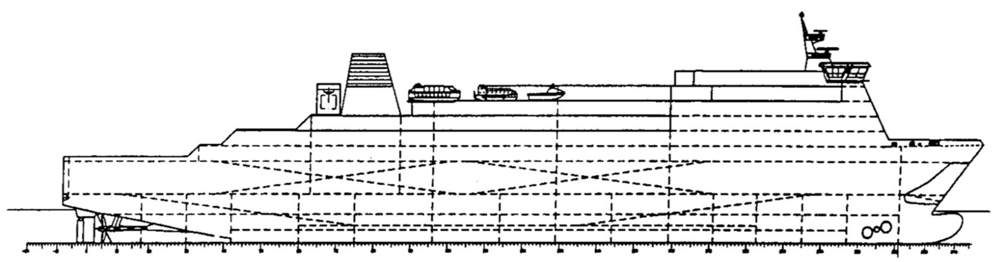
3. Questions

1. Describe the most important factors affecting the general arrangement of a passenger ship (or your project ship).
2. Describe the various possibilities to locate the cargo space on RoPax vessels and what the benefits and drawbacks for each possibility.
3. Describe the various possibilities to locate the cargo space on container vessels with respect to superstructure and what are the benefits and drawbacks for each possibility.
4. Describe the main issues affecting the positioning of the machinery space in ship general arrangement.
5. Identify and justify 3 strengths and 3 weaknesses in the general arrangement of the ship below. In case you need to implement LNG as the fuel and/or battery technology for auxiliary propulsion, in which place would you position the fuels tanks and betteries ? Discuss the factors affecting these choices. Define at least four general design objectives and criteria for the general arrangement of a ship.



6. You are designing a medium-sized container vessel. Describe the various possibilities to locate the deckhouse. Mention at least four criteria or measures of performance based on which you can compare the merits of the various options.
7. Define at least four general design objectives and criteria for the general arrangement of a ship. 2p

Lecture 7 : Ship Structures

Anyone who has been at sea in rough weather will be only too aware that a ship is heavily loaded and strained. Ship design starts with determination of the ship's operational profile, the main dimensions and the hull form characteristics but until this stage, the ship is just some data stored. However, structural design and analysis is the phase at which the ship changes to actual structural parts to be fabricated in the shipyard. This section is an introduction to structural design for preliminary design.

1. The ship structural design framework

Although structural design is a complex process, the structural designer can benefit from experience of other designers and classification societies. Commonly in the past, design comprises two steps; design of structural arrangement and derivation of scantlings. The ship structural design framework accounts for :

- Loads, defined as the forces acting on the ship structure whether as a beam girder or acting on one of its components. Structural loads result in stresses and deformation in the structure.
- Responses, defined as the load induced deformations and stresses due to an external load.
- Strength defined as the measure of the capacity of the structure to withstand the load without failure or plastic deformation.

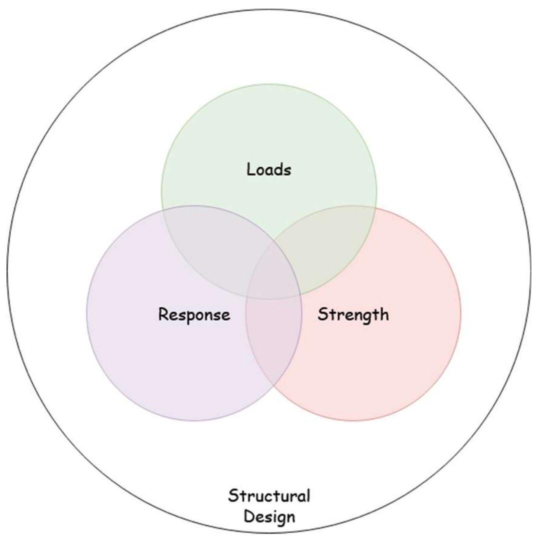


Figure 7.1 Structural design framework

1.1 Hierarchy levels and initial considerations

Ship structures comprise of units that are dealt upon individually and holistically. The smallest units of a ship's structure are panels bounded by stiffeners. These panels are subject to normal and in-plane loads that give rise to bending loads, buckling and shear deformations. These small units together form larger flat or curved surface of plating with sets of stiffeners, termed as grillages. Grillages are supported at their edges by bulkheads and deck edges that are relatively stiff. They are also exposed to normal and in-plane loads and experience bending, buckling and shear loads. Finally, bulkheads, grillages and decks together form a hollow box girder which can be dealt with as a beam. Consequently, analysis of ship structures are classified as **(a) primary; (b) secondary and (c) tertiary**.

Structural design starts defining the frame spacing, defining the major structural boundaries (e.g. double bottom height, twin deck height, longitudinal bulkhead location) and by designing the mid ship section. (see Figure 7.1) The required inputs are the beam, depth, draft, deadrise and bilge radius. Based on experience, some design choices may change based on the ship type and its operational characteristics (mission and owner requirements).Two systems of framing exist namely **(a) the transverse framing**

system and (b) the longitudinal framing system. The transverse framing system comprises of secondary members that are positioned in the transverse direction of the ship while in the longitudinal system of framing stiffeners are aligned in the longitudinal direction.

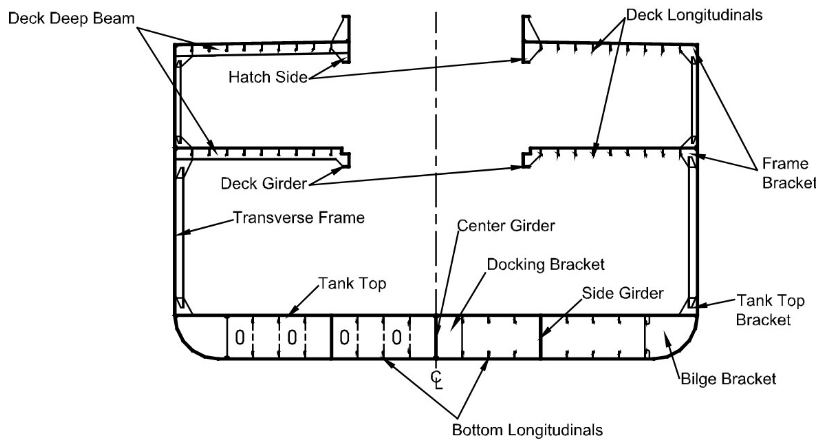


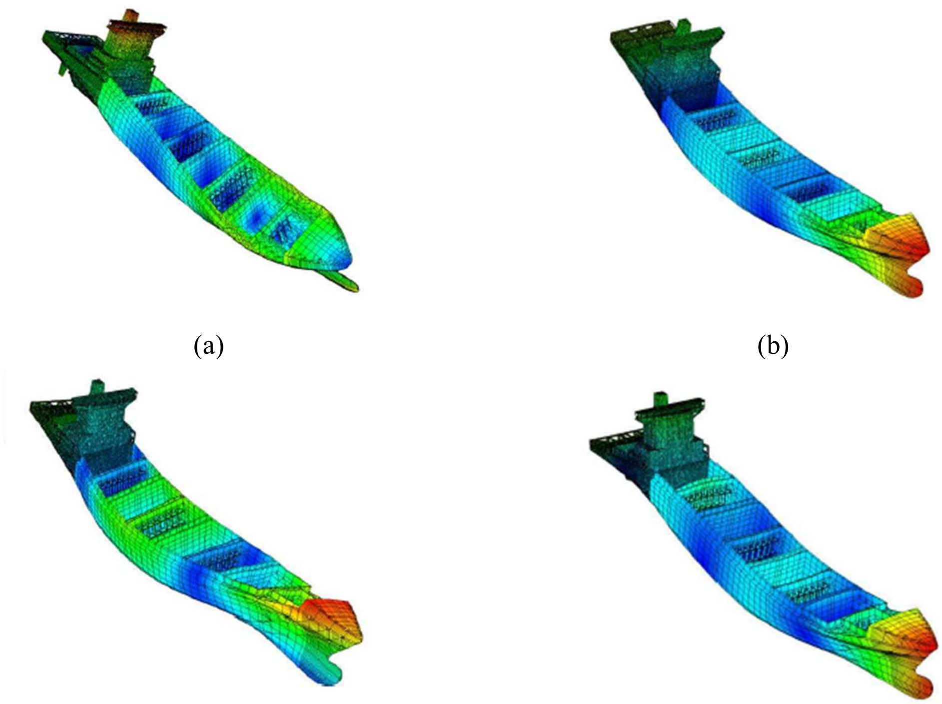
Figure 7.2 Main frame components. Image credits: (Thomas, 2003)

1.2 Ship loads

An overview to the background of ship loads is given by Hirdaris et al.(2014). They can be taxonomized on the basis of frequency and time duration, locality (e.g. global vs local) and limit states (e.g. intact vs damaged). **Static loads** are defined as the loads acting on a ship in either still water and they mostly vary during loading/unloading operations. They act over time that is much longer than the range of sea wave periods. Hence, time is ignored and they are considered as a function of a ship's loading conditions. **Quasi-static loads** have a period corresponding to wave actions (between 3-15 seconds). They are directly induced by waves and resonate with ship motions. **Dynamic Loads** result in responses with frequency components close or equal to resonance modes. When evaluating these responses, the dynamic properties of the ship has to be considered. Dynamic loads may be generated by resonance phenomena associated with wave induced hull vibratory distortions (e.g. springing), or by mechanical excitation of rotating equipment such as the main engine and the propeller. Impulsive loads result in free structural vibrations such as slamming and sloshing in tanks are also important. **High frequency loads** have higher frequency than resonance modes (higher than 10-20 Hz) and they are involved in the study of noise more than structural design. Loads acting on the ship as a girder or a box beam are known as **global loads or primary level loads** and the associated response is termed **primary response**.

Pressure on the hull due wave actions can be either described by **global or local loads**. Examples of local loads are: (a) **panting -** an in/out motion of the plating in the bow area due to unequal pressure through waves. It is significant for fine bow ships. Fore peak tanks are used to resist this load ; (b) **bow slamming** – resulting from sudden bow lift and sudden drops in waves at the forefoot with high acceleration. The phenomenon is linked to heave and pitch ship motions; (c) **Whipping**, usually defined as a transient ship structural response due to impulsive loading, usually slamming, or green water. Examples of global loads are: (a) **hydrostatic pressures** caused by water static pressures that are proportional the ship's hull; (b) **racking** caused ship rolling and accelerations on the ship structure;(c) **still water and wave bending moments** caused by the uneven distribution of buoyancy and weight (d) **shear forces** at each section of the ship (d) **springing**.

Accidental loads are low probability events related to collision, grounding or explosions (e.g. see Figure 7.3). They influence the ultimate strength. In recent years several studies have been conducted for investigating the mechanics of collision and grounding in order to find new ways to reduce their consequences. Since accidental loads relate with shipping operations traditionally they are not part of Classification Rules or procedures. Guidelines for the prediction of accidental limit states are still under development. In ship design ship loads are expressed in the form of **bending moments, shear forces and associated stresses**.



(a) (b)

(c) (d)

Figure 7.3 Springing modes of a container ship: (a) 1st torsion mode, (b) 1st vertical bending mode, (c) 1st horizontal bending & torsion mode (d) 2nd vertical bending mode

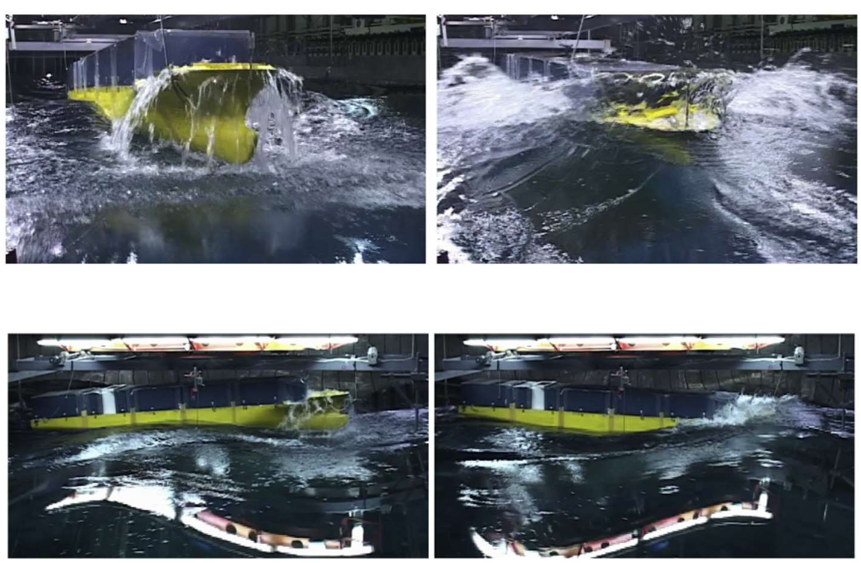


Figure 7.3 experimental investigations on ship bow slamming (kim et al., 2019)

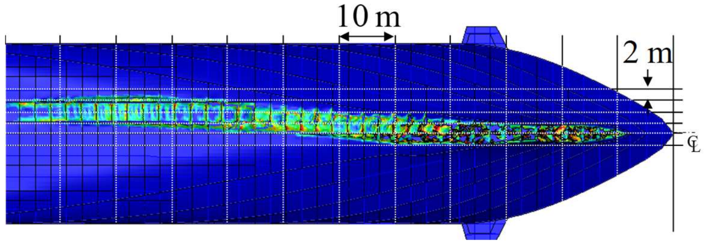


Figure 7.4 Finite Element Analysis simulation of passenger ship subject to hard grounding (Kim et al., 2020)

1.2.1 Still water loads

In still water conditions, the buoyancy forces acting on a ship must equal in total the sum of the weight of the ship. However, over any given unit length of the hull the forces will not balance out. If the mass per unit length at some point is *m* and the immersed cross-sectional area is *a*, then at that point we can define : Buoyancy per unit length = $\rho g a$; Weight per unit length = mg leading to **Net force per unit length =** $\boldsymbol{\rho g a - mg}$. If this net loading is integrated along the length there will be, for any point, a force tending to shear the structure defined as :

$$Shear\ force,\ S = \int(\rho g a - mg)dx \qquad (7.1)$$

The integration being from one end to the point concerned. Integrating a second time gives :

$$Longitudinal\ bending\ moment,\ M = \int S dx = \iint(\rho g a - mg)dxdx \qquad (7.2)$$

For any given loading of the ship the draughts at which it floats can be calculated. Knowing the weight distribution, and finding the buoyancy distribution from the Bonjean curves, gives the net load per unit length. The static forces of weight and buoyancy also act upon a transverse section of the ship as shown in Figure 7.5. The result is a transverse distortion of the structure which the structure must be strong enough to resist these forces. In addition, these forces can produce a local deformation of structure. The hydrostatic loads tend to dish plating between the supporting frames and longitudinals. The deck grillages must support the loads of equipment and cargo. Thus, there are three contributions made by items of structure, namely to the longitudinal, transverse and local strength. Longitudinal strength in a seaway is considered first.

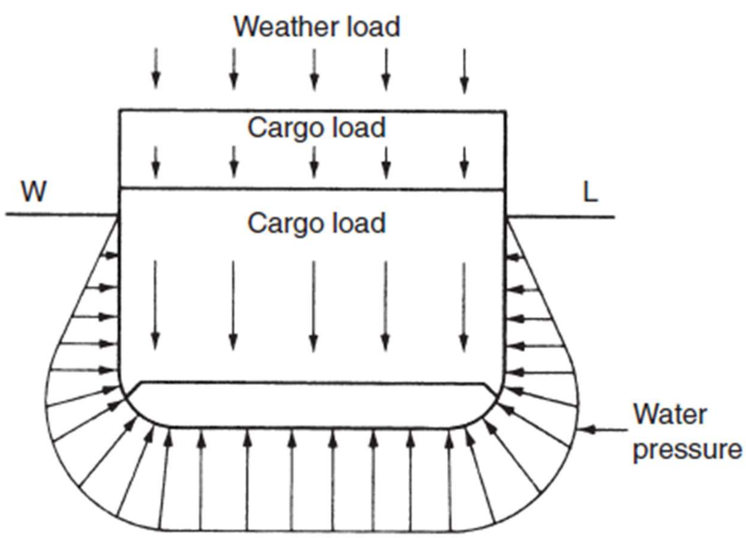


Figure 7.5 Static loads on a transverse ship section (Tupper, 2013)

1.2.2 Quasi Static wave loads

In wave conditions the mass distribution is the same as in still water for the same loading condition. The differences in the forces acting are the buoyancy forces and the inertia forces on the masses arising from **ship motions ship motion induced accelerations**. Ship motions are derived by what is known as **seakeeping analysis**. The term relates to **ship seaworthiness** and covers all those features of a vessel that may influence her ability to remain at sea in all conditions and carry out her intended mission. This is involving stability, strength, maneuverability and ship motions. Within the context of wave induced loads seakeeping needs to be considered early in design as most hull form parameters are decided then. In seakeeping the ship is faced as a 6 degree of freedom rigid body system (translation and rotation degrees of freedom for each axis). Ship motions are defined as **surge, sway and heave** for translations along the fore and aft, transverse and vertical axes respectively; **roll, pitch and yaw** for rotations about the three axes (see Figure 7.6). For example, ship rolling can be reduced by fitting stabilizers. However, such decisions should be based on the use of good seakeeping design.

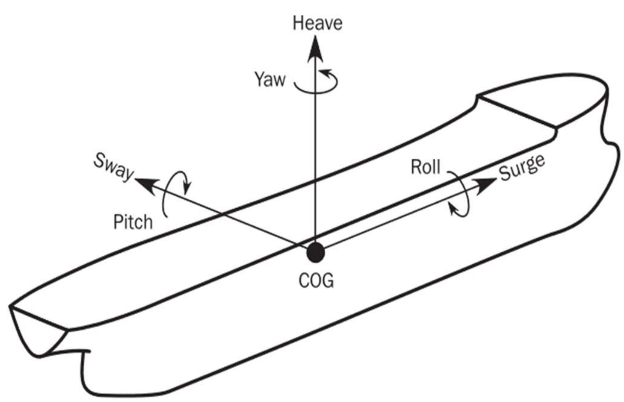


Figure 7.6 Ship motions (DNVGL,2017)

Among ship motions**, roll, pitch and heave** are oscillatory motions and they are the most significant form concept/preliminary design perspective. Other motions can be either dealt with separately in maneuvering and resistance analyses or can be coupled with the formerly mentioned motions in seakeeping analysis.

Definition of roll motion. If ϕ is the inclination to the vertical at any instant, and the ship is stable, there will be a moment acting on it tending to return it to the upright. For small disturbances the value of this moment will be proportional to ϕ and given by:

$$Displacement \times GM_T \times \phi = \Delta GZ \qquad (7.3)$$

This is the condition for simple harmonic motion with a period T_ϕ defined by:

$$T_\phi = 2\pi\left(\frac{k_x^2}{gG\quad T}\right)^{0.5} = \frac{2\pi k_x}{(gGM_T)^{0.5}} \qquad (7.4)$$

where k_x is the radius of gyration about a fore and aft axis. This period is independent of ϕ and such rolling is said to be isochronous. The relationship holds for most ships up to angles of about 10 degrees from the vertical axis.

The greater the GM_T (see Lecture 5, Section 1) the shorter the **period of rolling**. A ship with a short period of roll is said to be stiff and one with a long period termed tender. Most people find a longer period motion more comfortable.

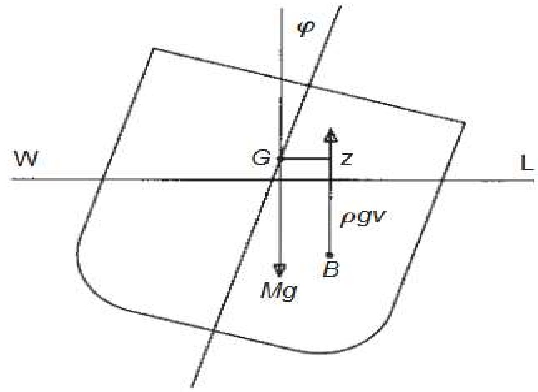


Figure 7.7 Rolling. Image credits: (Tupper, 2013)

Definition of pitch motion. The ship pitching motion is analogous to rolling but around the transverse axis. This is controlled by a similar equation to that for roll. In this case:

$$T_\theta = \frac{2\pi k_y}{(gGM_L)^{0.5}} \quad (7.3)$$

As the longitudinal metacentric height GM_L is much larger than the transverse metacentric height GM_T, the period of pitching is much smaller than that of rolling.

Definition of heave motion. If z is the downward displacement at any instant, there will be a net upward force on the ship tending to reduce the magnitude of z. This force is given by $\rho g A_w z$ and the motion period is defined by:

$$T_z = 2\pi(\frac{\nabla}{gA_W})^{0.5} \quad (7.4)$$

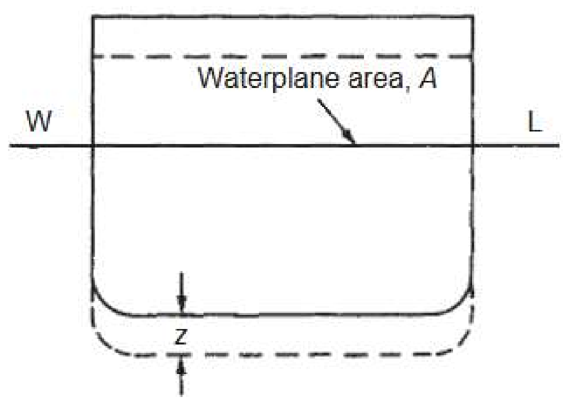


Figure 7.8 Heaving. Image credits: (Tupper, 2013)

Added mass is defined as the effective increase in mass of a hull, due to the entrained water, when in motion.**Added mass and damping** may influence ship motions and their periods. Added mass values vary with the frequency of motion. Typically, the effect for rolling is to increase the radius of gyration by about 5%. In heaving its influence is greater and may amount to as much as an apparent doubling of the mass of the ship. Damping leads to reduction of ship motion amplitudes over time. **Ship motions that influence design loads are mainly pitch and heave**.

If we consider quasi – static analysis, i.e. we ignore inertia forces and assume that the ship balances on a trochoidal wave the buoyancy forces will vary in comparison to still water by virtue of the different draughts at each point along the length due to the wave profile and the pressure changes with depth due to the orbital motion of the wave particles. Clearly this is a situation that can never occur in practice but the results can be used to indicate the maximum bending moments the ship may experience in waves. Accordingly, the choice of wave height is important and two conditions may be considered namely **hogging** (where the wave crest is amidships) and the **sagging** (where wave crests are at the ends of the ship) ; see Figure 7.9.

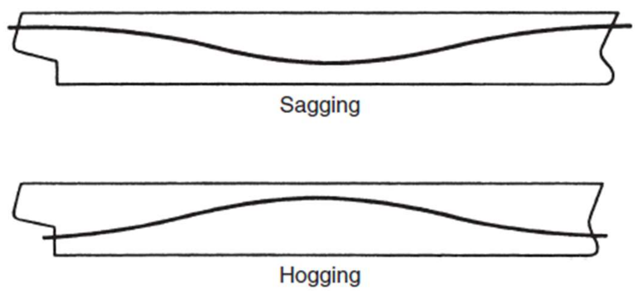


Figure 7.9 A ship on waves: (Tupper, 2013)

The bending moments obtained include the still water moments. However, it is useful to separate the two as, whilst the still water bending moment depends upon the mass distribution besides the buoyancy distribution, the bending moment due to the waves themselves depends only on the geometry of the ship and wave.

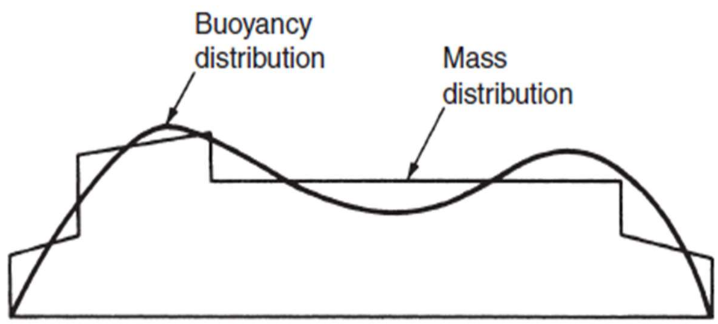


Figure 7.10 Buoyancy and mass distributions (Tupper, 2013)

Typical curves of wave induced forces are shown in Figure 7.9. Both shearing force and bending moment must be zero at the ends of the ship. The shearing force rises to a maximum value at points about a quarter of the length from the ends and is zero near amidships. The bending moment curve rises to a maximum at the point where the shearing force is zero, and has points of inflexion where the shearing force has a maximum value. The influence of the still water bending moment on the total moment is shown in Figure 7.10. For a ship with a given total mass and still water draughts, the wave sagging and hogging moments are effectively constant for a given wave. If the still water moment is changed by varying the mass distribution the total moment alters by the same amount. Whether the greater bending moment occurs in sagging or hogging depends on the type of ship depending, inter alia, upon its block coefficient (C_B). It is noted that for ships with low C_B the sagging bending moment is likely to be greater than the hogging. This trend inverts as C_B coefficient increases.

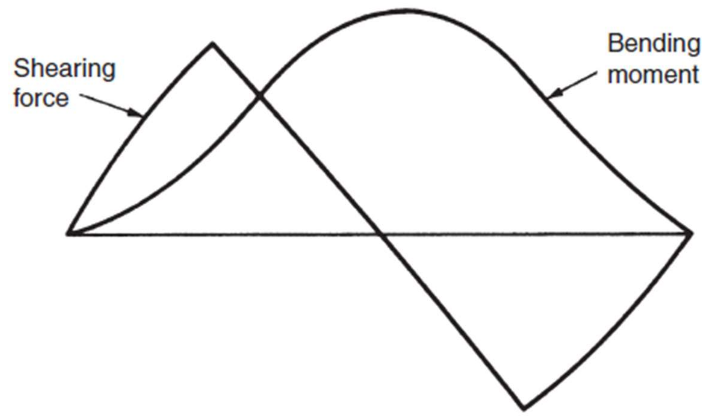


Figure 7.11 Bending moment and shear force distributions in waves (Tupper, 2013)

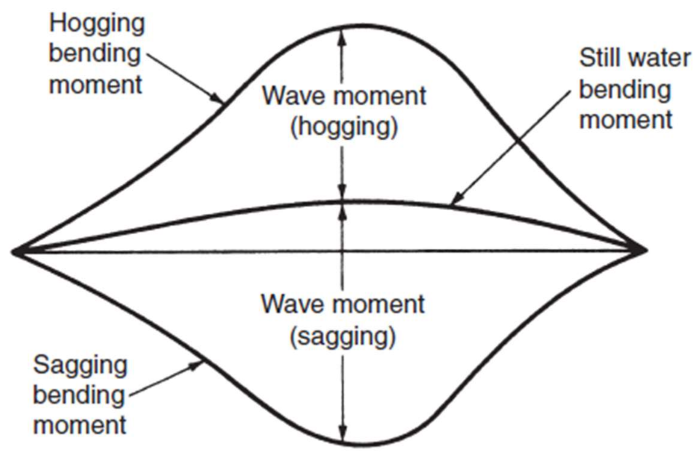


Figure 7.12 Still water versus wave bending moments (Tupper, 2013)

1.2.3 Section modulus

Having determined the shear forces and bending moments it is necessary to find the stresses in the structure. If we assume that ship hull is a beam for which plane sections remain plane at any longitudinal position of the ship's length, the bending moment is M, and the bending stress σ at z from the neutral axis is defined as:

$$\sigma = \frac{M \times z}{I} \quad (7.1)$$

where I is the second moment of area about the neutral axis of the section. Z is the maximum value of z, *I/Z* is known as the **section modulus**. Section modulus is needed to convert bending moments into stresses. The most important section to be considered at preliminary design stage is the mid ship section. This is the section where the ship experiences maximum bending moments. Typically, the members concerned are the longitudinally effective members namely: side and bottom plating, keel, deck plating, deck and side longitudinal stiffeners and longitudinal bulkheads. The section modulus is evaluated in tabular format (see Table 7.1). To achieve this an **A**ssumed **N**eutral **A**xis (**ANA**) is chosen at a convenient height above the keel. Accordingly, the area of each element above and below the ANA, the first and second moments about the ANA and the second moments about each element's own centroid are calculated. The differences of the first moments divided by the total area gives the distance of the true NA from the ANA. The second moments of area give the moment of inertia about the ANA and this can be corrected for the position of the true NA. This is shown in the section example (Figure 7.3) and the sectional modulus calculations in Table 7.1).

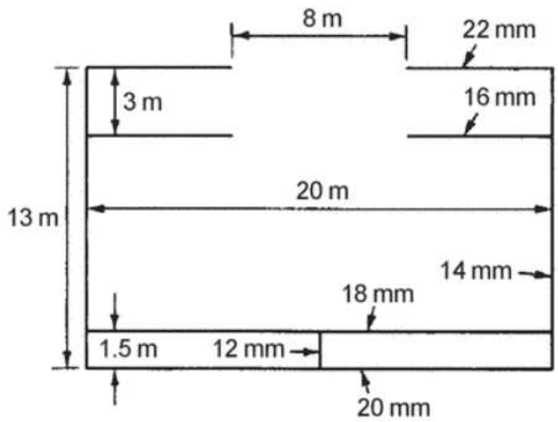


Figure 7.3 Idealized main frame (Tupper, 2013)

Item	Scantlings	Area (m^2)	Lever about keel (m)	Moment about keel (m^3)	2nd moment of Inertia (m^4)	2nd Moment of inertia about own centroid (m^4)
Upper deck	6 x 0.022	0.132	13	1.716	0	0
Second deck	6 x 0.016	0.096	10	9.600	0	0
Side shell	13 x 0.014	0.182	6.5	7.690	2.563	2.563
Tank top	10 x 0.018	0.180	1.5	0.405	0	0
Bottom shell	10 x 0.020	0.200	0	0	0	0
Center girder	1.5 x 0.006	0.009	0.75	0.005	0.002	0.002
Summation		0.799		4.136	40.008	2.565

Table 7.1 Sectional modulus table

The height of the NA above the keel $= \frac{4.136}{0.799} = 5.18\ m$. Second moment of area of half section about keel $= 40.008 + 2.565 = 42.573\ m^4$ and about NA $= 42.573 - 0.799(5.18)^2 = 21.163\ m^{4}$"

For the whole section the section modulus Z values are:

$$Z_{deck} = \frac{42.326}{7.82} = 5.41\ m^3$$

$$Z_{keel} = \frac{42.326}{5.18} = 8.17\ m^3$$

2. Modes of structural failures

Naval Architects tend to avoid structure failures by considering the potential limit states and failure modes associated with their designs. Whereas the scope of this course is not to define in detail issues associated with structural failures it is considered essential to be able to identify at least the following (basic) types of failure modes :

- **Material yield.** This limit stress level is termed yield stress. It is the stress at which material starts to plastically deform. At a higher stress level, known by the ultimate stress, structural fracture occurs. Although the aim of a successful structural design is to prevent yield in its members, localized yield in some portions of the structure is acceptable.

- **Buckling Failure.** When compressive loads act on a structural member, the structure may experience an in-plane deformation called buckling at a stress level lower than the material yield strength. Material buckling load is a function of the member geometry and material properties. The most common example of an instability failure is the buckling of a simple column under a compressive load that equals or exceeds elastic buckling criteria. A plate in compression also will have a critical buckling load whose value depends on the plate thickness, lateral dimensions, edge support conditions and material elasticity modulus.
- **Fatigue Failure.** It occurs at a stress level lower than the ultimate stress and as a result of a cumulative effects of loads on a structural member exposed to many cycles of stress. Theoretically, each cycle of stress causes some small but irreversible damage within the material and after the accumulation of such damage, the ability of the member to withstand loading is reduced below the level of the applied load.
- **Brittle fracture** relates with small cracks that may suddenly grow and lead to a catastrophic failure. Brittle fracture is mainly associated with the fact that below a certain temperature the ultimate tensile strength of a material (e.g. steel) dramatically diminishes. The originating crack is usually found to have started as a result of poor design or manufacturing practice.
- **Collision and Grounding**. IMO has developed some requirements regarding collision and grounding especially for ships carrying dangerous or pollutant cargoes such as tankers and ore carriers. The primary requirements for such ships are to arrange a double bottom of minimum height given by the IMO rules and double sides of minimum width to reduce the outflow of pollutant cargoes in ship collision or grounding accident.

3. Structural design assessment procedures

Structural design assessment procedures are mainly developed by Classification Societies and aim to ensure that high standards of safety, quality and reliability at the design stage and during construction. Compliance with the procedures may, upon application from the Shipowner, lead to what is known as a Classification Society notation or descriptive note for inclusion in a Class Society's ship registry. Such procedures require combination of Finite Element Methods to model the ship structure, linear hydrodynamic models to model the influence of waves and broad knowledge on marine structures, ship design and ship building (e.g. LR, 2020). They may apply at detailed design stage but for the case of innovative vessels they may be used to monitor design development early on in the design. Procedures considered more vital to the safety of a ship are mandatory while those which serve to further enhance the safety of a ship are optional. Mainly, structural design assessment procedures focus on structural integrity and are used to e**valuate global and local structural response due to static and dynamic loads, strength and fatigue assessment, shipbuilding construction monitoring.** The application of the procedures in this way ensures that:

- The critical design areas are identified early in the design phase.
- Structural details are designed to minimize the inclusion of stress concentrations.
- The steel weight distribution may be optimized.
- The construction tolerances will be applied to the critical areas during construction to reflect the increased diligence and care taken during the design stage.
- The Shipowner's commitment to safety is demonstrated.

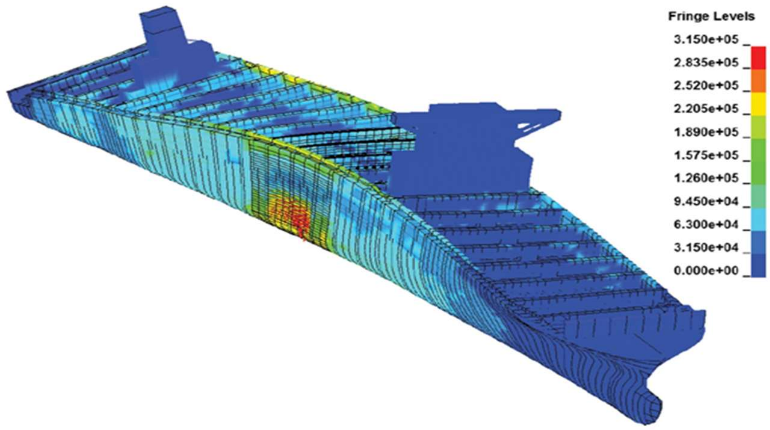


Figure 7.4 Quasi dynamic analysis using a mega container ship Finite Element Analysis (FEA) model (Lloyd's Register, 2020)

4. Shipbuilding materials

Structural design of a marine structure or vehicle, floating, submerged or fixed, includes the structural layout and determination of geometrical properties, commonly known as scantlings, of each structural element, each element being interconnected with other elements. The basis of this design is the mechanical properties of the material used such as yield strength, ultimate strength, compressive strength, elongation characteristics and plastic deformation, fracture and fatigue characteristics and other properties. Selection of construction material for marine fixed, floating platforms, ships and submarines is an important aspect of structural design. Materials depend on the following items:

- **Strength-to-weight ratio**. Marine structures and vehicles are generally weight sensitive. The displacement for a vessel being constant, higher weight of material means lower payload. Submersibles and submarines are particularly weight sensitive. In vehicles and structures where strength of the platform is a major consideration, such as deep-diving submarine or decks of large ships, higher strength to weight (or density) ratio means lower material weight.

- **Fracture (or notch) toughness.** This is a measure of material's ability to absorb energy before plastic deformation leading to fracturing. This also means ability of a material to resist brittle fracture in the presence of a notch.

- **Fatigue strength**. Fatigue failure can occur in a material due to low-cycle highstress fatigue, high-cycle low-stress fatigue or corrosion fatigue leading to stress corrosion cracking. The mechanism of fatigue is complex, failure being initiated due to generation of a small crack which grows to a major failure under repeated cyclic loading.

- **Ease of fabrication, weldability and ease of maintenance**. Welding causes a lot of problems in high-strength steels, aluminium and titanium. An additional problem is hydrogen induction into the metal leading to hydrogen embrittlement.

- **Cost and availability.** Cost of material depends on unit cost of material and the quantity of material used. Generally, in steels of various types, unit cost is quite high so that a small reduction in weight may not have significant effect on cost. So using higher strength steels is expensive and they can be used only if other technology considerations predominate. Titanium alloy is very strong though very expensive and used in submarine construction. Aluminium alloy are much lighter than steel though unit cost is higher.

Key materials to be considered as part of this selection process are :

- **Mild Steel** metallurgical variants have been used for shipbuilding construction since the end of the 19th century. They are cheap, available and tolerant with respect to quality deficiencies during fabrication and small damage during operation. Additionally, it has a relatively high strength to weight ratio (compared to wood for instance), a good reserve strength after serious damage, and easy to repair after damage. Steel characteristics have been improved over decades to obtain better properties such as increasing the yield strength and reducing the critical temperature to avoid brittle fracture. Structural steel in marine construction is designated as Grade A, B, D or E which have gone through a process of deoxidation by thermomechanically controlled processes (TMCP) or have been cooled by a process of normalisation (N) or have been control - rolled (CR). High strength steel is obtained by changing the carbon percentage in steel and using special heat treatment. High-tensile steels for ship structures are generally specified at three levels of yield strength – 32, 36 and 40 (representing yield strength 355 N/mm^2; ultimate strength 490 – 620 N/mm^2) with four designated grades – AH, DH,EH and FH based on increasing notch toughness.

- **Aluminum alloys** that have nearly the same strength of the traditional mild steel. In recent years, aluminium alloys have found extensive use in marine applications. Mainly hulls of small boats such as commercial pleasure craft (planing boats), sailing craft, personnel and work boats, fishing vessels, survey boats and naval boats have been made of aluminum. Superstructures and deck houses of large commercial vessels and many naval vessels, marine fittings (e.g. hatch covers, ladders, railings, gratings, windows and doors) are also important applications. Aluminium alloys are highly ductile materials and, if not properly stiffened, may be prone to large deflections. They have lower fracture toughness making them unsuitable where such requirements are essential. Aluminium alloy welding has to be done with care. Since strength of welded aluminium is less than non-welded plate, defects in welds cannot be afforded. If an aluminum alloy and steel are joined as would be required for aluminum deck house on steel hull, aluminum will waste away due to galvanic action, and so, the aluminum and steel must be separated at the joints by non-metallic separators. One of the main disadvantages of use of aluminum as structural material such as partition bulkheads is that aluminum deforms easily and melts when exposed to fire for a long time. Since fire hazard increases with aluminum, it cannot be used in fire-prone areas.

- **Fiber Reinforced Plastics (FRP)** are widely used for high speed boats, re-creational craft and novel hull forms. The material consists of reinforcing fibers of glass or carbon embedded in a matrix; a polyester for instance. Such a material is light compared to steel, has a relatively high strength useful for ship construction and relatively low cost. Small sailing boats and luxury yachts use composites because they can be shaped very easily in complex three-dimensional forms such as superstructures. Another advantage of composites are the smooth finish and easy maintenance. The main disadvantage of FRP is its poor resistance to fire and potential emission of noxious gases. Application of GRP/FRP and composites on ocean going hull forms would lead to increased fire safety and dry-docking requirements. As engineering application it is placed in the distant future.

5. Questions

1. Name and sketch the main structural elements of hull girder.
2. Name and sketch the main structural elements of hull girder and describe what is their main role in load-carrying mechanism.
3. Describe the main structural elements of a ship and how they participate to the load-carrying mechanism of a ship. What are the loads ship experiences?
4. Describe the load carrying mechanism of a ship.
5. What is the load-carrying mechanism of ship structure? What does hierarchy mean in this context?
6. What main dimensions are the most important ones in terms of hull girder strength?
7. What are the main elements of ship structural design process?
8. Describe the hierarchy of a ship structural design.

9. Define at least six different categories or types of structural loads.
10. What happened in the picture below? Analyze the situation from shipbuilder's point-of-view.