and have moveable watertight divisions to enable vehicles and tractor-trailer units to be driven into and off the vessel
  - Having such a long continuous deck means that any appreciable accumulation of water will have a magnified effect on the vessel's stability (free surface effect – covered in slide section b)
  - Ro-Ro vessels typically provide a transport interlink, though some specialist, large car carrying capacity variants move considerable numbers of cars world-wide
  - The loss of Herald of Free Enterprise (1987) and Estonia (1994) resulted in attention being directed at damage stability. This led to regulations onstrengthening and surveillance of bow doors and internal watertight doors

Module 1 (section a)

Vessel Type: Roll-On Roll-Off

- Procyon Leader
  Built in 2000
  Flag: Japan
- Draught 8.1m
  Length 180m
  Beam 32 m
- Current position
  Port of Singapore on
  17th Aug. 2021

Module 1 (section a)

Vessel Type: Roll-On Roll-Off

Ro-Ro Variations

Type	Comments
ConRo	A ConRo (or RoCon) vessel is a hybrid of a Ro-Ro and a container ship. This vessel type has a below deck area used for vehicle storage while stacking containerized freight on the top decks
LMSR	Large, medium-speed, Roll-on/Roll-off (LMSR) refers to several classes of military sealift command (MSC) roll-on/roll-off type cargo ships
RoLo	A RoLo (Roll-on/Lift-off) vessel is another hybrid type, with ramps serving vehicle decks but with other cargo decks only accessible when the tides change or by the use of a crane
RoPax	RoPax describes a RoRo vessel built for freight, vehicle transport and has passpassenger-carrying capacities, in practice ships with facilities for >500 passengers are referred to as cruiseferries.

Module 1 (section a)

Vessel Type: Roll-On Roll-Off

- Loch Seaforth: Ullapool to Stornoway, Isle of Lewis

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Professional Qualification
in Marine Corrosion

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Module 1
(section b)

Ship Hydrodynamics, Stability and Strength Aspects

Module 1 (section b) Summary

- **Laws of Flotation and Archimedes Principle**
  - Flotation and conditions for a body to float
  - Basic ship stability related parameters
- **Ship Stability**
  - Centre of gravity and buoyancy
  - Stability at low heel angles
  - Stability at high heel angles
  - Angle of loll
  - GZ Curves
  - Cross and hydrostatic curves
- **Strength Aspects**
  - Strength curves
  - Buoyancy and load curves

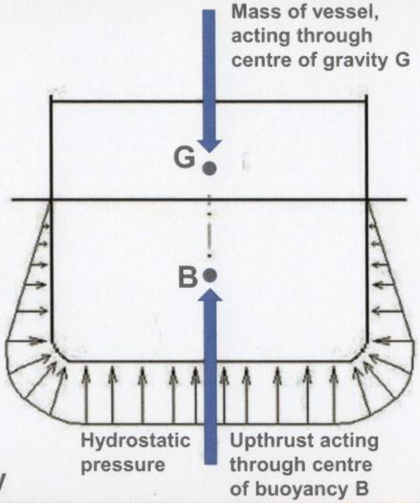
Module 1 (section b) Laws of Flotation

- **Archimedes Principle**
  - The principle states that any object, wholly or partially immersed in a fluid, experiences an upward force equal to the weight of the fluid displaced by it
  - The weight of fluid displaced by the body is directly proportional to the volume of the displaced fluid, since the density of the fluid is constant
  - A body floats in a fluid under any of the following two conditions
    - The density of the body is less than the density of the fluid
    - The volume of the fluid displaced by the immersed part of the body is such that its weight is equal to the weight of the body

Module 1 (section b)

Buoyancy: Forces on a Ship's Hull

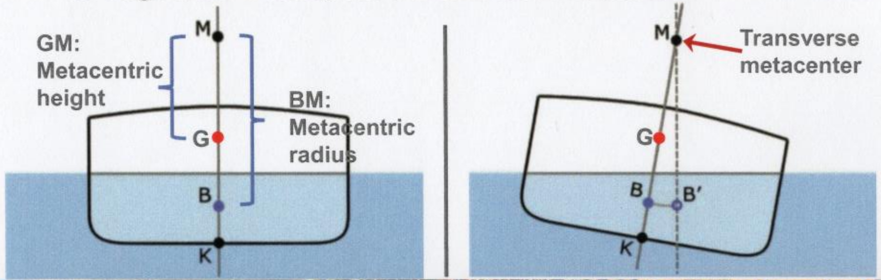
- Floating Bodies
  - The % volume of a floating body that is immersed depends upon its relative density and the relative density (rd) of the liquid
  - A body of rd 0.8 will float in fresh water with 80% of its volume immersed and in seawater, with 1.000/1.025 x 80% = 78% of its volume immersed i.e. slightly less seawater is displaced to produce sufficient buoyancy



Module 1 (section b)

Ship Stability at Small Heel Angles

- Transverse Stability at Small Heel Angles ≤ 6°
  - On a ship with an even keel we can identify the keel K, vertical centre of gravity G and the centre of buoyance B
  - For small heel angles the centre of buoyancy B moves through a small arc and a vertical line drawn through the new centre of buoyance B/ intersects the original vertical line through K-B-G at M, the transverse metacentre



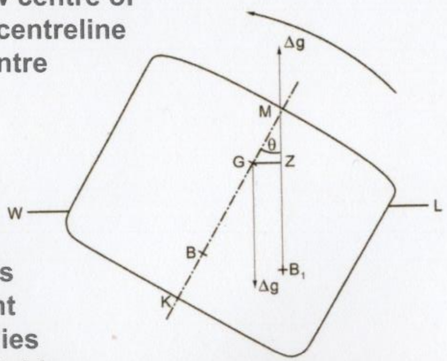
Module 1 (section b)

Ship Stability at Small Heel Angles

- For small heel angles
  - The centre of buoyancy moves from B to B1 while the weight still acts through G creating a moment Δg x GZ
  - The vertical through the new centre of buoyancy B_1 intersects the centreline at M, the transverse metacentre and from figure we have

    $$GZ = GMSin\theta$$

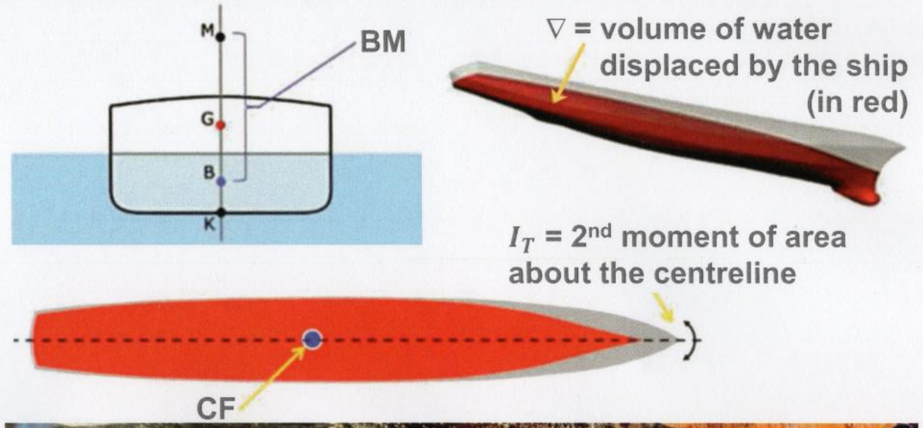
  - Thus for small heel angles GZ is a function of GM and the initial stability of a ship in can be expressed in terms of GM the metacentric height
  - G is said to be +ve when G lies below M and the vessel is stable



Module 1 (section b)

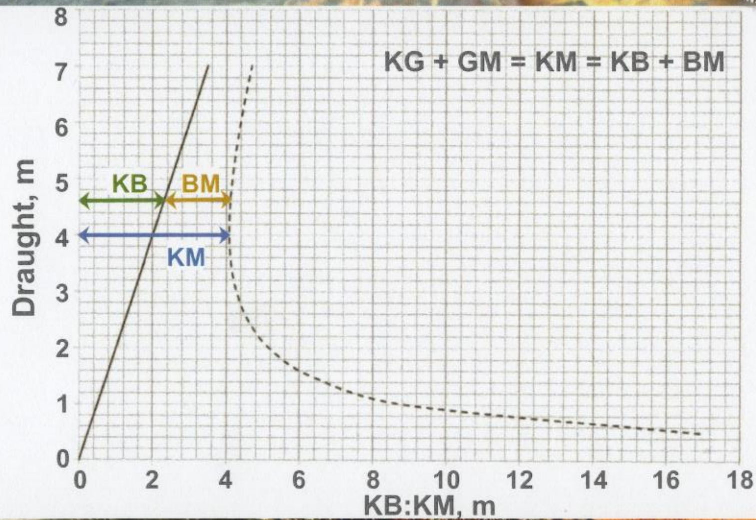
Ship Stability: Calculating BM

- Determination of BM $\mathrm{BM} = \dfrac{I_T}{\nabla}$



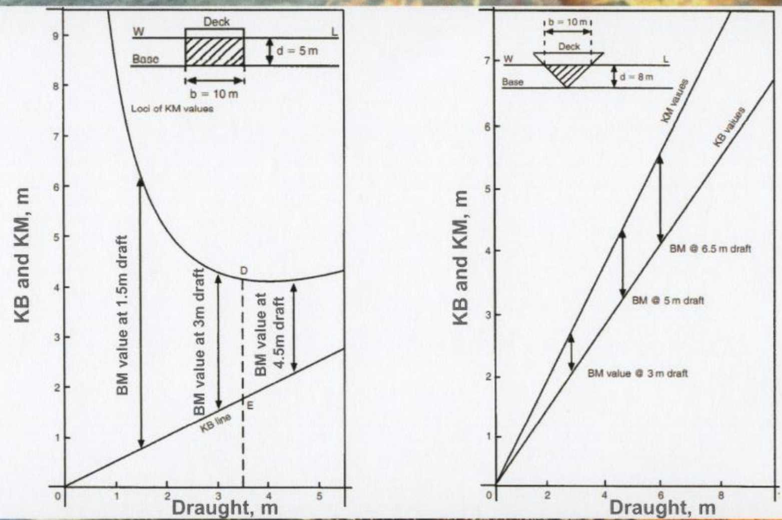
Module 1 (section b)

Ship Stability: Metacentric Diagrams



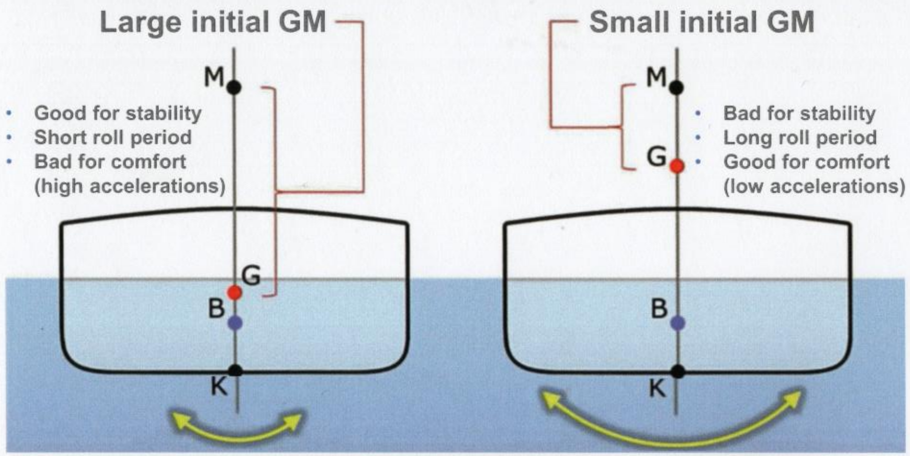
Module 1 (section b)

Ship Stability: Metacentric Diagrams



Module 1 (section b)

Ship Stability: Influence of Initial GM



Module 1 (section b)

Ship Stability: Metacentre

- Why is a Ship's Metacentre important?
  - The position of the metacentre is found by considering small inclinations or angles of heel about the ship centreline
  - When a ship heels (rolls sideways), the centre of buoyancy of the ship moves laterally. It might also move up or down with respect to the water line. The point at which a vertical line through the heeled centre of buoyancy crosses the line through the original, vertical centre of buoyancy is the metacentre
  - The relative positions of vertical centre of gravity G and the initial metacentre M are extremely important with regard to their effect on the ship's stability
  - The ship is in stable equilibrium if G is below M, in neutral equilibrium if the vertical centre of gravity (VCG) and M are coincident and in unstable equilibrium if VCG is above M

Module 1 (section b)

Ship Stability: Determining GM

- KB, BM and KM depend on the shape of the hull
  - KM provided from ship's hydrostatic curves
- KG and GM depend on the loading of the ship
  - KG determined by 'weights and moments' calculation

$$GM = KM - KG$$

GM > 0	GM = 0	GM < 0
stable	neutrally stable	unstable

Module 1 (section b)

Recommended GM Values by Ship Type

- GM is crucial for ship stability; recommended working values of GM by ship type are shown below

Ship Type	GM* *at fully-loaded condition*
General cargo ship	0.30-0.50m
Oil tankers	0.50-2.00m
Double-hull supertankers	2.00-5.00m
Container ships	1.50-2.50m
Ro-Ro vessels	~1.50m
Bulk ore carriers	2-3m

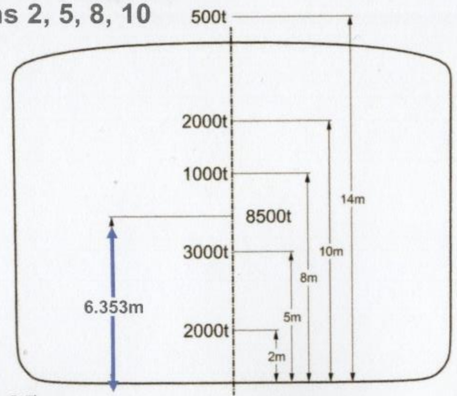
* Dept. of transport stipulates GM must never be <0.15m

Module 1 (section b)

Position of Ship Centre of Gravity above Keel

- Calculating position of G for a ship of 8500 tonne displacement composed of masses 2000, 3000, 1000, 2000 and 500t at positions 2, 5, 8, 10 and 14m above the keel

Mass (tonne)	Kg (m)	Vertical moment t.m
2000	2	4000
3000	5	15000
1000	8	8000
2000	10	20000
500	14	7000
8500		54000

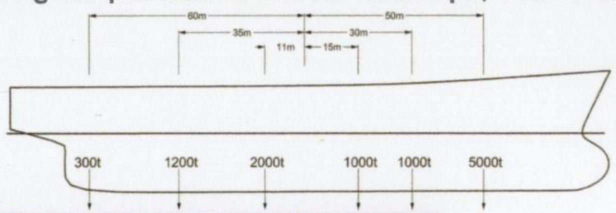


$$KG = \frac{total\ moment}{total\ displacement} = \frac{54000}{8500} = 6.35m$$

Module 1 (section b)

Position of Ship Centre of Gravity from Midships

- Calculating the position of G from midships, see schematic



Mass, tonne	Lcg from midships, m	Moment forward (t.m)	Moment aft (t.m)
300	60 aft	----	18000
1200	35 aft	----	42000
2000	11 aft	----	22000
1000	15 forward	15000	----
1000	30 forward	30000	----
500	50 forward	25000	----
6000		70000	82000

$$Excess\ Moment\ Aft = 8200 - 7000 = 12000\ tonne\ m$$

$$KG = \frac{Excess\ Moment\ Aft}{Total\ Displacement} = \frac{12000}{6000} = 2.00m$$

Module 1 (section b)

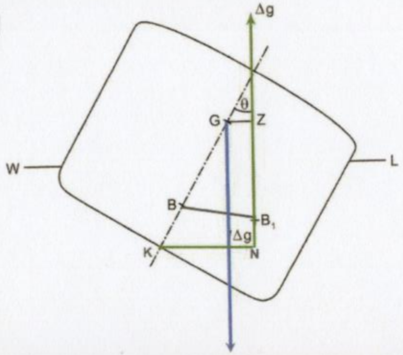
Ship Stability at Large Heel Angles

- When a ship heels to an angle >10° the principles on which initial stability is based are no longer true i.e. formula for BM based on assumption that the two waterplanes intersect at the centre line and that the wedges are right angled triang
- Consequently, the stability of the ship is determined from first principles
- It can be shown that for large heel angles that,

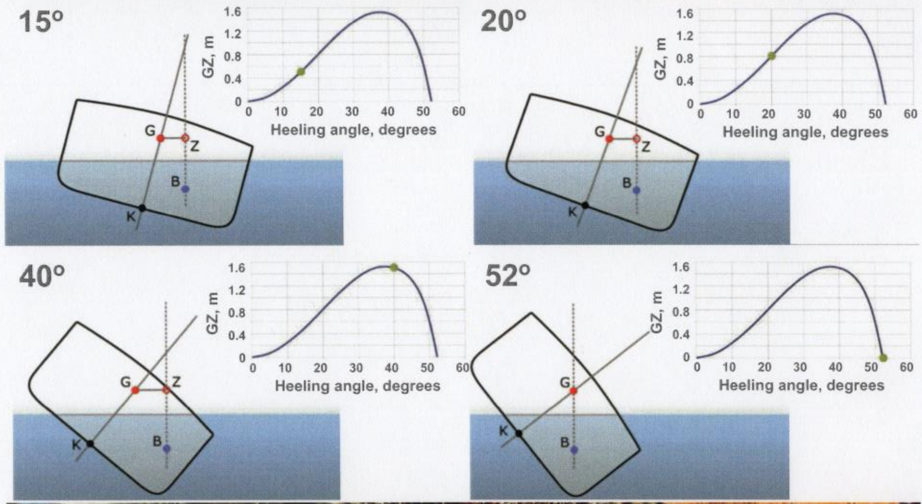
$$KN = KG\sin\theta + GZ$$

hence

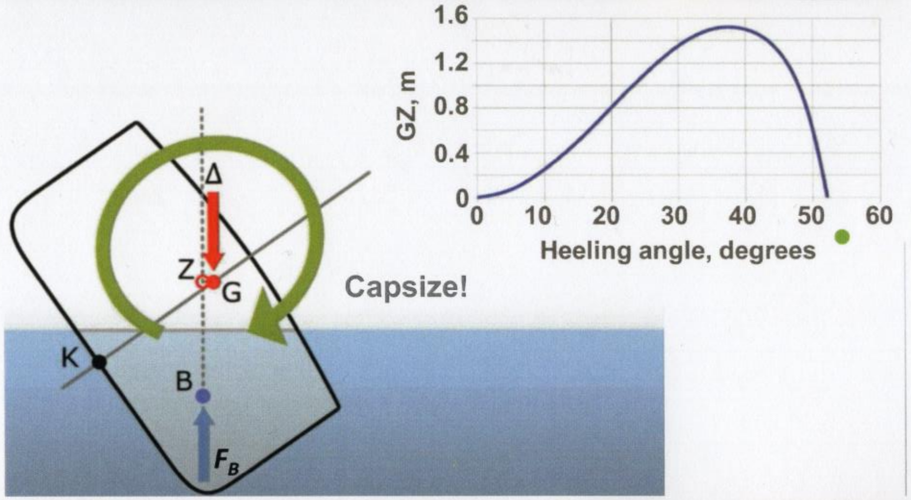
$$GZ = KN - KG\sin\theta$$



Module 1 (section b)
Ship Stability at Large Heel Angles

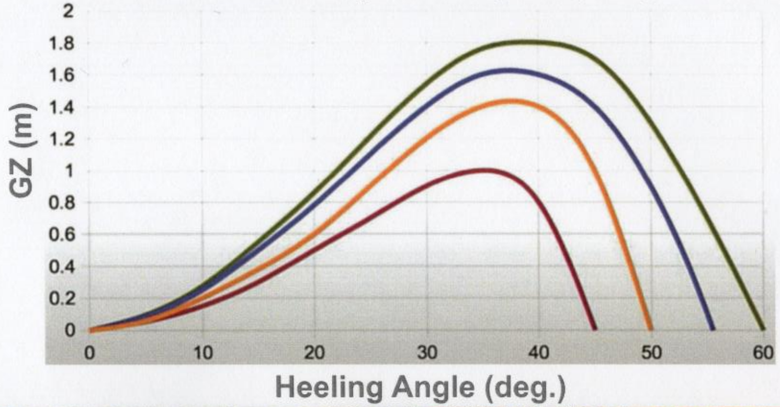


Module 1 (section b)
Ship Stability at Large Heel Angles



Module 1 (section b)
Ship Stability at Large Heel Angles

- Hydrostatic Curves
  - A program will calculate GZ curves for different combinations of displacement, draft, trim, etc.



Module 1 (section b) — Ship Stability: GZ Stability Curve

- Features of a Statical 'GZ' Stability Curve
  - The slope of the GZ curve at the origin is a measure of the initial stability GM
  - The maximum ordinate of the curve multiplied by the displacement gives the largest steady heeling moment the ship can withstand without capsizing
  - The range of angle over which GZ is positive is termed the range of stability
    - Freeboard and reserve buoyancy are important factors in determining the range of stability
  - The angle of deck immersion and bilge emersion vary along the ship length, however, they often occur over a reasonable length within a small angle and in such a case the GZ curve exhibits a point of inflexion in that angle

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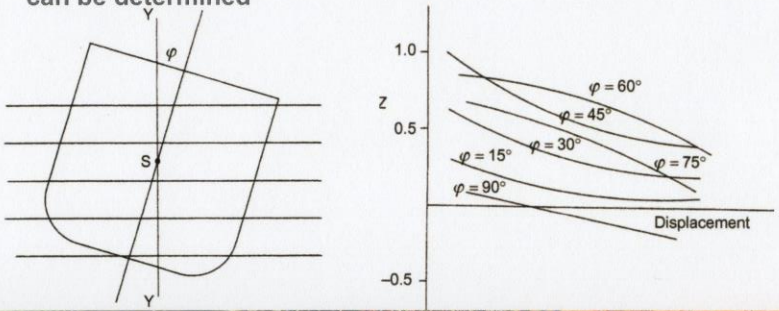
Module 1 (section b) — Ship Stability: Cross Curves of Stability

- Cross curves of stability
  - Cross curves of stability are drawn to overcome the difficulty in defining waterlines of equal displacement at various angles of heel
  - By appropriate calculation, for a range of waterlines, the righting moment at different displacements and heel angle can be determined



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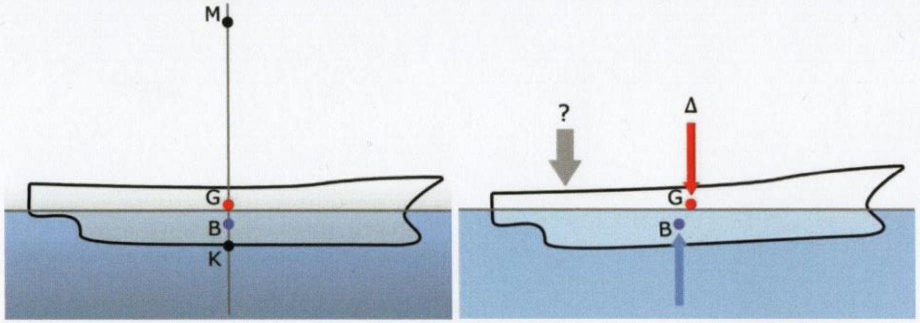
Module 1 (section b) — Ship Stability: Longitudinal Stability

- Longitudinal stability – what happens when the ship is pitched?



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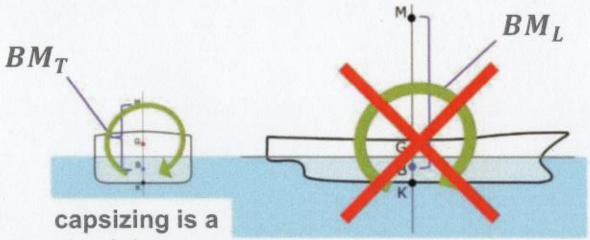
Module 1 (section b) — Ship Stability: Longitudinal Stability

- Transverse versus longitudinal stability

$$BM = \frac{I}{\nabla} \qquad I_L \gg I_T \;\rightarrow\; BM_L \gg BM_T$$



capsizing is a real danger here

capsizing almost impossible in this case

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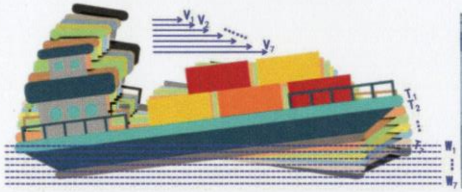
Ship Longitudinal Stability: Optimization Methods

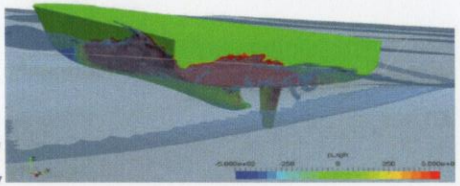
Module 1 (section b)

- Four main methods to determine ship's optimum trim:

Sea Trial Method

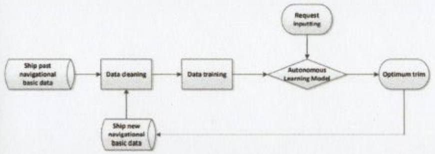


Computational Fluid Dynamics



Tank Testing

Machine Learning Programs



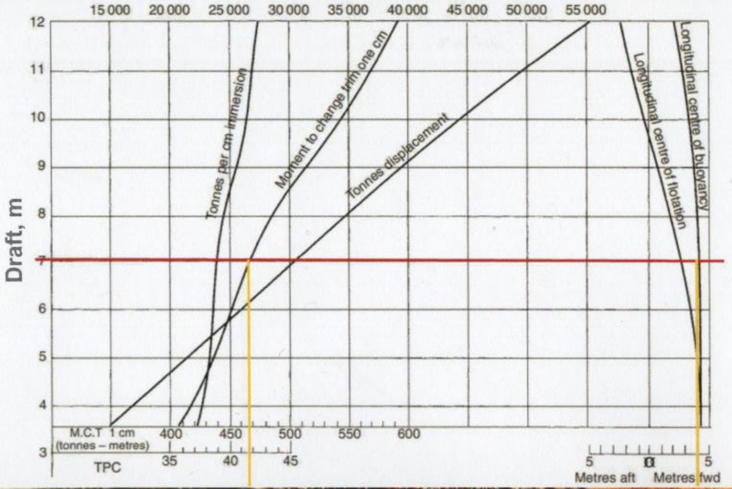
Ship Stability: Hydrostatic Curves

Module 1 (section b)

- Hydrostatic Curves
  - It is customary to obtain the displacement and position of B, M and F for a range of waterplanes parallel to the design waterplane and plot them against draught
  - Such a set of curves are called hydrostatic curves and each curve will have its own scale on the horizontal axis (next slide)
  - The curves often show moulded and extreme displacement, the extreme displacement allows for displacement to the outside of the hull plating and perpendiculars, bossings, bulbous bows etc.
    - This displacement is relevant to flotation and stability
    - The additions to the moulded figure can have a measurable effect upon displacement and position of B

Ship Stability: Hydrostatic Curves

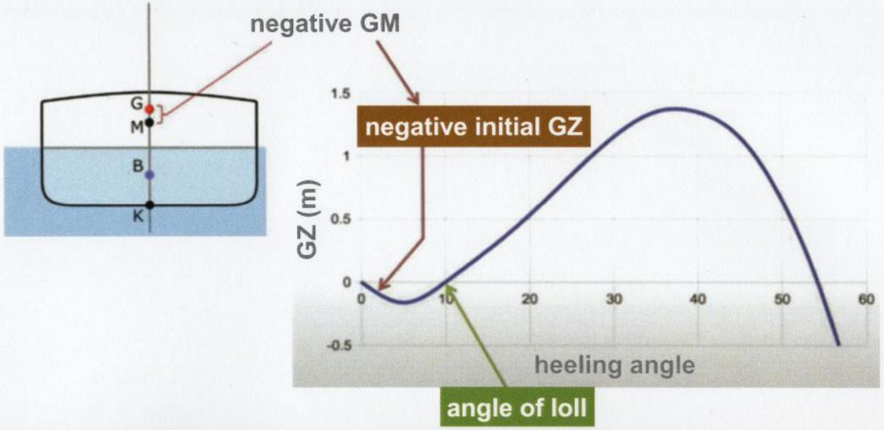
Module 1 (section b)



Ship Stability: Angle of Loll

Module 1 (section b)

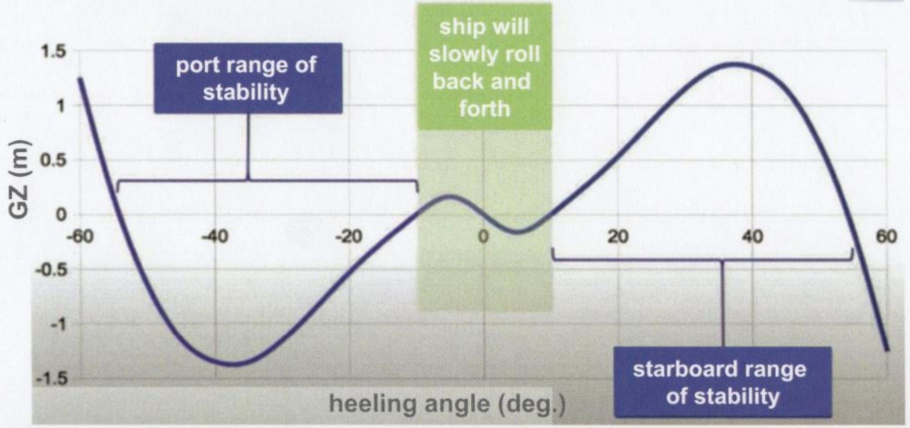
- Influence of negative GM: Loll – unstable equilibrium
  - Reduces the range of ship stability from 0° – 55° to 10° - 55°



Module 1 (section b)

Ship Stability: Angle of Loll

- Influence of negative GM: Loll – unstable equilibrium
  - Range of stability Port and Starboard



Module 1 (section b)

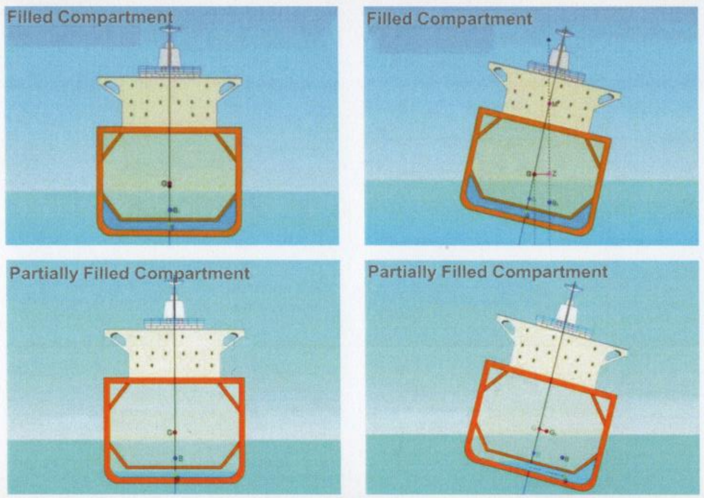
Ship Stability: Unstable Equilibrium

- Measures to correct unstable equilibrium
  - Weights already in the ship may be lowered.
  - Weights may be loaded below the centre of gravity of the ship.
  - Weights may be discharged from positions above the centre of gravity.
  - Free surfaces within the ship may be removed (next slides)

NB if ship takes up a loll angle first check this is due to a negative GM and not an uneven distribution of weights onboard

Module 1 (section b)

Ship Stability: Effect of Free Surface



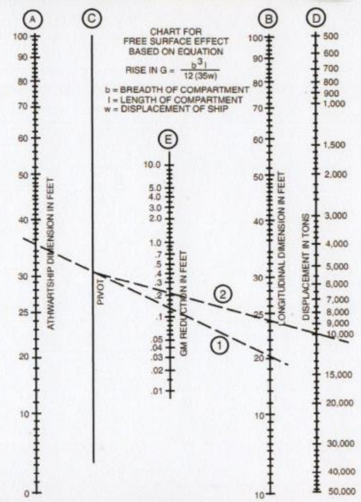
Module 1 (section b)

Ship Stability: Effect of Free Surface

- Charts for determining free surface effect, based on

$$Rise\ in\ G = \times \frac{B^3 L}{12(35w)}$$

- To use chart:
  - draw line from the appropriate point on the ATHWARTSHIP DIMENSION scale (A) to the appropriate point on the LONGITUDINAL DIMENSION scale (B)
  - draw a second straight line from the point of intersection on the pivot scale (C) to the appropriate point on the displacement scale (D)
  - Intersection on GM scale gives reduction in GM in feet



Ship Stability: Effect of Free Surface

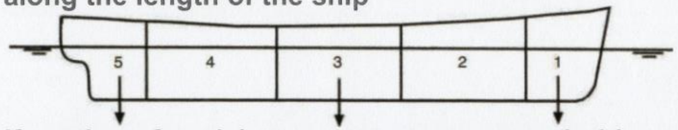
Module 1 (section b)

- Important points about effect of free surface
  - Free surface correction (FSC) - zero for full or empty tanks
  - To reduce the total FSC, the number of slack tanks must be minimized as each slack tank contributes to the total FSC
  - By fitting longitudinal division in the tank equally spaced, the FSC can be reduced to $1/n^2$ times the undivided value, where n = no. of spaces e.g. 3 spaces are produced by 2 longitudinal divisions and FSC reduces to 1/9th value of undivided tank
  - FSC will make the situation worse before the bottom weight increases to a sufficient level to bring G down, hence, better to fill a DB(double bottom) tank first to improve stability. The smallest tank on the lowest side should be filled first, if the ship is at an angle of loll

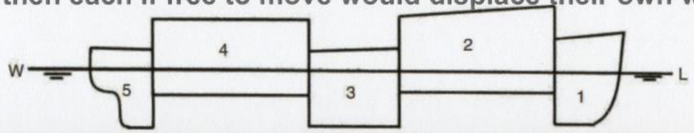
Ship Strength Curves: Longitudinal Stresses

Module 1 (section b)

- In a simple analysis the response of a ship can be approximated to that of a beam
  - In still water the weight of the ship is balanced by the total force of buoyancy, though neither is distributed uniformly along the length of the ship



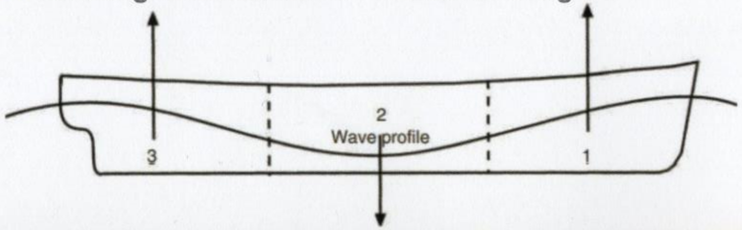
  - If sections 2 and 4 represent empty cargo holds, providing excess buoyancy and 3 the engine room then each if free to move would displace their own weight



Ship Strength Curves

Module 1 (section b)

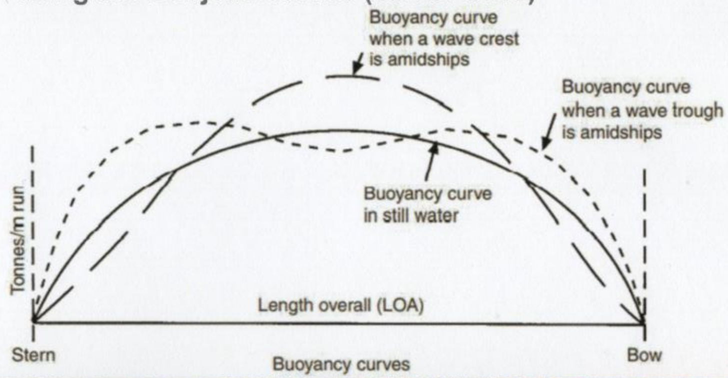
- Strength curves consist of five curves that are closely inter-related
  - Weight curve – tonnes/m run or kg/m run.
  - Buoyancy curve – either for hogging or sagging condition - tonnes/m or kg/m run.
  - Load curve - tonnes/m run or kg/m run.
  - Shear force curve - tonnes or kg.
  - Bending moment curve - tonnes m or kg m.



Ship Strength Curves: 'Buoyancy Curves'

Module 1 (section b)

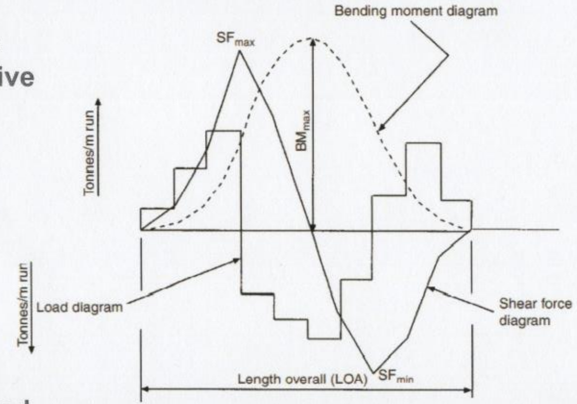
- Buoyancy curves
  - A buoyancy curve shows the longitudinal distribution of buoyancy and can be constructed for any wave formation using the Bonjean curves (earlier slide)



Module 1 (section b)

Ship Strength Curves: 'Load Curves'

- **Load Curves:** Load curves show the difference between the weight and buoyancy of each section throughout the length of the ship
  - Shear force curve is the first derivative of the bending moment diagram i.e. gradient of bending moment curve (dM/dx)
  - After still water load curves are drawn the changes due to waves can be found



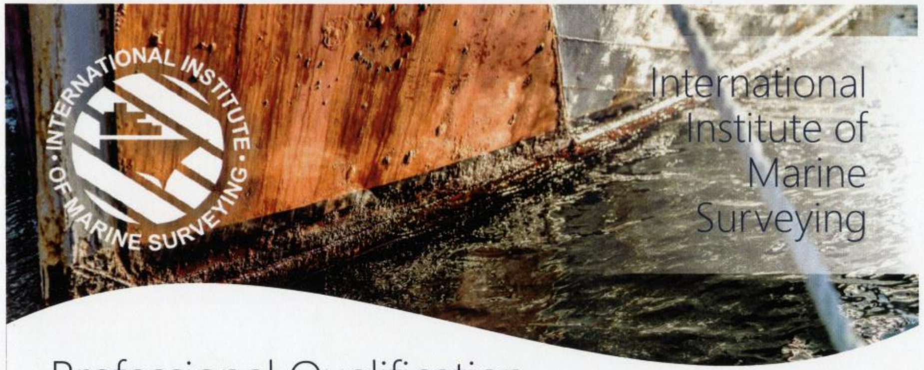
Module 1 (section b)

Ship Strength Curves: 'Bending Moment in Waves'

- Longitudinal bending moment amidships on a ship in waves: 'Murray's Method'
  - Based on response of a ship supported by a standard wave
  - Standard Wave has a length equal to the length of the ship (L), and whose height is equal to $0.607\sqrt{L}$
- Murray's method is in two parts
  - First, find still water bending moment
  - Second, find Wave Bending Moment (WBM) using the formula,

$$WBM = b \times B \times L^{2.5} \times 10^{-3} tonne\ metres$$

where B = beam, b is a constant based on the ship's block coefficient (C_b) and on whether the ship is hogging or sagging



Professional Qualification

in Marine Corrosion

Presented by **Mike Lewus**

Module 1

(section c)

Corrosion Control Strategies

Module 1 (section c) Summary

- Corrosion Protective Paints
  - General requirements
  - Paint Types
  - Surface preparation
  - Application methods
- Antifouling Paints
- Inhibitors
  - Film forming
  - VPIs
- Cathodic Protection
  - SACP
  - ICCP

Module 1 (section c) Corrosion Prevention: Protective Paint Systems

- Critical areas for painting
  - Underwater hull sections
  - Boot-top areas
  - Ballast tanks
  - Cargo tanks
- Requirements from a paint system
  - For underwater parts a ship coating should be corrosion-inhibiting, antifouling, abrasion-resistant, smooth, and compatible with cathodic protection
  - Coating should remain smooth in-service to minimize fuel costs

    NB hull friction due to fouling can result in up to 40% more fuel consumption compared to a clean hull and greater air pollution due to additional fuel burned to maintain speed

Module 1 (section c) Corrosion Prevention: Protective Paint Systems

- Protective coatings have the capacity to:
  - Create a barrier that keeps out charged ions and retards the penetration of water and oxygen
  - Provide metallic contact between the steel and a less noble metal, such as zinc are aluminium in the paint, which provides cathodic protection of the steel by utilizing the galvanic effect
  - Cause water on its passage through the paint coating to take on special properties or form compounds that inhibit its corrosive action
  - Retain a sufficient level of smoothness or increase smoothness i.e. self polishing copolymers (SPC)

Module 1 (section c) Corrosion Prevention: Protective Paint Systems

- Coatings Types
  - Cross-Linked Thermoset Coatings
    - Epoxy resins
    - Polyurethan resins
    - Alkyd resins
    - Inorganic resins
  - Thermoplastic Coatings
    - Chlorinated rubber resins
    - Vinyl resins
  - Antifouling and Foul Release Coatings

Module 1 (section c) Corrosion Prevention: Protective Paint Systems

- Organic, Cross Linked 2-Component Thermosets
  - Epoxy based paints are used in both underwater and above water situations and show good resistance to many marine environments
    [these paints generally cover the greatest vessel area and include seawater ballast tanks]
    - The rate of cross-linking or curing is dependent on temperature. The curing rate of standard epoxies are considerably reduced below 5°C (41°F). Full cure is essential to obtain optimal film properties
    - Epoxies will cure or set with special curing agents at temperatures down to –5°C (23°F)
    - Tendency to chalk in sunlight. This occurs when the binder is degraded by ultraviolet light to produce a loose and friable surface, with the pigment particles remaining on the surface

Module 1 (section c) Corrosion Prevention: Protective Paint Systems

- Organic, Cross Linked 2-Component Thermosets
  - Polyurethanes based paints are used topside and superstructure applications
    - These are polymers formed by reaction between hydroxyl compounds and compounds containing isocyanates
      [In two-pack systems, a special polyether or polyester resin with free hydroxyl groups is reacted with a high molecular weight isocyanate curing agent]
    - Polyurethane resins have excellent chemical and solvent resistance and are superior to standard epoxies in acid resistance
      [Epoxies are more resistant to alkaline than polyurethanes]
    - A problem with these polyurethanes is their water sensitivity on storage and on application hence care must be taken during transport and application

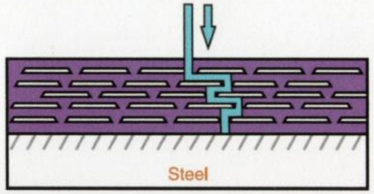
Module 1 (section c) Corrosion Prevention: Protective Paint Systems

- Inorganic Resins-Component Thermosets
  - Comprise silicates which are almost always used in conjunction with zinc dust pigments
    - Water-based inorganic silicates based on lithium, potassium, or sodium silicate and solvent based inorganic silicates normally based on ethyl silicate
    - Coatings based on these resins are very hard, corrosion resistant and temperature resistant. They require a good standard of surface preparation and are often repaired using organic coatings
    - Zinc in the inorganic resins can dissolve under acid or alkali conditions, coatings perform best at neutral pH and are often used as tank coatings
    - Often used as tank coatings

Module 1 (section c) Corrosion Prevention: Protective Paint Systems

- Paints Containing Anti-corrosive Pigments
  - Metallic zinc is widely used in primers for protecting steel from corrosion
  - Metallic aluminum flake is commonly used as an anti-corrosive pigment by producing a circuitous pathway for water and also forming aluminum oxides which fill up pores
  - Zinc phosphate ($Zn_3(PO_4)_2$) pigments are also widely used in corrosion-inhibiting coatings for steel surface corrosion protection

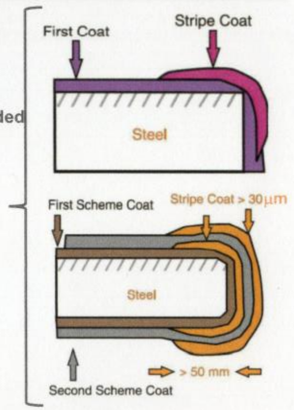
Flake pigments increase diffusion path length for water



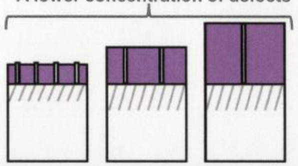
Module 1 (section c) Corrosion Prevention: Protective Paint Systems

- Factors Affecting Coating Performance
  - Oxygen Permeability
  - Water Vapor Permeability
  - Liquid Water Uptake
  - Ionic Permeability
  - Coating Porosity
  - Surface Contamination
  - Surface Profile

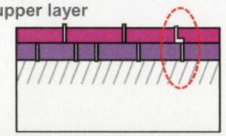
To achieve specified DFTs with good adhesion stripe coatings are recommended at welds and edges before sprayed coatings are applied



Thicker coatings tend to contain A lower concentration of defects



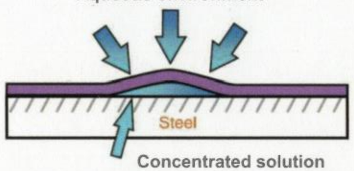
Defect density in multilayer less likely, but pores in lower layer can nucleate pore in upper layer



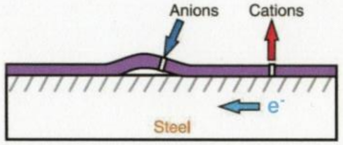
Module 1 (section c) Corrosion Prevention: Protective Paint Systems

- Types of Coating Breakdown
  - Coating should remain smooth in-service to minimize

Osmotic Blistering



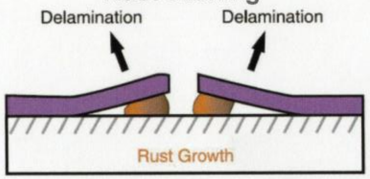
Electro-Osmotic Blistering

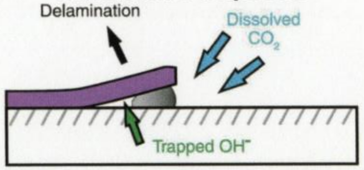


  - Osmotic blisters are usually small and relatively closely spaced
  - Electro-osmosis typically produces larger blisters
  - Osmosis and electro osmosis tend to occur early in the lifetime of a coating while it retains a degree of plasticity

Module 1 (section c) — Corrosion Prevention: Protective Paint Systems

- Types of Coating Breakdown
  - Rust jacking or rust leverage is the predominant mechanism of coating failure during the late stages of the service life of the coating



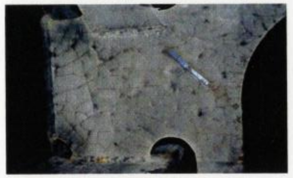


  - Calcareous deposits breakdown is similar to rust jacking in that the coating is levered from the surface by a deposit growing beneath it but, in this case, hydroxyl ions are generated at the cathodic site and induce a precipitation reaction by changing local seawater pH

Module 1 (section c) — Corrosion Prevention: Protective Paint Systems

- Other Coating Failures

'Coating Cracking'



- over thickness of paint
- plastic structural deformation exceeding elongation properties of paint film
- localised fatigue stress, due to poor design

Coating Flaking

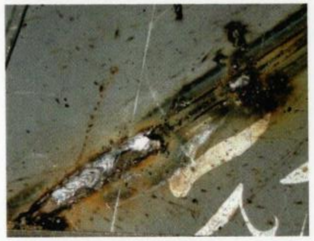
- poor surface preparation
- incompatibility with underlayer
- contamination between layers,
- excessive curing time between layers

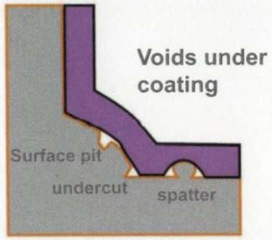
Coating Blistering

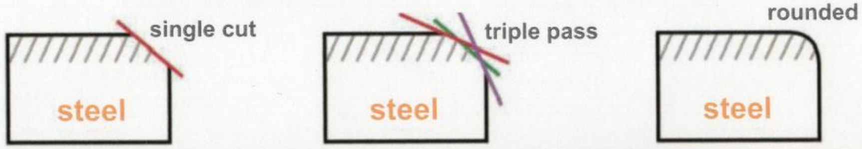
- Solvent retention,
- Improper coating application,
- Soluble salt contamination under the paint film, due to an insufficient
- cleaning of the surface

Module 1 (section c) — Surface Preparation: Welds and Edges

- Cleaning and dressing welds and, edge preparation are vital for ensuring well adhered paint coverage







Module 1 (section c) — Corrosion Prevention: Protective Paint Systems

- Surface Preparation:
  Good surface preparation is the most important part of the entire coating process in that the greatest percentage of coating failures can be traced directly to poor surface preparation
  - All paint systems fail prematurely unless the surface has been properly prepared to receive the coating. No paint system gives optimum performance on a poorly prepared surface
  - Surface preparation has two important effects:
    - It provides mechanical keying, by providing an 'anchor roughness' for the coating
    - It provides a chemical bridge, by allowing intimate contact (cleanliness) of between coating material molecules and the steel (or other material) substrate

Corrosion Prevention: Protective Paint Systems

Module 1 (section c)

- **Preparation Methods:**
  Good surface preparation is the most important part of the entire coating process in that the greatest percentage of coating failures can be traced directly to poor surface preparation
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Corrosion Prevention: Protective Paint Systems

Module 1 (section c)

- Coating Application
  - The normal methods of application of coatings are by:
    - Stripe coating by brush or roller
    - Spray coating by conventional air
    - Airless spray
    - Plural airless spray
  - Conventional Air spray
    - method commonly used for applying zinc silicates to large surfaces. The equipment is relatively
    - simple and inexpensive and is usually confined to fairly low-viscosity paints
  - Airless Spray
    - the most important and efficient method for the application of heavy duty marine coatings
    - allows rapid application of large volumes of paint as well as the application of high build coatings without thinning

Corrosion Prevention: Protective Paint Systems

Module 1 (section c)

- Coating Application
  - Plural Airless Spray
    - To spray solvent free or high solid coatings, it is often necessary to heat the components to reduce their viscosity to an acceptable level for spraying
    - As these paints can cure very rapidly once mixed, the components are often heated separately and fed to a mixing head which is a short distance from the spray tip

Brush Applied Touch-Up

Stripe Coating on Weld

Airless Spray Application

Corrosion Prevention: Protective Paint Systems

Module 1 (section c)

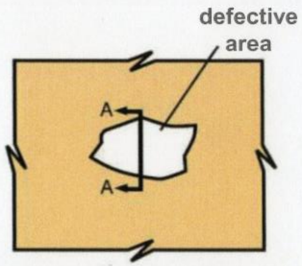
- **Coating Application Conditions**
  - Condition of the substrate
  - Temperature
  - Relative humidity
  - Weather conditions
  - Condensation
  - Ventilation
  - Ultraviolet light (UV)

  - **Condition of substrate**
    - The surface to be coated must be clean and free from dirt, dust, abrasive blast medium (if used), oil, grease and soluble salt contamination.

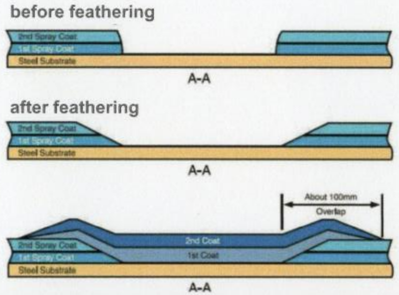
Corrosion Prevention: Protective Paint Systems

Module 1 (section c)

- **Local Coating Repairs**
  Spot blasting is commonly used to remove localized corrosion products and loose coatings and produce feathered coating edges



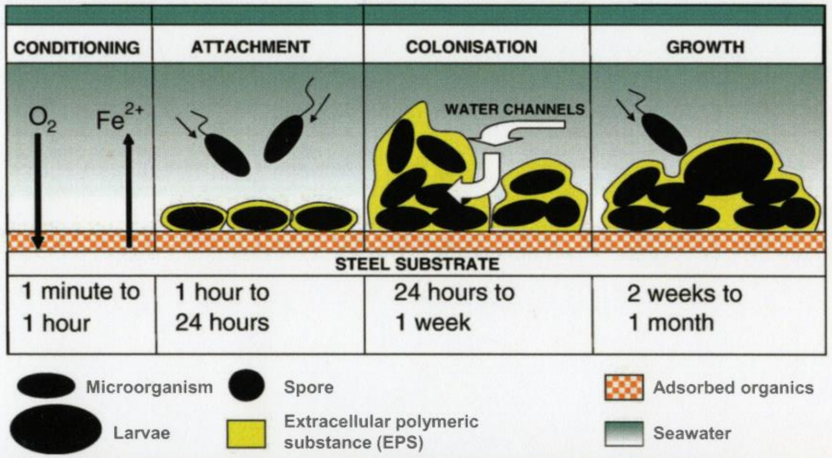
Plan view of coated surface



Corrosion Prevention: Lines of Defense

Module 1 (section c)

- **Critical steps in biofouling**



Antifouling Coatings

Module 1 (section c)

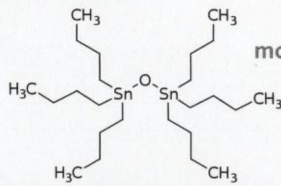
- **Due to penalties associated with and the severe impact of unwanted colonisation of a hull surface by marine organisms, primarily through negative impact on hydrodynamics via increased drag, antifouling systems are in great use in the maritime industry**
  - **Three main forms of biocides that can be used in anti-fouling systems:**
    - **Metallic**
    - **Organometallic**
    - **Organic**
  - **Few biocides have had the necessary combination of characteristics to make them safe, yet effective antifouling agents**

Antifouling Coatings

Module 1 (section c)

- **Mercury, arsenic and their compounds, and now the organotins, are examples of effective antifouling agents that have been deemed unacceptable due to adverse environmental or human health risks**
- **Tributyltin (TBT) based coatings were introduced in the mid1960s and were common in the latter half of the 20th century as an effective anti-fouling solution**

  Their acute toxicity to non-target marine organisms and severe environmental impacts led to a ban on TBT paints in September 2008



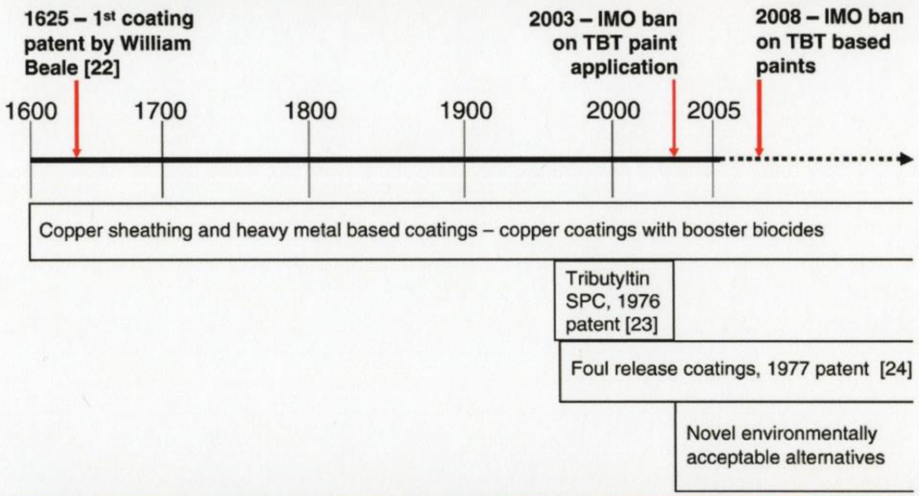
TBT molecule

- **Copper-based biocides are the most commonly used, and often in combination with organic biocides**

Module 1 (section c) Foul Release Coatings

- Foul Release Coatings (FRC):
  Principle: coatings which do not use biocides to control the fouling but prevent the fouling organisms adhering effectively to the paint surface
  - A relatively new addition to the category of anti-fouling paint:
    - Mechanism for effective anti-fouling based on the low free surface energy of the coating surface
    - Do not use heavy metals
    - Biocides are not used, hence these coatings are not affected by legislation which affect biocide containing antifouling paints
    - Two main types: fluoropolymer and silicone based
  - In 2008, Cunard, Queen Mary converted from a silyl-based TBT-(SPC) antifouling fluoropolymer foul release

Module 1 (section c) Corrosion Prevention: Lines of Defense



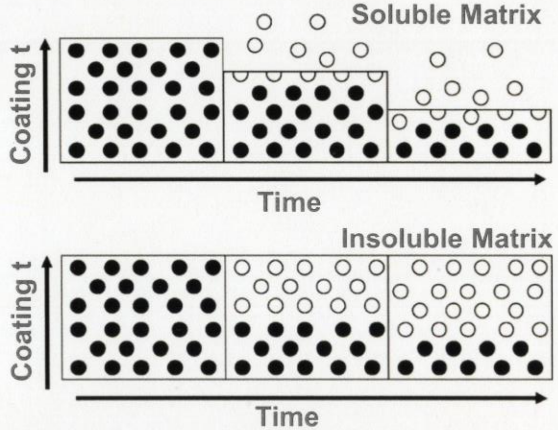
Module 1 (section c) Requirements of Antifouling Coatings

- Properties required of an effective antifouling coating

Required Properties	Undesirable Properties
Anticorrosive	Toxic to Environment
Antifouling	Persistent in Environment
Environmentally Acceptable	Expensive
Economically Viable	Chemically Unstable
Long Service Life	Target Non-Specific Species
Compatibility with underlying systems	
Capable of protection, regardless of Operational Profile	
Smooth	

Module 1 (section c) Corrosion Prevention: Lines of Defense

- Two key methods for controlling the release of antifouling compounds from a coating, by using either a soluble or insoluble matrix
- In insoluble matrix systems biocide leaching rates decrease exponentially with time



Module 1 (section c)

Corrosion Inhibitors Classification

From Module 9, Slide Section 1c

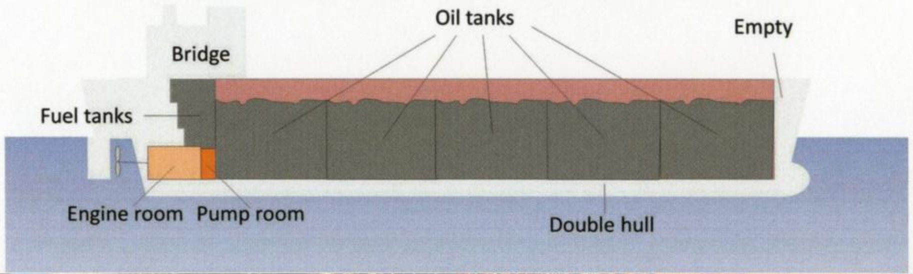
Inhibitors Types

- **Inorganic**
  - **Anodic**: Chromates, Phosphates, Nitrates, Molybdates (also called passivation inhibitors)
  - **Cathodic** (Zinc Phosphate)
    - **Poisons**: Arsenic
    - **Precipitators**: Calcium Carbonate
- **Organic**
  - **Film Former**
- **Environmental Conditions**
  - **Scavengers**: Sodium sulphite
  - **Biocides**: Ozone

Module 1 (section c)

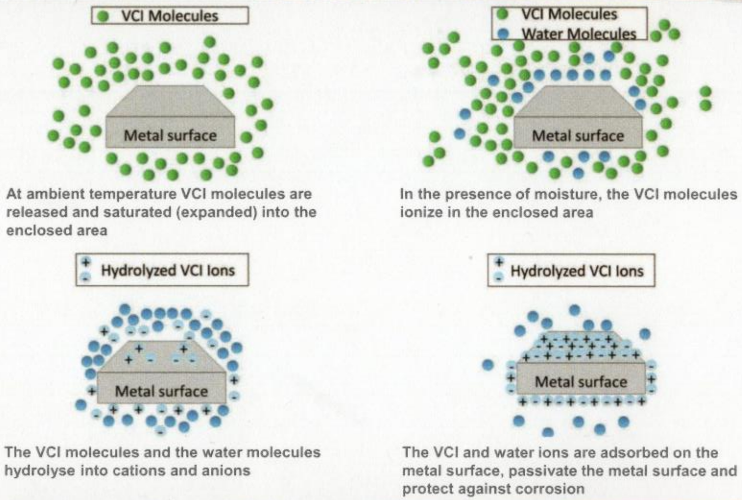
Inhibitors: Vapour Phase Corrosion Inhibitors

- **Vapour release corrosion inhibitors (VPIs)**
  Void spaces are an inherent part of all ship designs and may be considered dry but often are not as the ship may be using the spaces as ballast. **In addition, all void spaces are subject to condensation which contributes to corrosion**
- **VCI products available in solid and liquid form**
- VPI powder used in tanker holds containing ballast water



Module 1 (section c)

Inhibitors: Vapour Phase Corrosion Inhibitors

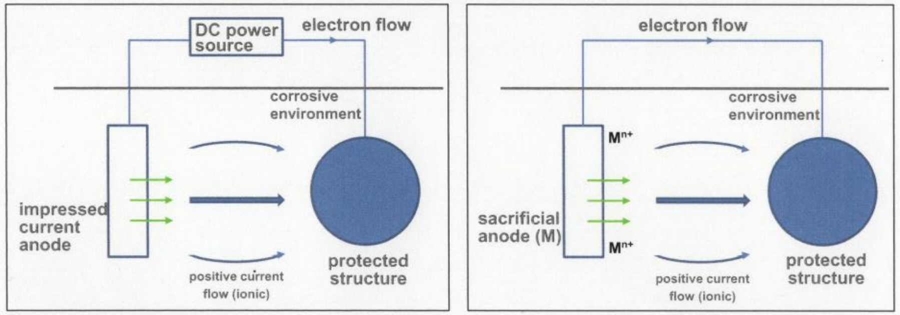


Module 1 (section c)

Principles of Cathodic Protection

From Module 9, Slide Section 1b

- **Two main cathodic protection methods:**
  i) ICCP impressed current cathodic protection
  ii) SACP sacrificial anode cathodic protection



a simple ICCP system
(not usually found on small vessels)

a simple SACP system

Module 1 (section c)

Sacrificial Anode Cathodic Protection

- Sacrificial anode cathodic protection – General points
  - A cathodic protection system uses galvanic anodes
  - The cathodic protection system should be selected and designed either for the design life of the ship or on the basis of expected dry docking intervals, which are normally specified by the owner

Corrosion Protection Required		
Zone	Structural Steelwork	Protection Method
Submerged zone	Main hull	Coatings or coatings combined with cathodic protection
Splash zone	Main hull	Coatings
Atmospheric zone	All structure above the splash zone	Coatings only

Module 1 (section c)

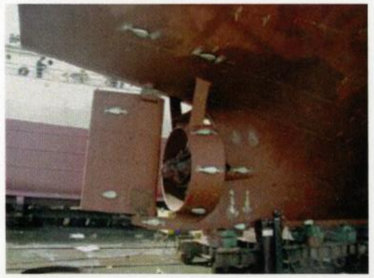
Sacrificial Anode Cathodic Protection

- Sacrificial anode cathodic protection – General points
  - A cathodic protection system uses galvanic anodes
  - Galvanic anodes for use on ship hulls are usually made of zinc- or aluminum-based alloys
    - Zinc anodes have a natural potential approximately -1030 mV (relative to Ag/AgCl reference electrode)
    - Aluminum is preferred for seawater applications because it has a lower consumption rate than zinc
  - The most efficient protection is achieved by the use of a large number of small anodes well distributed around the hull
  - Anodes shouldn't be attached to areas likely to sustain regular mechanical damage e.g., in way of the anchor). In way of the bilge, the anodes should be arranged so that they cannot be damaged when the ship is berthed

Module 1 (section c)

Sacrificial Anode Cathodic Protection

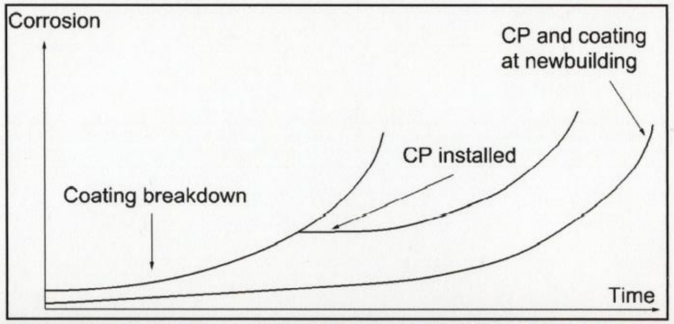
- Sacrificial anode cathodic protection: General points
  - Anode designs and details usually agreed between shipyard and owners
  - For calculation on number and location of anodes consideration should be given to: design life (yrs), anode type Ah/kg, net and gross weight, means of attachment (weld/bolted?), location, anode design utilization factor etc.



Module 1 (section c)

Corrosion Prevention: Lines of Defense

- Sacrificial anode cathodic protection: General points
  - The installation of a CP system after coating breakdown is a temporary and expensive solution
  - A combination of CP and coating at the construction stage is the most effective and economical approach



Module 1 (section c)

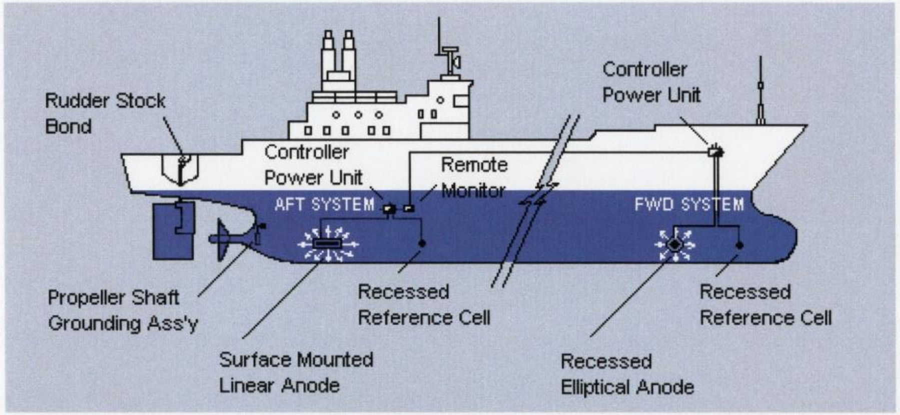
Impressed Current Cathodic Protection: ICCP

- ICCP Systems
  - Although modern hull coatings provide some protection against corrosion they do not offer a complete solution. For this reason, most operators choose to protect their vessels with a purpose designed impressed current cathodic protection system
  - A typical system uses an arrangement of hull mounted anodes and reference cells connected to a control panel(s), the system produces a more powerful external current to suppress the natural electro-chemical activity on the wetted surface of the hull
  - The systems automatically control the current output while the voltage output is varied. This allows the protection level to be maintained as the seawater resistivity alters
    - In a sacrificial anode system, increases in the seawater resistivity can cause a decrease in the anode output and a decrease in the amount of protection provided; an ICCP systems protection does not decrease in the range of standard seawater
    - As the hull coating breaks down a greater level of protection is required and ICCP systems adjust the anode output appropriately

Module 1 (section c)

Impressed Current Cathodic Protection: ICCP

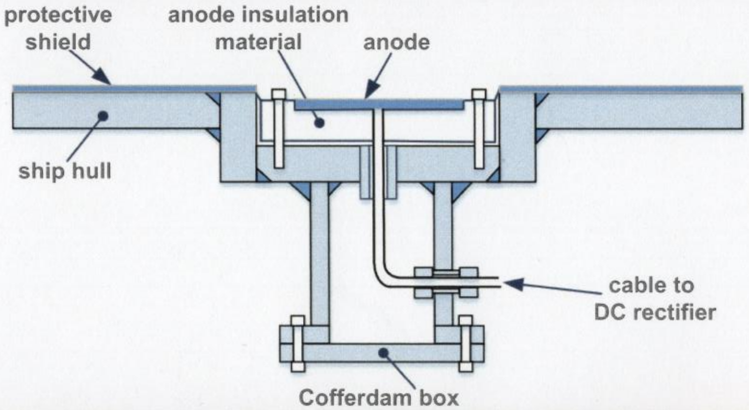
- Typical layout of an impressed current cathodic protection system



Module 1 (section c)

Impressed Current Cathodic Protection: ICCP

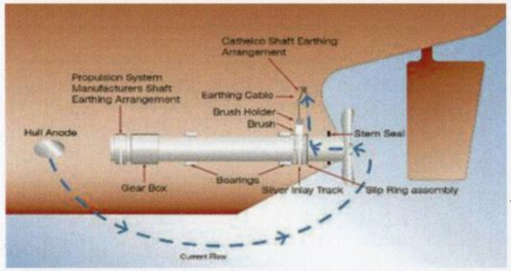
- Typical recessed impressed current anode with a cofferdam
  - A cofferdam is an empty space provided in a ship so that compartments on each side have no common boundary and give added protection



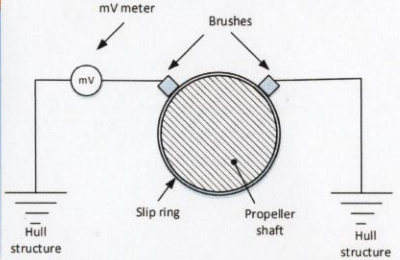
Module 1 (section c)

Impressed Current Cathodic Protection: ICCP

- Protection of propeller shaft bearings
  - Even on ships fitted with ICCP or sacrificial anode systems, propeller shaft bearings are vulnerable to corrosion
  - The problem can be eliminated if the shaft is earthed to the hull using a propeller shaft slipring



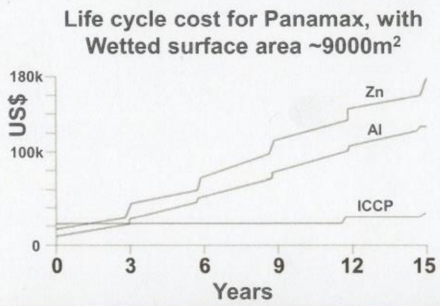
Typical arrangement for shaft grounding and monitoring

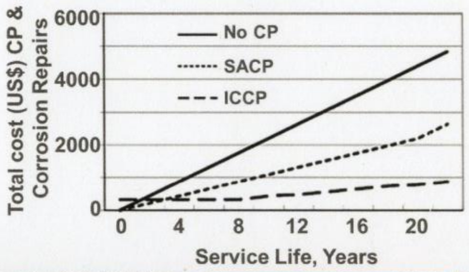


Module 1 (section c)

Comparison of SACP and ICCP

- Cost Comparison for SACP and ICCP
  - LHS Figure: shows initial cost is slightly higher for ICCP, whereas the cost after 15 years is of the order of 7 to 8 times higher for SACP
  - RHS Figure: shows cost comparison between submerged steel without any CP technique and with SACP and ICCP





Module 1 (section c)

LR Surveyors Responsibilities

- Lloyds register surveyor responsibilities
  - Inspection of design drawings w.r.t. scantlings. Sometimes plate thickness has to be increased. Sometimes the sectional modulus of the plating and stiffener has to be modified. When considered satisfactory, the drawing is given the 'Lloyd's Approved' stamp
  - Inspection and testing of materials used in the construction of the vessel. Sample tests may be asked for on wood, steel, aluminum, or glass reinforced material
  - Examination of shearing forces and bending moments with respect to longitudinal bending of the ship. Racking and buckling stresses are considered and analyzed
  - Examination of jointing within the structure of the vessel. This could mean tests carried out on specimen welds. These may be destructive or nondestructive tests that use X-rays and ultrasonics

Module 1 (section c)

LR Surveyors Responsibilities

- Lloyds register surveyor responsibilities
  - To arrange special surveys to ensure that a vessel has retained its standard of seaworthiness perhaps after maintenance repairs or after a major accident. Special surveys are carried out on the ship every 4 or 5 years; survey severity increases with each successive special survey
  - Examining to see if corrosion or wear and tear over years of service have decreased scantlings to a state where the structure is no longer of adequate strength
  - Check that the ship is built as per drawing and that inferior material is not being substituted. The surveyor will also check the standard and quality of workmanship
  - Final positioning of the load line and freeboard marks together with the official ship number and the official port of registry. This responsibility is shared with the Maritime Dept. for Transport surveyor

Module 1 (section c)

Dept. Of Transport Surveyors Responsibilities

- Maritime Dept. of Transport Surveyor Responsibilities
  - Inspection of drawings. Care is taken with accommodation plans that the floor area for all cabins and communal spaces are above a certain minimum requisite area
  - Care and maintenance of all life-saving appliances. Inspection of inventory of flares, life-jackets, life-rafts, etc.
  - Inspection of fire-fighting appliances. Examining arrangements for prevention, detection, and extinguishing fire
  - Consideration of navigation lights. Provision of emergency lighting
  - Consideration of sound-signaling apparatus. The arrangements for radio contact in the event of incidents such as fire or flooding. Emails are now used for quick communication, especially when crew or passengers have to leave the ship for emergency medical assistance. shipbuilder to the ship

Module 1 (section c)

Dept. Of Transport Surveyors Responsibilities

- **Maritime Dept. of Transport Surveyor Responsibilities**
  - Inspection of the stability information supplied by the shipbuilder to the ship
  - Inspection of lighting, heating, and ventilation in accommodation, navigation spaces, holds, and machinery spaces
  - Attendance at the inclining experiment or stability test. To verify that the test had been carried out in a correct and fitting manner. Final stability calculations also checked out at the local DfT office
  - Written and oral examinations for masters and mates
  - Final positioning of load line and freeboard marks together with the official ship number and port of registry. This responsibility is also shared with the Lloyd's surveyor
  - If the ship has undergone major repair, or conversion to another ship type, or the ship has had major update/retrofit, then the surveyors check for strength and safety. If deemed of satisfactory quality, then new certificates will be signed, dated, and issued to the shipowner