

# 1

## Ship Structures and Structural Design Practice

The task of assessing the adequacy of a ship's structure is perhaps the most complex structural engineering problem there is.

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In this book we shall describe concepts and techniques that have been used in the analysis and design of ship structures, the intention being to provide an understanding of their behaviour using the principles of engineering mechanics. At the outset it is important to underline that the form and layout of ships are unique amongst engineering structures because of the purpose for which they are built and the environment within which they operate.

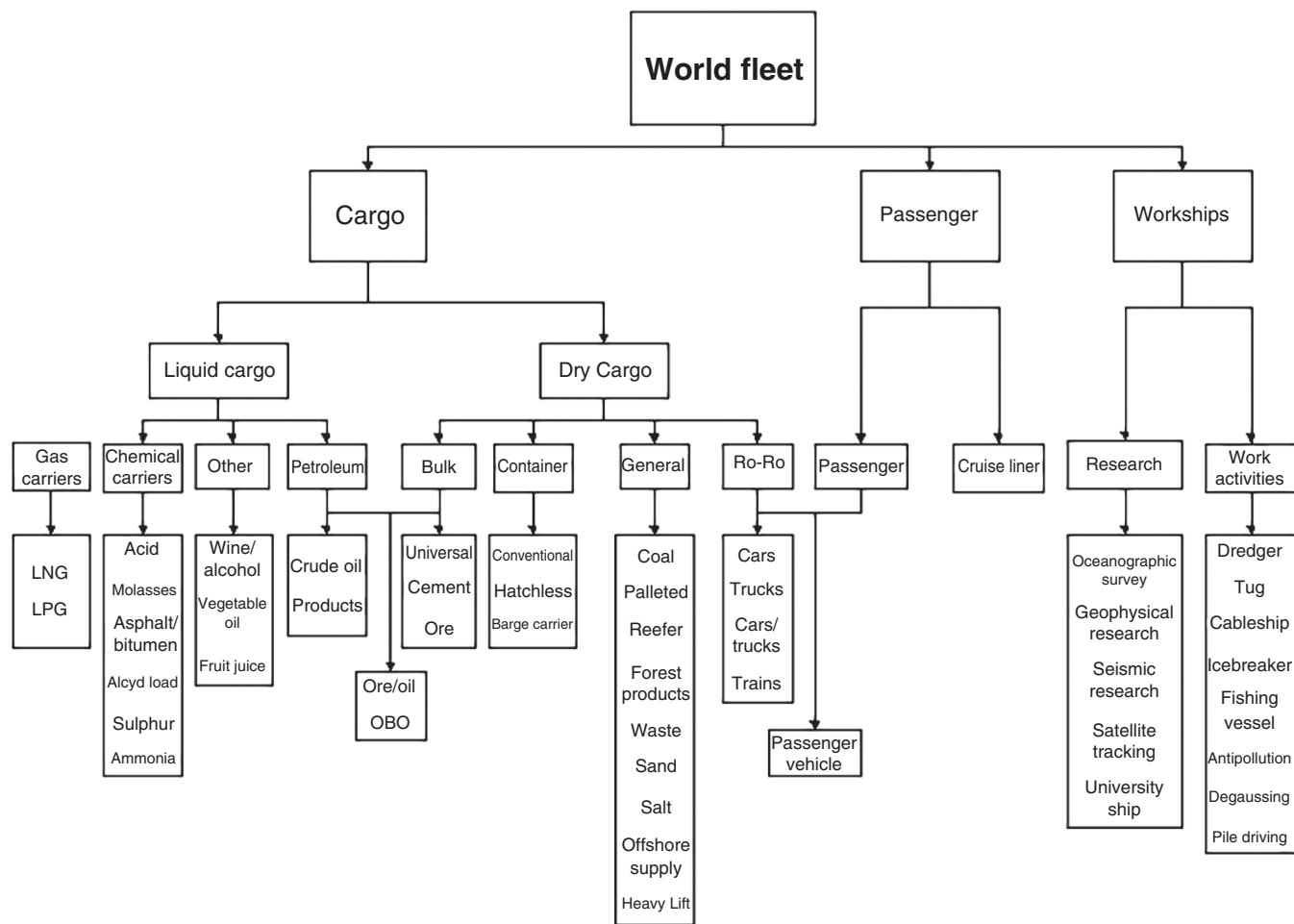
It is possible to employ sophisticated computer-based tools in ship structural analysis and design, but in order to make responsible and effective use of these tools, it is necessary to have a firm understanding of the characteristics and behaviour of ship structural members. This can only be achieved by developing a sound physical insight of the mechanics involved, in parallel with a good command of the corresponding mathematical tools. Difficulties arise from the fact that it is not easy to develop an intuitive understanding of ship structural behaviour because the environment within which they operate, the loadings to which they are subjected to, the materials used and their form lie outside most people's everyday experience.

We shall begin by providing a brief description the types of structures we shall be dealing with, starting from an overview of the world fleet of merchant ships.

### 1.1 The World Fleet

An idea of the present-day makeup of the world fleet can be gained from Figures 1.1 to 1.3, which contain information on ship types and distribution by deadweight and ship type. Figure 1.1 includes practically all known non-naval ship types, classified according to their purpose.

Clearly the most important group is that of cargo ships, which are used to carry dry and wet cargoes. Passenger ships still play an important role, although the role of ships in passenger transportation nowadays is limited. More important is that of leisure, which is catered for by cruiseships. There exists also a large, diversified fleet of workshops that



**Figure 1.1** Classification of world fleet of merchant ships.

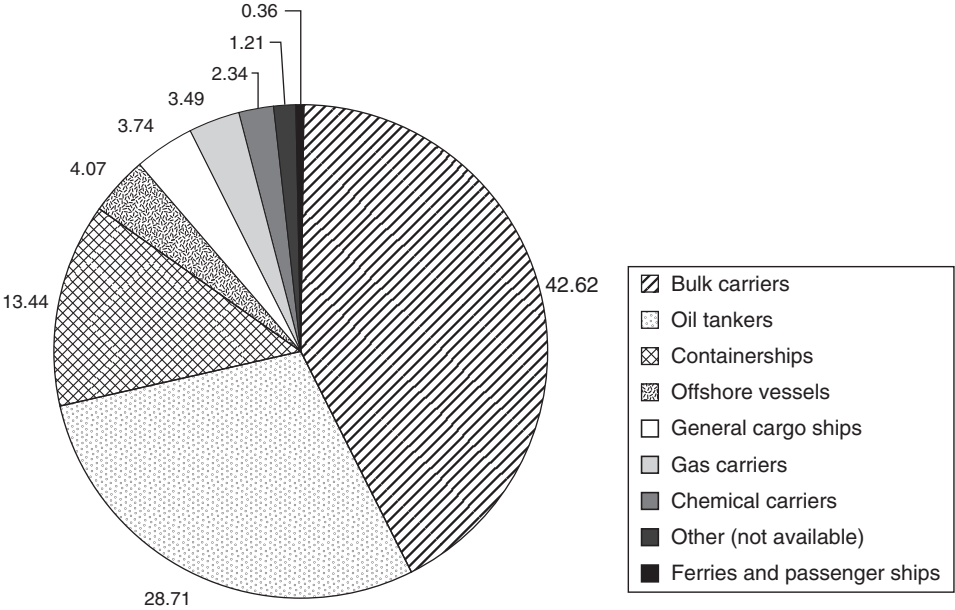


Figure 1.2 World cargo fleet breakdown [28]. (Percentage by deadweight tonnage.)

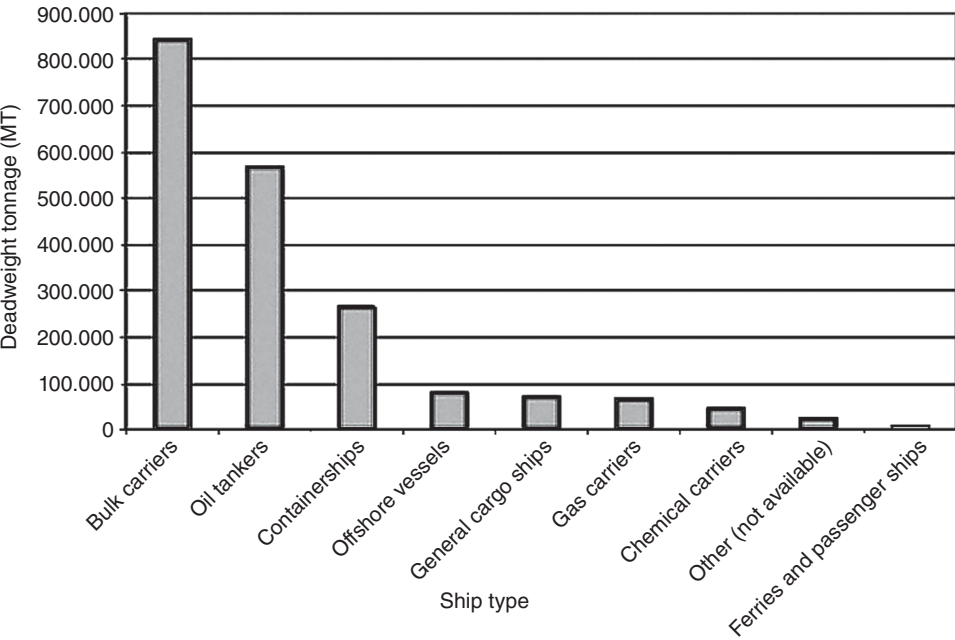


Figure 1.3 Deadweight of world cargo fleet per ship type [28].

perform specialised duties and that cannot be grouped together with the other types. Their structural features are such that they need to be considered on an individual basis.

Figures 1.2 and 1.3 contain information on the world cargo fleet. It is seen from Figure 1.2 that the overwhelming proportion of the total volume of cargo transported by sea is currently carried in bulk carriers (43 per cent) and tankers (29 per cent). At this point in time container ships account for another 14 per cent whereas the remaining 15 per cent is transported in a large number of other specialized ship types. In this text we shall therefore concentrate on the more important ship types, which are bulk carriers, tankers and containerships. These account for approximately 85 per cent of the world cargo fleet in terms of deadweight capacity.

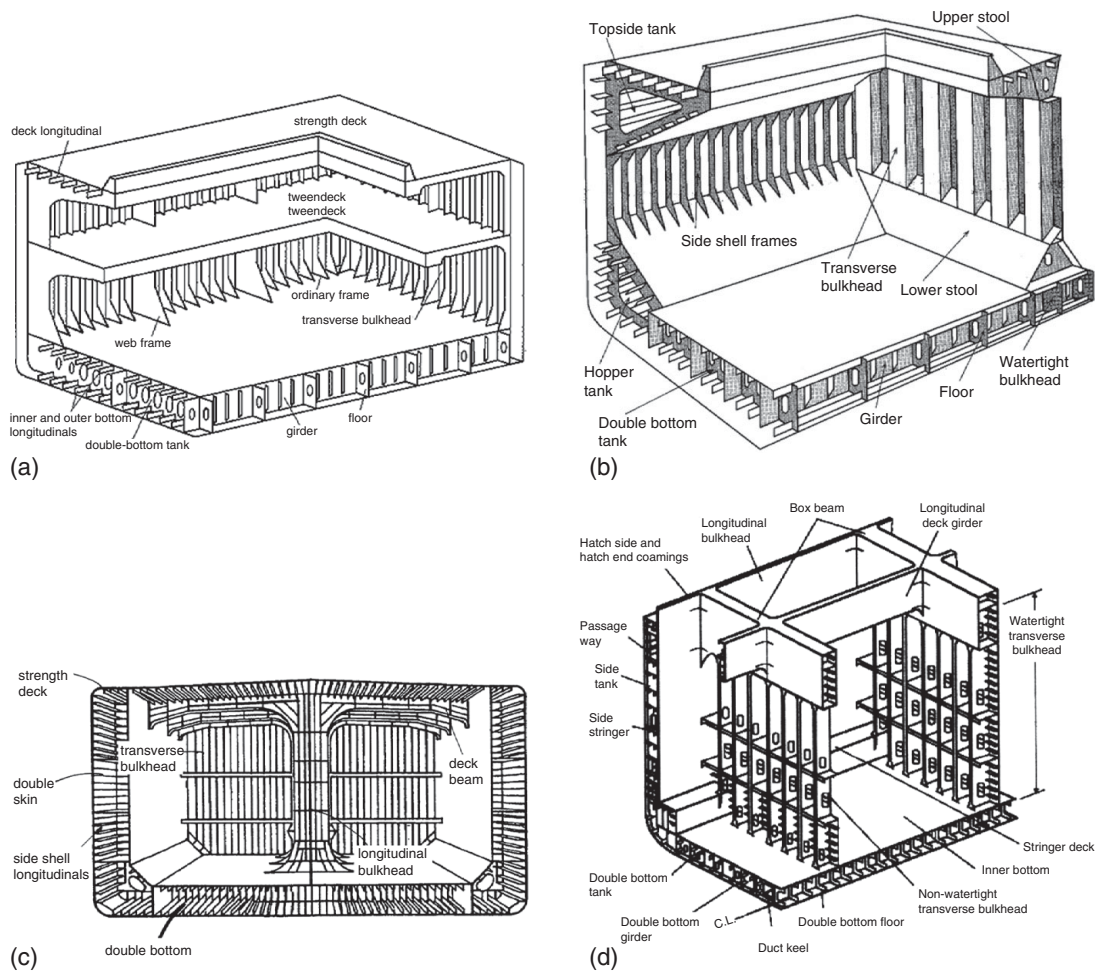
The overwhelming proportion of present-day ocean-going ships are made of steel, and as can be seen from Figure 1.4, their structure consists of thin plating that is stiffened using some type of stiffening system. In the case of oil tankers, containerships and a number of bulk carriers, in addition to the outer shell there exists an inner shell in way of the side shell and bottom plating. The spaces between the outer and inner shells are used to isolate the cargo from the outer shell plating and are generally used to store ballast seawater. In certain cases double bottom compartments that are located in way of the centreline are used to carry fuel oil.

One important role of the double skin is to enhance the pollution prevention capability of the ship. If it is constructed in a cellular form, it furthermore enhances the torsional rigidity of the structure. This is necessary in the case of containerships and other ships that have large deck openings, such as bulk carriers and multi-purpose (MPP) carriers

In contrast to dry cargo ships, the cargo spaces of oil tankers are totally enclosed. In the case of large oil tankers, the tanks are subdivided by longitudinal bulkheads that are also important as a means of providing sufficient strength. They also reduce the sloshing motion of the cargo carried, since this may result in significant loading of the internal structure of tanks. The cargo tanks of oil tankers are further subdivided by *swash bulkheads*. These are additional transverse non-watertight bulkheads that provide additional strength and rigidity and also contribute to limiting the sloshing of the cargo.

In the case of large cargo ships, the parallel body extends over a significant proportion of the length and is wall-sided – that is, it has a rectangular form with proportions that vary depending on the size and type of ship. The general layout of ships is to a large extent dictated by other than structural issues; it is general ship design and hydrodynamic performance that define the hull form. These factors have an important bearing on the layout of internal spaces as well. As a result, structural designers have to keep in mind the consequences of any decisions they may be contemplating on these other aspects. Once the hull form and internal arrangement of spaces have been defined, a wide range of choices are available in terms of structural form, material selection, stiffening arrangements and scantlings.

The primary role of the structure of a ship is to ensure its integrity under its intended operating conditions. Related to this, a number of more specific issues arise. These include the maximum load that the structure ought to be expected to withstand during its lifetime, the acceptable response of individual structural components under load, the expected life of



**Figure 1.4** Cargo spaces of various merchant ship types. (a) General cargo (MPP) ship; (b) bulk carrier; (c) oil tanker; (d) containership.

the hull structure, the costs of construction, maintenance and repair and, last but not least, the preservation of the environment. These issues will be discussed throughout the book.

In order to appreciate the range of questions that arise, an overview of the different types of configurations and structural layouts that are encountered in present-day ships will be provided. The range in size, function and layout is wide, and it is important to understand how the principles of mechanics can be applied to study existing ship structures and to propose suitable arrangements for a new design. To be able to perform such an exercise it is essential to understand the reasons for which particular structural arrangements are used in different ship types.

The principal dimensions of commonly encountered merchant ship types are included in Table 1.1.<sup>1</sup>

## **1.2 Structural Configurations, Materials and Modes of Failure**

Before embarking on detailed considerations of structural analysis and design of ship structures, it is necessary to gain an understanding of the morphology of the structures in question, and of the materials used, given the environment within which ships operate. Structural arrangements used differ substantially from those used in other fields of engineering (civil, mechanical, offshore, aerospace), and thus it is necessary to gain an understanding of arrangements used, given the loads that act.

### ***1.2.1 Structural Arrangements in Way of Cargo Spaces***

The sketches included in Figure 1.4 show structural arrangements in the cargo-carrying spaces of some representative ship types. In all cases the structure is composed of thin plating that is stiffened by orthogonal systems of stiffeners. The internal plating of decks and bulkheads is also orthogonally stiffened, although stiffening systems can differ widely in form, materials used and dimensions.

In many texts that describe the structure of waterborne craft, the bottom structure is cited first. This is because when a ship is being constructed, the keel is laid first and acts as the foundation upon which the frames and shell plating are added. In order to fulfil this role in traditional shipbuilding in which the length of ships does not exceed 100 metres or so, the keel is sized so that it has sufficient strength to provide support to transverse members. In modern large ships in which the length exceeds 100 metres, it is the main (strength) deck that assumes the role of providing sufficient strength to the hull girder, especially when it bends in the longitudinal direction. The bottom structure and the strength deck complement each other in terms of their strength capability and work in tandem in that they act as flanges of the hollow girder that resembles a ship's hull when it bends in the longitudinal

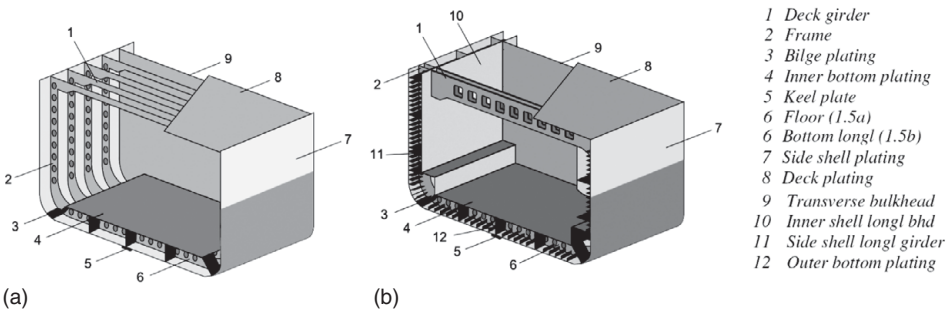
<sup>1</sup> Data for LNG, LPG, containerships and passenger ships from [27].

Table 1.1 Main dimensions of various ship types [27].

| <i>Ship type<br/>and size category</i> | <i>Cargo capacity</i> | <i>Length BP<br/>(m)</i> | <i>Breadth<br/>(m)</i> | <i>Draught<br/>(m)</i> |
|----------------------------------------|-----------------------|--------------------------|------------------------|------------------------|
| <i>Bulk carriers</i>                   | (metric tonnes)       |                          |                        |                        |
| Handysize                              | 10,000–40,000         | 110–200                  | 20–30                  | 8.0–12.5               |
| Handymax/Supramax                      | 40,000–60,000         | 200–220                  | 30–32                  | 11.5–12.5              |
| Panamax                                | 60,000–80,000         | 220–225                  | 32–37                  | 12.5–14.0              |
| Capesize                               | >80,000               | 250–350                  | 40–65                  | 15.0–23.0              |
| <i>Containerships</i>                  | (TEU)                 |                          |                        |                        |
| 300–500                                | 5,000                 | 101                      | 17.9                   | 6.3                    |
| 630–850                                | 10,000                | 129                      | 22                     | 7.9                    |
| 1,300–1,500                            | 20,000                | 165                      | 27                     | 10.0                   |
| 2,000–2,200                            | 30,000                | 191                      | 30.4                   | 11.4                   |
| 2,600–2,900                            | 40,000                | 211                      | 30.6                   | 12.5                   |
| 2,100–4,600                            | 30,000–60,000         | 187–285                  | 32.3                   | 11.3–13.4              |
| 4,300–5,600                            | 60,000–70,000         | 260–268                  | 37.2–40                | 12.7–14.0              |
| 6,300–6,700                            | 80,000–100,000        | 285–292                  | 40.0–42.8              | 13.5–14.5              |
| 7,200–7,900                            | 100,000–105,000       | 332–336                  | 42.8                   | 14.0–14.5              |
| 8,000–8,500                            | 99,000–102,000        | 308–312                  | 42.8                   | 14.0–14.5              |
| 12,500                                 | 140,000               | 380                      | 56                     | 15                     |
| 13,500–21,300                          | 170,000–200,000       | 400                      | 56–59                  | 16                     |
| <i>Oil tankers</i>                     | (metric tonnes)       |                          |                        |                        |
| Small                                  | 5,000–10,000          | 100–120                  | 16–19                  | 3.0–7.5                |
| Handysize                              | 20,000–30,000         | 130–160                  | 22–26                  | 8.5–9.0                |
| Handymax                               | 30,000–47,000         | 138–174                  | 23–32                  | 9.0–11.0               |
| Panamax                                | 70,000–80,000         | 228.6                    | 32.2                   | 11.0–12.6              |
| Aframax                                | 85,000–115,000        | 233–239                  | 42–44                  | 11.0–13.6              |
| Suezmax                                | 120,000–180,000       | 256                      | 45–52                  | 13.5–15.5              |
| VLCC                                   | 200,000–300,000       | 333                      | 59–60                  | 17.7–20.5              |
| ULCC                                   | >300,000              | 327–440                  | 65–70                  | 21.5–22.8              |
| <i>Gas carriers</i>                    | (gross tons)          |                          |                        |                        |
| LNG carriers                           | 20,000                | 166                      | 27.8                   | 8.4                    |
|                                        | 30,000                | 188                      | 31.4                   | 9.2                    |
|                                        | 50,000                | 223                      | 36.7                   | 10.4                   |
|                                        | 80,000                | 260                      | 42.4                   | 11.5                   |
|                                        | 100,000               | 281                      | 45.4                   | 12.1                   |
| LPG carriers                           | 3,000–5,000           | 92–109                   | 16.1–18.6              | 6.3–7.3                |
|                                        | 5,000–10,000          | 109–136                  | 18.6–22.7              | 7.3–8.9                |
|                                        | 10,000–30,000         | 136–193                  | 22.7–31.1              | 8.9–12.1               |
|                                        | 30,000–50,000         | 193–228                  | 31.1–36.0              | 12.1–14.0              |
| <i>Passenger and cruiseships</i>       | (gross tons)          |                          |                        |                        |
|                                        | 3,000                 | 88                       | 16.5                   | 4.3                    |
|                                        | 5,000                 | 104                      | 18.6                   | 5.0                    |
|                                        | 10,000                | 131                      | 21.8                   | 6.4                    |
|                                        | 20,000                | 165                      | 25.7                   | 7.8                    |
|                                        | 30,000                | 189                      | 28.2                   | 7.8                    |

Table 1.1 (cont.)

| Ship type<br>and size category | Cargo capacity | Length BP<br>(m) | Breadth<br>(m) | Draught<br>(m) |
|--------------------------------|----------------|------------------|----------------|----------------|
|                                | 50,000         | 224              | 32.3           | 7.8            |
|                                | 70,000         | 250              | 32.3           | 8.1            |
|                                | 100,000        | 281              | 32.3           | 8.1            |



**Figure 1.5** Stiffening systems. (a) Transverse stiffening system; (b) longitudinal stiffening system.

direction. Both of these components consist of thin plating that in many cases is longitudinally stiffened.

Since the structure is additionally subjected to transverse loads such as hydrostatic pressure and the weight of the cargo, these components have to be able to carry these loads as well. To support the side shell structure in carrying lateral loads, transverse frames are fitted (item 2 in Figure 1.5a). Frames form part of a stiffening arrangement that generally extends over the whole internal perimeter of any transverse section (frame-floor-frame-deck girder), as seen in Figures 1.4 and 1.5a. Continuity in the transverse direction ensures stiffness and strength. The presence of transverse members such as frames also increases the compressive strength of longitudinal members where these are fitted by acting as points of support lying between stiff members such as bulkheads.

The side shell structure that comprises the outer shell plating, its stiffening and the inner longitudinal bulkhead if fitted, as in the case of the oil tanker and containership (Figures 1.4c, 1.4d), ensures watertightness of the cargo compartment. It is subjected to both lateral and in-plane loading in the longitudinal direction. The critical region of the side shell structure is the strake (a strake is a longitudinal series of shell plates) that is joined to the deck plating (*sheer strake*), which carries the highest in-plane loads. The lateral loading consists of the hydrostatic pressure that acts below the waterline and wave impact above the waterline.

The most important major internal structural components are the *transverse bulkheads* (item 9 in Figures 1.5a–b, also shown in Figure 1.4). These serve a number of

functions. Firstly, they subdivide the internal spaces, thereby enabling a variety of cargo types to be transported. Secondly, they provide support to the deck, bottom and side shell structures, since they are much more rigid than transverse frames. Thirdly, they contribute to the torsional strength of the hull girder. Last but not least, they ensure survivability of the ship when in a damaged condition by preventing the flooding of adjacent compartments.

In large ships and especially in oil tankers, the cargo tanks are subdivided by *longitudinal bulkheads* as well (Figure 1.4c). These enhance the longitudinal strength and also provide the number of compartments that are necessary to transport different types of cargoes. Transverse *swash bulkheads* may also be fitted in order to provide sufficient strength to tank structures. These are not watertight and permit the motion of the liquid cargo within the tank, although their presence dampens the fluid motion and thus reduces the magnitude of *sloshing* loads that may otherwise act on the internal structure.

In addition to cargo spaces, the other major components of the hull girder are the fore and aft ends (Section 1.2.3) as well as the superstructures. The loads that act on the fore and aft ends arise from the action of the sea environment and include wave impacts of all types. In the case of the aft end, the external plating is additionally loaded as a result of propeller action. A large part of the volume enclosed within the fore and aft peaks is used for the carriage of ballast seawater and, these tanks are used to adjust trim, since they are furthest from the longitudinal centre of gravity of the ship. Since the most important external loads that act here are lateral loads, in order to withstand these, the fore and aft structures are transversely stiffened. The structure needs to be sufficiently rigid, especially in way of the propulsion equipment in order to withstand the vibration loads that arise as a result of main engine and propeller shaft operation.

In cargo ships, superstructures house the crew and navigation equipment. They are located at the aft end and thus do not contribute to longitudinal strength. In the case of large passenger ships, however, superstructures are particularly important structural items, as they extend over a large proportion of the length of the ship.

### 1.2.2 Stiffening Systems

In theory, flat plating can carry both lateral and in-plane loads without the need for any type of stiffening. However, it quickly becomes apparent that the structure becomes very inefficient from the points of view of weight, cost and ease of fabrication; in addition, limitations to ship size are imposed. Stiffening systems are thus used and, for ease of fabrication, are arranged in the form of orthogonal grids.

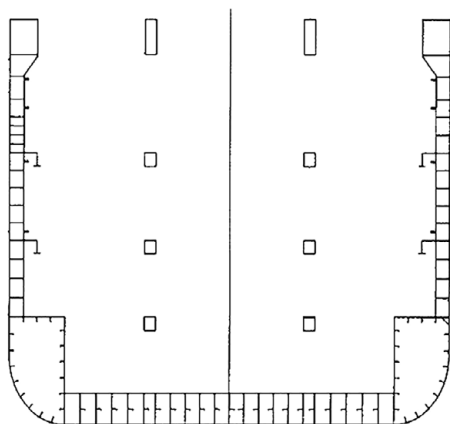
In vessels whose length does not exceed 100 metres, the lateral loads that act, such as hydrostatic pressure and cargo weight, are critical. The most efficient system of stiffening to withstand these loads is the *transverse* stiffening system, which consists of closely spaced frames that subdivide the spacing between *web frames* (Figure 1.4a). In an efficient design the frame extends around the perimeter of the hull envelope and, by a system of brackets that connect the ends of each member, ensures an efficient transfer of loads. Thus, along the bottom structure, *floors* are aligned with side shell frames. These provide continuity and act as supports to the frames by being loaded in compression. They also

carry lateral loads, by supporting the inner bottom plating upon which rests the cargo within each hold, this being their primary function. In way of the under-deck structure, *beams* provide continuity to frames and, as in the case of floors, provide support to the strength deck by withstanding lateral loads such as the weight of deck equipment, deck cargo and deck wetting loads. In the case of cargo ships with large deck openings, beams also contribute to the rigidity of the deck. In this way a rectangular *ring frame* is formed, which is an efficient structural arrangement.

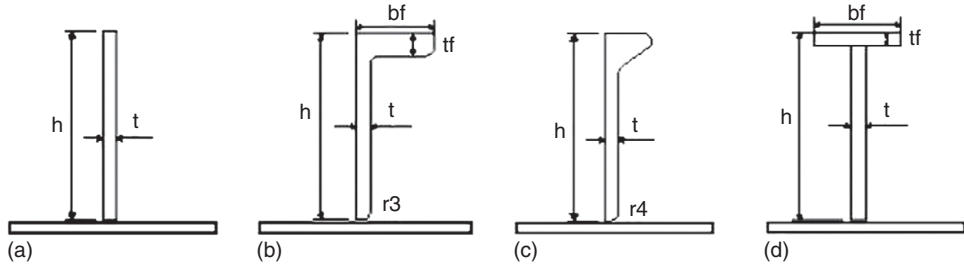
In the case of ships whose length exceeds 100 metres, it is longitudinal strength that is critical, and the most efficient stiffening system is the longitudinal one. This consists of closely spaced longitudinal stiffeners whose cross-section is much smaller than that of frames. A large variety of forms is used depending on the magnitude, direction of loads as well as the size and type of vessel. Shipyards around the world use different kinds of sections according to national industry standards and availability, but in every case these are required to fulfil minimum strength requirements that are expressed in classification society rules in terms of the respective section moduli.

In certain ship types both transverse and longitudinal stiffening systems are used (*mixed stiffening system*). Examples are the MPP cargo ship and the bulk carrier shown in Figures 1.4a and 1.4b, respectively. The MPP vessel is seen to be transversely stiffened throughout except in way of the double bottom structure. The bulk carrier, on the other hand, is transversely stiffened only in way of the side shell plating between the top side and lower hopper tanks. Elsewhere it is longitudinally stiffened. In bulk carriers the transverse bulkheads are vertically stiffened with corrugations instead of the more usual flat, vertically stiffened plating. This is done in order to reduce weight and fabrication costs.

One other system that has been proposed in order to simplify fabrication and reduce weight is the *unidirectional* stiffening system. In this system the number of transverse members is substantially reduced when compared to conventional designs. Strength and stiffness are provided by a double hull system in which the inner and outer plating are connected by longitudinal members (Figure 1.6). It has been used by the US Navy in the design of a 43,000



**Figure 1.6** Unidirectional system in advanced double hull [2].



**Figure 1.7** Stiffener sections used in ship structures [7]. (a) Flatbar; (b) angle bar; (c) bulb section; (d) T-bar. Reprinted courtesy of Det Norske Veritas, Høvik.

dwt tonne containership as well as by certain Japanese shipyards and has its origin in the cellular type of structure used in containerships. Such an arrangement provides the necessary torsional strength that is required when there are large openings in the strength deck.

Stiffeners can be subdivided into rolled and built-up sections. For primary (longitudinal) strength purposes the types used are shown in Figure 1.7.

*Flatbars:* Flatbar stiffeners are used as strength deck and longitudinal bulkhead longitudinals. They have lower torsional strength than other types of stiffeners. However, they are easier to produce and hence are competitively priced.

*Angle bars:* Angle bars have a higher section modulus than flatbars but are prone to twisting when exposed to lateral loading due to their asymmetry about the web axis. They are more prone to fatigue cracking as well as grooving (necking) corrosion.

*Bulb profiles:* These are widely used because they have a higher section modulus than flatbars. As in the case of angle bars, they are prone to twisting and bending about the line of attachment to the plating because of their asymmetry about the web axis.

*T-bars:* These have a higher section modulus than other sections and, being symmetrical, are not prone to twisting. As a result, they have good fatigue strength characteristics. Care is needed when selecting the slenderness of the web and the flange in order to avoid local buckling.

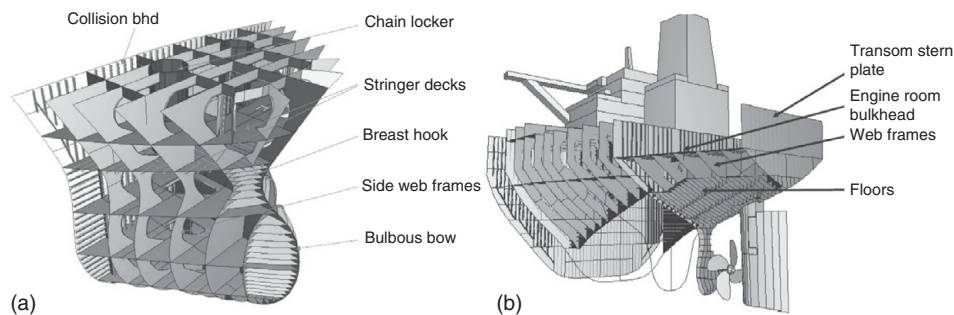
### 1.2.3 Structural Arrangements in Way of the Fore and Aft Ends

The use of transverse stiffening systems is evident in both the fore and aft ends of the vessel (Figure 1.8).

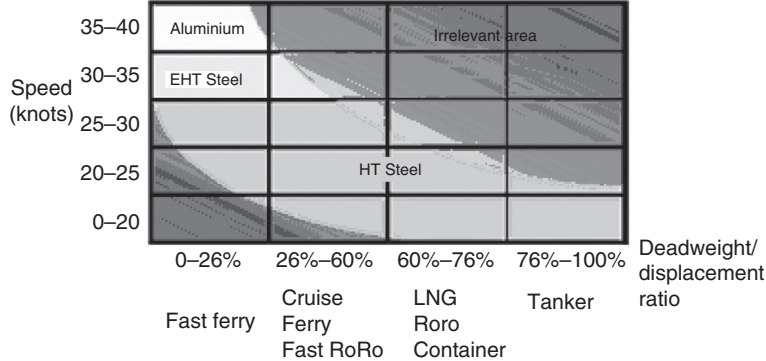
As mentioned previously, the most important loading in these regions of the hull girder are lateral static and time-varying external loads as well as vibration excitation in the case of the machinery spaces aft.

### 1.2.4 Materials Used in Ship Structures

Figure 1.9 gives an overview of the use of materials in merchant ships. Mild steel is generally used for smaller ships that operate at speeds below 20 knots. For larger ships that



**Figure 1.8** Structural arrangements in way of fore and aft ends of a cargo ship [7]. (a) Fore end structural arrangement; (b) aft end structural arrangement. Reprinted courtesy of Det Norske Veritas, Høvik.



**Figure 1.9** Suitability of materials according to the deadweight to displacement ratio and speed [16].

have a high deadweight-to-displacement ratio, such as oil tankers and bulk carriers, in addition to mild steel, high tensile steel is used in order to reduce weight and facilitate fabrication. If, however, the speed requirements exceed 30 knots, as in the case of fast passenger craft, extra high tensile steel or aluminium is used to reduce the weight even further, thereby reducing powering requirements for the desired payload.

The most important criteria upon which material selection is based are strength, stiffness and cost. Other criteria are notch toughness and ease of fabrication, ship construction being a competitive commercial activity. In more specialised applications materials with enhanced properties such as low flammability and low susceptibility to corrosion are required.

*Mechanical and Other Properties*

Conventional ocean-going ships have been built using steel since the second half of the 19th century. The use of steel in conjunction with improvements in fabrication techniques has permitted the multifold increase of ship size. Its use has continued to the present day

Table 1.2 *Major iron ore producers [9].*

| <i>Company</i>   | <i>Country</i>      | <i>2017 one quarter production,<br/>In million tonnes (mt)</i> |
|------------------|---------------------|----------------------------------------------------------------|
| Vale             | Brazil              | 91.8                                                           |
| Rio Tinto        | Brazil              | 85.0                                                           |
| BHP Billiton     | Australia, Brazil   | 55.6                                                           |
| Fortescue Metals | Australia           | 50.1                                                           |
| Anglo-American   | South Africa et al. | 15.7                                                           |
| Arcelor Mittal   | several countries   | 14.2                                                           |

Table 1.3 *Comparison of manufactured material costs.*

| <i>Material</i>    | <i>Cost (US\$/mt)</i>  |
|--------------------|------------------------|
| Shipbuilding steel | 600–2,000              |
| Aluminium          | Steel price $\times$ 5 |
| FRP                | 2,000                  |
| Composites         | 15,000                 |

and will most likely continue in the foreseeable future, given its availability and comparatively low cost (Tables 1.2 and 1.3).

Iron ore is abundantly available in the earth's crust and is mined around the world. Major producers and exporters are Brazil and Australia, represented by the top four companies included in Table 1.2.

The cost of shipbuilding steel, as that of other potential candidates for ship construction, depends on supply and demand and thus fluctuates. For purposes of comparison, Table 1.3 gives an idea of relative costs as they were in 2020.

The success of steel as a prime candidate for ship construction depends not only on its low cost but also on its mechanical properties, that is, its strength, stiffness, hardness, ductility, fatigue and fracture toughness.

*Strength* is a measure of the ability of a material to transmit a specified load without suffering failure, generally by yielding. For structural applications it is expressed in terms of a critical *yield stress* whose units are  $\text{N/mm}^2$  (MPa) (Table 1.4).

*Stiffness* is a measure of the amount of distortion that a structural member suffers when subjected to a particular load and should be distinguished from elastic modulus which characterizes a material rather than a member. It is measured in units of force/elongation (N/m).

*Hardness* is a measure of the extent to which a structural member is indented when struck by an object [10]. Thus, the impression of a striker on a soft material is much greater than the one left on a hard material. There are many types of tests that are based either on the measurement of depth (Rockwell, Brinell) or the size of the indentation (Vickers and others) made by a striker under known conditions. For relatively soft metals and for steel,

Table 1.4 *Properties of metals used in shipbuilding [26].*

| Properties                                            | Low carbon steels |       | Aluminium<br>(5000 series) |       | Titanium<br>( $\alpha$ alloy) |       |
|-------------------------------------------------------|-------------------|-------|----------------------------|-------|-------------------------------|-------|
|                                                       | Range             | Mean  | Range                      | Mean  | Range                         | Mean  |
| <i>Physical properties</i>                            |                   |       |                            |       |                               |       |
| Density ( $\text{kg/m}^3$ )                           | 7,640–8,080       | 7,860 | 2,640–2,720                | 2,670 | 4.42–4.84                     | 4.54  |
| <i>Mechanical properties</i>                          |                   |       |                            |       |                               |       |
| Hardness, Brinell                                     | 86.0–562          | 247   | 28.0–120                   | 68.5  | 290–411                       | 348   |
| Hardness, Knoop                                       | 103–682           | 281   | 68.0–150                   | 98.9  | 315–450                       | 379   |
| Hardness, Rockwell B                                  | 30.0–105          | 89.5  | 49.0–75.0                  | 57.1  |                               |       |
| Hardness, Vickers                                     | 22.0–661          | 268   | 68.0–137                   | 89.9  | 304–480                       | 368   |
| Tensile Strength, Ult. (MPa)                          | 250–2,450         | 788   | 110–450                    | 268   | 825–1,580                     | 1,070 |
| Tensile Strength, Yld (MPa)                           | 140–2,400         | 593   | 40–435                     | 194   | 759–1,410                     | 981   |
| Elongation at Break (%)                               | 1.00–48.0         | 20.8  | 3.50–35.0                  | 13.8  | 4.00–18.0                     | 11.2  |
| Modulus of elasticity (GPa)                           | 183–213           | 202   | 68.9–72                    | 70.0  | 105–123                       | 114   |
| Compressive Yield Strength (MPa)                      | 152–1,800         | 1,480 | 160–325                    | 261   | 860–1,280                     | 1,030 |
| Bulk Modulus (GPa)                                    | 148–163           | 160   |                            |       |                               |       |
| Compressive Modulus (GPa)                             |                   |       | 70.0–72.4                  | 71.7  |                               |       |
| Poisson's Ratio                                       | 0.23–0.30         | 0.29  | 0.33                       | 0.33  | 0.31–0.34                     | 0.322 |
| Charpy Impact (J)                                     | 8.13–339          | 60.1  |                            |       | 9.50–25.0                     | 18.7  |
| Fatigue Strength (MPa)                                | 207–772           | 664   | 82.7–159                   | 127   | 140–1,160                     | 497   |
| Fracture Toughness ( $\text{MPa}\sqrt{\text{m}}$ )    | 66.0–82.0         | 72.4  |                            |       | 24.0–105                      | 55.5  |
| Shear Modulus (GPa)                                   | 62.1–82.7         | 79.5  | 25.9–26.4                  | 26.0  | 41.0–46.0                     | 43.5  |
| Shear Strength (MPa)                                  |                   |       | 75–270                     | 159   | 550–760                       | 672   |
| <i>Thermal properties</i>                             |                   |       |                            |       |                               |       |
| CTE, linear ( $\mu\text{m/m}^\circ\text{C}$ )         | 10.1–16.6         | 12.6  | 23.8–26.6                  | 25.6  | 8.30–11.7                     | 9.26  |
| Specific Heat Capacity ( $\text{J/g}^\circ\text{C}$ ) | 0.448–0.615       | 0.478 | 0.880–0.904                | 0.897 | 0.368–0.670                   | 0.542 |
| Thermal Conductivity ( $\text{W/m-K}$ )               | 12.0–93.0         | 43.6  | 108–205                    | 147   | 6.10–10.9                     | 7.19  |
| Melting Point ( $^\circ\text{C}$ )                    | 1,230–1,530       | 1,440 | 568–657                    | 623   | 1,300–1,680                   | 1,650 |

respectively, there is a very simple relation between the *Vickers Hardness*  $H_V$  and the yield stress  $\sigma_0$  or the tensile strength  $\sigma_t$ , expressed in  $\text{kg/mm}^2$ :

$$H_V \gg \begin{cases} 3 \sigma_0 & \text{for soft metals} \\ 3.2 \sigma_t & \text{for steel} \end{cases}$$

*Ductility* of a material is a measure of the extent of distortion it can undergo without fracturing when subjected to external loading. Thus low-ductility materials will fracture when subjected to comparatively low loads.

Ductility can be quantified in terms of the fracture strain, which is the engineering strain at which a test specimen fractures during a uniaxial tensile test. Another commonly used measure is the reduction of area at fracture.

*Fracture toughness* denotes the ability of a material to resist fracture.<sup>2</sup> It is denoted  $K_{Ic}$  and has units of  $\text{MPa}\sqrt{\text{m}}$ . The subscript ‘Ic’ denotes mode I crack opening under a normal tensile stress perpendicular to the crack, since the material can be made thick enough to resist shearing (mode II) and tearing (mode III).

Table 1.4 gives the numerical values for selected properties of metals used in shipbuilding. A study of this table reveals the comparative advantages of each material. For hull structural use, *rolled steel* is used, and this may be either of ordinary or of higher strength. Cast and forged steel is also used for items such as rudder components, the stem and stern, anchors and anchor chains. Ongoing efforts to improve the properties of shipbuilding steels and processes are aimed at reducing the cost of assembly and fabrication (*TMCP* steels, laser welding) and also to improve performance under particular conditions, in particular container ships, oil and chemical tankers (corrosion resistance).

*Aluminium* is used in superstructures and for navigation instrument components. It is also used in vessels up to 80 metres in length especially when weight reduction is a high priority. Its stiffness (65 GPa) is one-third of that of steel (207 GPa), and thus the resulting deflections render it impracticable for use in the hull structure of large vessels.

*Titanium* has been used in the construction of a small number of yachts in Japan because of its corrosion resistance and its low density. In the shipbuilding industry it is more commonly used for mechanical components (heat exchangers, piping and valves), although efforts are underway to make its use more widespread by reducing production costs [17]. It is also used in the offshore industry for risers and ballast systems. In the past it was used by the Soviet navy in submarine construction.

*Fibre-reinforced plastic (FRP)* materials are used for specialist applications such as the hull construction of mine-hunters, patrol craft, yachts, etc. A major technical drawback of composite materials is their low fire resistance.

Table 1.5 lists the elements found in low-carbon steels and their presence whereas Table 1.6 lists the effects of the most important of these elements when used in steel alloys.

### *Classification Society Requirements for Shipbuilding Steels*

Table 1.7 includes the most important mechanical properties that classification societies normally require of steels used in hull construction. These are yield strength and fracture toughness. Shipbuilding steels are classed as of ordinary or of high strength, and within each class they are allocated grades that are used to distinguish their fracture toughness, which increases from A through to E. Below a certain temperature, termed the *transition temperature*, steels that normally exhibit ductile behaviour behave in a brittle manner and can fracture under low loads. The transition temperature is influenced by the chemical composition of the alloy, grain size and heat treatment. By modifying one or more of these parameters it is possible to reduce the transition temperature, thereby increasing fracture toughness.

<sup>2</sup> If the material contains a defect or crack the property is *notch toughness*.

Table 1.5 Presence of elements in low-carbon steels [19].

| Element                     | Range (%)      | Average value (%) |
|-----------------------------|----------------|-------------------|
| Aluminium, Al               | 0.010–1.5      | 0.412             |
| Boron, B                    | 0.00050–0.0060 | 0.00273           |
| Carbon, C                   | 0.0030–0.80    | 0.182             |
| Chromium, Cr                | 0.20–10        | 0.891             |
| Cobalt, Co                  | 7.5–12         | 8.84              |
| Copper, Cu                  | 0.020–1.5      | 0.372             |
| Iron, Fe                    | 63–100         | 96.0              |
| Lead, Pb                    | 0.15–0.36      | 0.251             |
| Manganese, Mn               | 0.10–2.2       | 0.783             |
| Molybdenum, Mo              | 0.080–4.8      | 0.570             |
| Nickel, Ni                  | 0.030–18.5     | 3.13              |
| Niobium, Nb (Columbium, Cb) | 0.0050–0.15    | 0.0485            |
| Nitrogen, N                 | 0.0010–0.070   | 0.0200            |
| Phosphorus, P               | 0.0010–0.40    | 0.0362            |
| Silicon, Si                 | 0.010–1.0      | 0.283             |
| Sulphur, S                  | 0.0010–0.50    | 0.0432            |
| Titanium, Ti                | 0.010–1.4      | 0.416             |
| Vanadium, V                 | 0.0050–0.95    | 0.0912            |
| Zirconium, Zr               | 0.010–0.15     | 0.0211            |

Table 1.6 Effects of the most important elements on steel alloys.

| Element    | Effect on steel alloy                                                                                           |
|------------|-----------------------------------------------------------------------------------------------------------------|
| Carbon     | Increases toughness, yield stress, tensile strength<br>Decreases ductility, max. elongation, welding properties |
| Manganese  | Increases tensile strength and improves weldability<br>Deoxidises steel and forms manganese sulphide (MnS)      |
| Silicon    | Increases toughness, tensile strength and yield strength<br>Reduces maximum strain and cold-forming ductility   |
| Phosphorus | Decreases ductility and notch toughness                                                                         |
| Sulphur    | Decreases ductility, weldability and notch toughness                                                            |
| Nitrogen   | Reduces resistance against brittle fracture                                                                     |
| Hydrogen   | Reduces ductility and weldability                                                                               |
| Copper     | Improves corrosion properties                                                                                   |

For hull construction, the International Association of Classification Societies (IACS) Common Structural Rules (CSR) give detailed guidance as to the class and grade of steel to be used, depending on the thickness of the individual member, its exact location and the nature of the load it is subjected to (Table 1.8). More precisely, whether the member is within  $0.4L$  from the midship section, and also whether it forms part of the *primary*

Table 1.7 Mechanical properties of shipbuilding steels [12].

| Class                | Grade              | Yield stress<br>(N/mm <sup>2</sup> ) | Tensile<br>strength<br>(N/mm <sup>2</sup> ) | Elongation<br>5.65√S <sub>0</sub><br>A <sub>5</sub> (%) min | Charpy V-notch tests |                            |        |
|----------------------|--------------------|--------------------------------------|---------------------------------------------|-------------------------------------------------------------|----------------------|----------------------------|--------|
|                      |                    |                                      |                                             |                                                             | Test temp<br>(°C)    | Average energy<br>min. (J) |        |
|                      |                    |                                      |                                             |                                                             |                      | Long.                      | Trans. |
| Ordinary<br>strength | A                  | 235                                  | 400–490                                     | 22                                                          | –                    | –                          | –      |
|                      | B                  |                                      |                                             |                                                             | 0                    | 27                         | 20     |
|                      | D                  |                                      |                                             |                                                             | –10                  | 27                         | 20     |
|                      | E                  |                                      |                                             |                                                             | –40                  | 27                         | 20     |
|                      | AH 32 <sup>3</sup> |                                      |                                             |                                                             | 0                    | 31                         | 22     |
| Higher<br>strength   | DH 32              | 315                                  | 440–590                                     | 22                                                          | –20                  | 31                         | 22     |
|                      | EH 32              |                                      |                                             |                                                             | –40                  | 31                         | 22     |
|                      | AH 36              |                                      |                                             |                                                             | 0                    | 34                         | 24     |
|                      | DH 36              | 355                                  | 490–620                                     | 21                                                          | –20                  | 34                         | 24     |
|                      | EH 36              |                                      |                                             |                                                             | –40                  | 34                         | 24     |

Table 1.8 Material grades [12].

| Thickness <i>t</i><br>(mm) | Material class |       |       |
|----------------------------|----------------|-------|-------|
|                            | I              | II    | III   |
| $t \leq 15$                | A, AH          | A, AH | A, AH |
| $15 \leq t \leq 20$        | A, AH          | A, AH | B, AH |
| $20 \leq t \leq 25$        | A, AH          | B, AH | D, DH |
| $25 \leq t \leq 30$        | A, AH          | D, DH | D, DH |
| $30 \leq t \leq 35$        | B, AH          | D, DH | E, EH |
| $35 \leq t \leq 40$        | B, AH          | D, DH | E, EH |
| $40 \leq t \leq 51$        | D, DH          | E, EH | E, EH |

structure, the *secondary structure*<sup>4</sup> or is considered to be a special item, subjected to more severe loading. From Table 1.7 it is evident that as the thickness is increased, so do fracture toughness requirements.

Indeed, for a specimen under mode *I* loading with a tensile stress that develops normal to the crack, tests have shown that fracture toughness decreases as the thickness is increased.

### 1.2.5 Modes of Failure

Failures in ship structures can be classified as *major*, involving the entire hull girder, thereby leading to loss of the vessel; or *minor*, involving a single structural member or a

<sup>3</sup> The letter *H* designates higher strength, and the number is the yield stress expressed in kgf/mm<sup>2</sup> (1kgf ≡ 9.81 N).

<sup>4</sup> These terms are discussed in more detail in Section 1.3 and in Chapter 10. The rules give details as to the appropriateness of material class. 'Special' items are considered to be the sheer strake and the stringer plate of the strength deck, deck strakes i.w.o. longitudinal bulkheads, strength deck plating in way of hatch openings, the bilge strake and longitudinal hatch coamings [12].



**Figure 1.10** Major failures involving hull girder collapse.

limited number of members. In this case overall loss or incapacitation of the vessel does not take place.

Major failures are generally complex events that involve more than one failure mode, such as extensive elasto-plastic buckling, deep plastic collapse, fatigue, fracture and weld tearing. In the majority of cases when a ship is lost at sea, it is not possible to verify events in order to understand how collapse took place. There exist, however, a number of cases such as those illustrated in Figure 1.10 that have enabled investigators to understand what happened and what the prime cause was. Of most interest to the structural designer are failures that are due to inadequate design, from which useful lessons can be learnt. It has to be said that these are rare; at least they are rarely important enough to be documented in public. Two occasions that involve inadequate structural design are:

- a. The design of strength members in the cargo tanks of the first-generation very large crude carriers (VLCCs) (early 1970s). Shipyard design offices and classification societies at the time relied on extrapolating the empirical rules that were used up to that time for existing ships, which were much smaller. The result was inadequate strength of the transverse members, which led to local buckling collapse. This could have had even more serious consequences.
- b. The use of high-strength steel in second-generation VLCCs. High-strength steel permits the use of lighter scantlings. However, as a result, the stress range increases accordingly. This leads to a reduced fatigue life, and a large number of cracks during the early stages in the life of second-generation VLCCs were discovered.

The important lesson that the maritime industry has learnt from failures such as these is that when innovation or departure from well-established practice is contemplated, it is necessary to resort to engineering mechanics methods that have a firm theoretical foundation. These can be either purely mathematical such as those described in the present text, measurements in situ, computational methods or a combination of these.

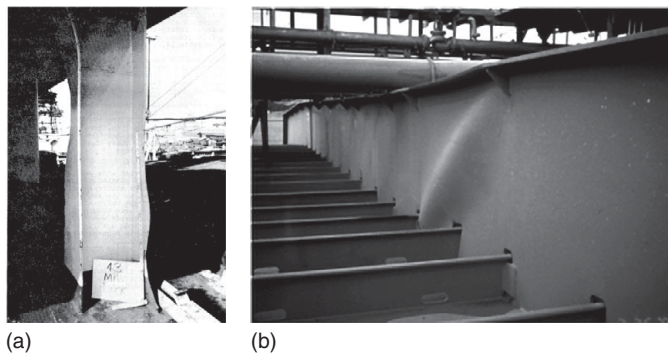
Table 1.9 includes a list of major problems that have been faced and solved in the design and operation of ultra large ships that were built during the second half of the 20th century. They include structural as well as non-structural problems. We note that expertise from a

Table 1.9 *Technical challenges related to the design of ultra-large ships [22].*

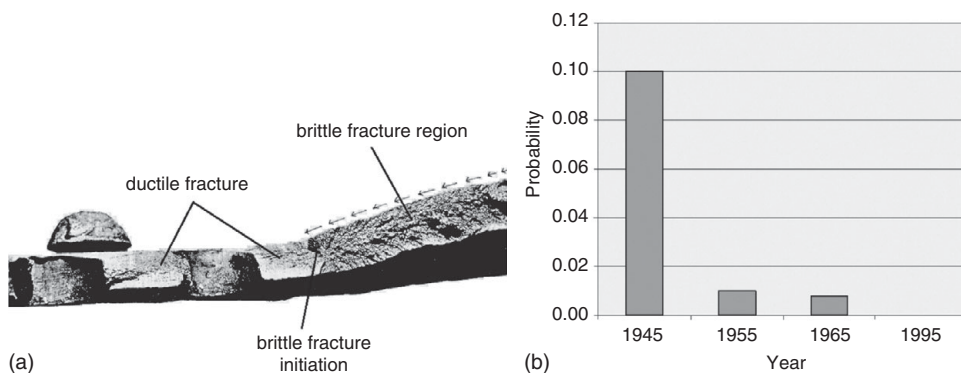
| <i>Oil tankers</i>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <ul style="list-style-type: none"> <li>a) Failure of transverse frames in cargo tanks solved by measurements and stress computation</li> <li>b) 300,000 tonnes dwt with high-strength (HS) steel: early fatigue cracking solved by fatigue tests, detail new designs</li> <li>c) 550,000 tonnes dwt: springing phenomenon solved by ship behaviour and structural response computation verified by hull stress monitoring</li> </ul>                                                                                                                                                                                                                                                                             |
| <i>Bulk carriers</i>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |
| <ul style="list-style-type: none"> <li>a) First generation: lamellar tearing at bulkhead foot solved by steel plate testing requirement (Z-grade plating)</li> <li>b) Hatch coaming and hatch cover stiffness: hold tightness solved by hatch coaming deformation computations</li> <li>c) Ballast in cargo holds: sloshing and damages solved by model tests and upper tank shape design</li> <li>d) Fatigue cracks and domino effect: shell brittle fracture solved by stress computations, fatigue and crack propagation studies</li> <li>e) Fast loading by gravity (16,000 metric tonnes/hr): bottom pressure determined by theoretical calculations and impact structural response computations</li> </ul> |
| <i>Containerships</i>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |
| <ul style="list-style-type: none"> <li>a) Large open deck: torsion and fatigue problems arising in hatch corners solved by measurements at sea, then stress computations</li> <li>b) Wave impacts: slamming, slapping, green water solved by hydrodynamic computations, hull monitoring</li> <li>c) Dynamic wave loads: hull girder springing, whipping solved by stress computation and fatigue verification</li> <li>d) Motion accelerations: on deck container lashing solved by load and stress computations, lashing design</li> <li>e) Propulsion power: shaft alignment, rudder erosion solved by elastic alignment, rudder shape and material</li> </ul>                                                 |
| <i>Cruiseships</i>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |
| <ul style="list-style-type: none"> <li>a) Superstructures: hull girder deformation loads solved by structural stress computations</li> <li>b) Large wide spaces: structural discontinuities solved by structural computations</li> <li>c) Large shell opening: structural discontinuities solved by structural computations</li> <li>d) Passenger comfort: reduced vibration, noise solved by structural computations (finite element studies)</li> <li>e) Propulsion: increased manoeuvrability requirements provided by pods</li> </ul>                                                                                                                                                                        |

number of fields has been drawn upon to provide permanent solutions to these problems that in certain cases are quite complex.

*Minor* failures, on the other hand, arise from any one of a large number of causes and result in plastic bending, elasto-plastic buckling, fatigue and/or fracture of one or more members. In ship structures minor failures do not cause overall collapse of the hull girder. This is because the structure is highly redundant, since loads are redistributed amongst neighbouring members and are thus able to be sustained. Figure 1.11 shows two cases of buckling that involve individual structural members. In both cases the cause was overloading. In the first case dynamic loading of the hull girder was transmitted by the vertical



**Figure 1.11** Buckling collapse of structural members (minor failures). (a) Compressive buckling of stanchion. (b) Shear buckling of deck web.



**Figure 1.12** Ductile and brittle fracture. (a) Liberty ship plating [5]. (b) Probability of occurrence of brittle fracture [18].

stanchion from the deck below to that above. In the second case it is likely that excess vertical load was applied to the transverse deck beam by the piping as a result of inertial accelerations during heavy seas. This led to shear failure of the web that, as noted, is not stiffened.

In both cases the members were not designed to withstand the loads that led to their failure. We note that buckling is elasto-plastic, so that the members have collapsed and cannot sustain any further load. The repairs required thus involve cropping and renewal. Furthermore, since the excess load is attributable to environmental factors and is not the result of normal wear and tear, to avoid repetition of failure, the structure will have to be redesigned.

An altogether different type of failure is illustrated in Figure 1.12a, which shows a portion of the shell plating of a Liberty ship. On the left-hand side of the section two rivet holes are visible. Between the two holes and also on their right-hand side the material has failed in a ductile manner. From the location to which the arrows point the material has failed in a brittle manner, as evidenced by the herringbone pattern and the rough surface. This particular type of brittle fracture is now of historical interest, given material quality has

improved drastically since the time that these fractures occurred. Figure 1.12b shows the dramatic reduction in the probability of occurrence of brittle fracture during the second half of the 20th century. The figure for 1995 is approximately 0.0012, which is one order of magnitude lower than that for 1965. It has to be said that tearing may still occur, mainly as a result of excess dynamic loading in severe weather conditions combined with a weakened structure as a result of corrosion.

### 1.3 A Systematic Approach for Ship Structural Problems

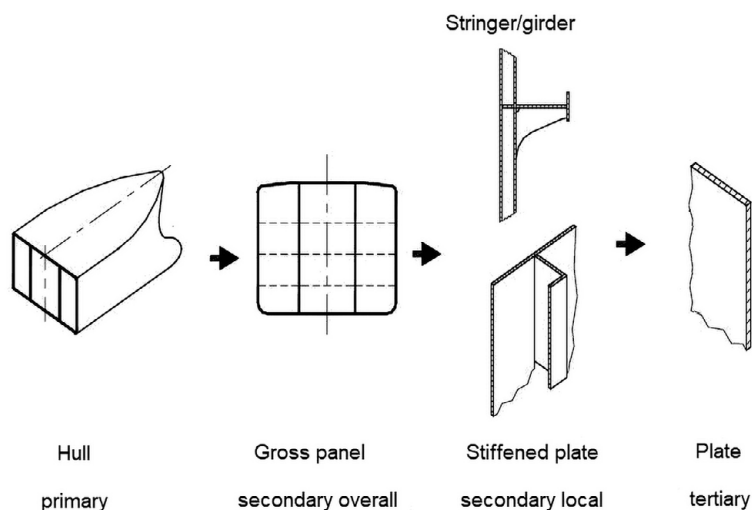
A first impression of the various types of ship structural arrangements was gained from Figure 1.4. Our objective is to be able to perform strength analyses of the entire hull girder as well as of each and every individual structural component. However, in the case of individual components, it is not possible to do this directly because of the complex geometry and the nature of the applied loads. The task has to be broken down into a number of stages, or levels of analysis. This makes it possible to understand the role and contribution of individual members as well as major sections of the hull girder such as transverse frames, bulkheads, decks and so forth.

#### 1.3.1 A Top-Down Approach in Ship Structural Analysis and Design

Modern ship structures are the result of progressive evolution, with past experience acting as a guide. It is only relatively recently that an in-depth understanding of structural behaviour and how individual members interact with each other has become possible. When ships grew in size on an unprecedented scale after the Second World War, strength problems arose, and it became apparent that a proper understanding of structural behaviour is needed, based on engineering principles. Structural arrangements in use today have in many cases been chosen on the basis of experience rather than analysis. Nevertheless, the means available to study structures today, which include analytical as well as numerical techniques, have proven invaluable in both analysis and design. In many cases they have reaffirmed past choices, whereas in others it has become apparent that new solutions are required.

It is possible to perform a *multi-level assessment* of the structure of a ship in more than one way, depending on the aim of a particular study. If the study is limited to a prediction of overall response, a simplified structural model of the ship, or part of it, is sufficient. In such a model, only essential features are retained. In some other cases, information may be needed for detail design and a *top-down* approach is followed.

Alternatively, the study can be initiated at the level of a component and then built up in a sequential manner, eventually encompassing the entire vessel. This is termed the *bottom-up* approach. The two approaches have different aims and are complementary in that results obtained from one assist in the other. The essential information needed when a particular member is designed concerns the nature of the loads that act on it and the manner in which it is supported by the adjoining structure. Once answers to these questions are available,



**Figure 1.13** The top-down approach in ship structural analysis and corresponding levels [7]. Reprinted courtesy of Det Norske Veritas, Høvik.

form, materials and scantlings can be determined. This requires an understanding of loading at every level as well as that of load transmission mechanisms.

In the design of ships for longitudinal strength, the traditional approach involves analysing a typical *transverse section*. This achieves economy of effort, as the structural arrangement is duplicated to a significant extent along the length of the ship. Therefore, if the effort is concentrated on a critically loaded section whose scantlings are then extended sufficiently in the longitudinal direction, an inherently safe design will, in theory at least, result. This has to be supplemented by strength calculations for the fore and aft ends, as their layout and loading are different from those of the wall-sided, cargo-carrying compartments.

Figure 1.13 shows typical components of the structure that are studied at different levels. Before proceeding to identify different levels, it is necessary to identify the different types of response that may arise. For example, when considered in its entirety, the hull girder behaves as a beam. However, at a local level, the behaviour can be modelled as a grillage, as an assembly of panels, as a stiffened plate or else as an individual member. A successful subdivision is thus possible once the characteristic behaviour of particular subunits has been identified. In Figure 1.13 the hull girder is subdivided into major components such as the transverse bulkhead shown here, and following this into the typical members of which it consists, such as stiffened plate members. At the most detailed level, the behaviour of an individual plate that is supported by the orthogonal stiffening system is studied.

Other ways of subdividing the structure are possible and indeed are used. Major subsections or modules such as a portion of the midship region that extends fore and aft of an entire cargo compartment can be studied, as is done in finite element analysis. Another example is a complete superstructure, which consists of several decks and related appendages. These are subdivided into their major components such as decks, side shell structure and bulkheads.

In order to gain a complete picture of the response at one particular level, it is necessary to sum the effects at all higher levels. For example, when studying stiffened plate behaviour, we may need to determine beforehand the behaviour at the hull girder level and at the major (gross panel or grillage) component level, inasmuch as these affect local behaviour. When studying a stiffened plate, it is assumed that its boundaries are rigid, although in reality this is not the case. The effect of finite boundary stiffness is taken into account when the analysis is performed at the immediate higher level, such as that of the deck transverses, which in turn are attached to longitudinal girders and the side shell structure. Therefore, as we consider the structure in greater detail, it is necessary to have results for stresses and deflections at all higher levels. This is the underlying justification for a top-down approach in the study of ship structures.

### 1.3.2 Structural Modelling and Models for Global Strength Assessment

Structural engineers make use of *structural models* that are selected in part on the basis of past practice, although it is always necessary to have an understanding of the suitability of the model and its limitations. Needless to say, the accuracy of the results will depend in each case on the suitability of the chosen model. Therefore, the need for an understanding of the mechanics of the response and the selection of a suitable model cannot be overemphasised.

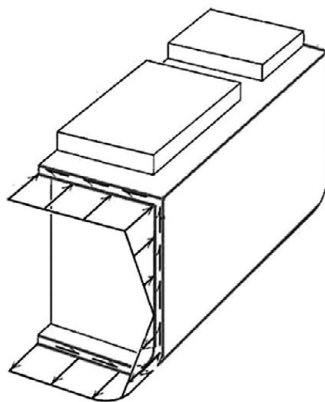
A structural model is an abstraction created in order to focus on a particular part or aspect of the behaviour of a structure whilst at the same time enabling a mathematically tractable solution of the problem to be obtained. The development and use of structural models must be based on an understanding of the behaviour of the particular structure or structural component under the specified loading conditions.

Many different structural models have been developed and are in use. In the case of ship structures, it is necessary to differentiate between global and local strength considerations.

When considering global strength of ships, the most important structural model in use in the case of longitudinal bending is the *linear elastic beam* (Figure 1.14). The analogy with beam behaviour is based on the form of ship hulls and the distribution of the primary loads.

In linear elastic beam theory, due account is taken of the longitudinal (axial) stresses along the length of hull girder and within each transverse cross-section, but the effect of shear stresses on the longitudinal stresses is not included (Chapter 6). The contribution of shear stresses varies along the length of the hull girder, and maximum values are expected at the quarter-length positions. Shear stresses are also important in ships that are fitted with longitudinal bulkheads. It has to be added that the linear elastic (Euler–Bernoulli) beam model has been validated from full-scale measurements and has widespread use in the marine industry.

A more accurate structural model, which does allow for the effect of shear stress, is the *Timoshenko beam*. Timoshenko beam theory is presented in Chapter 8, which deals with hull girder vibration. This is a type of response that necessitates the use of a more refined beam theory because linear beam theory is unable to predict the higher mode frequencies of vibration with sufficient accuracy.



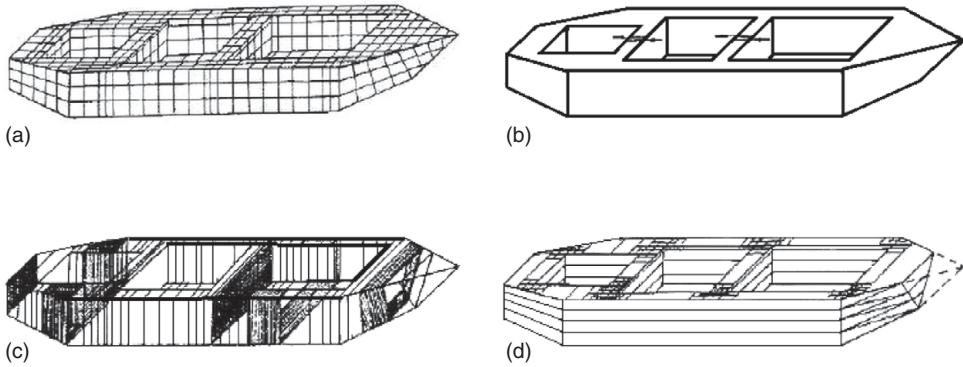
**Figure 1.14** The hull girder in longitudinal bending can be modelled as a beam [11].  
Reprinted courtesy of the Society of Naval Architects and Marine Engineers.

Other than longitudinal bending the other important distortion mode of the hull girder is due to *torsion*. This is important in the case of open-deck ships such as container ships (Chapters 6 and 7). In this case also the hull girder is treated as a beam, although a number of complications arise that need to be accounted for in order to obtain meaningful results. The first point to make is that it is necessary to consider the entire hull girder and not rely on the analysis of a typical cross-section, as is done in longitudinal bending analysis. The reason for this is that the geometry of the hull girder varies continually along the length of the ship, as does the distribution of the loading (torque). In the torsion theory of beams, the important basic assumption is that the transverse cross-sections along the length of the beam do not distort in their plane, nor do they distort in the direction normal to their plane. On this basis a *linear theory of torsion* is developed (Saint-Venant theory), and this provides a first-order analysis of torsion behaviour (Chapter 6).

In real structures, however, the assumptions upon which linear torsion theory is based do not hold, and in the case of ships it is necessary to consider the distortions of transverse sections. These out-of-plane distortions are termed *torsional warping*, and to this end *warping torsion* theory has been developed, with various degrees of sophistication (*Vlasov beam* and *beam-shell theories*). Warping arises in general in prismatic sections that are subjected to torque, and if the ends of the structure are free, *free warping* will arise. In the case of ship hull girders, however, the ends of the structure are attached to torsionally stiff regions such as the fore and aft ends and the engine-room spaces, all of which are enclosed. As a result, *constrained warping* arises, and to this end several theories have been advanced (Pedersen beam model, Senjanović model). This question is discussed in Chapter 7.

All of the above beam theories that are used to represent the global behaviour of ships neglect local effects. The stresses predicted by beam models are thus *nominal stresses*, to which local stresses need to be added.

In addition to the beam theories discussed above, the hull girder can be modelled using numerical techniques, the most important of which is the *finite element method* and its



**Figure 1.15** Structural models for hull girder analysis [29]. (a) Finite element model. (b) Discontinuous beam model. (c) Module-element model. (d) Finite strip/finite element model.

variants. Because finite element modelling is laborious and time consuming, a variety of simplified models have been developed. Examples are presented in Figure 1.15 and discussed in Chapter 13.

## 1.4 The Practice of Ship Structural Design

We shall now turn our attention to the question of how ship structures are designed in practice. An overview of industrial practice will be given in the remainder of this chapter whereas detailed ship structural design procedures are described in Chapters 10 and 14.

Ships are designed by entities that vary in size, complexity and degree of sophistication. First there is the merchant shipbuilding industry that is served by yard design offices, consultants and owners' design teams. Second there are national bodies such as navies that have at their disposal dedicated teams of experts and research teams that may or may not be directly employed by them. For organisations such as these, ship design, including structural design, is a major task that has to be conducted with a view to ensuring that defence requirements are successfully fulfilled – an issue that carries especial weight. The financial outlay for any government in such cases is considerable, and decisions have to be correct from the beginning, particularly since the lifetime of a new class of ship may extend to several decades.

### 1.4.1 Merchant Ship Structural Design

In merchant shipping the owner may range from a large multinational corporation that operates a large fleet to a small private owner who operates a few second-hand vessels and who may at one point in the life of his company decide to place an order with a yard for a new ship. The needs of owners are served in various ways:

- By forming or by using existing design teams from within their own organisations. These will have a deep understanding of owners' requirements and can transfer available

experience into a properly drafted design specification, which can then be negotiated with a shipyard.

- By appointing naval architectural consultancies that can perform complete or part design studies as well as supervise construction.
- By negotiating directly with a shipyard on the basis of one of the standard designs that may be on offer. This is a practice that is becoming more common, especially as designs have become more sophisticated and the volume of regulations has increased in recent years. Yards are increasingly reluctant to divert from their own specifications for a variety of reasons. If, however, an owner intends to place an order for a series of ships, then their negotiating power increases at the technical as well as financial levels.

Stripped down to its bare essentials, for the majority of merchant ships, the essential task is to produce a design of the hull structure that will satisfy the current classification society rules and other statutory requirements given:

- Ship type
- Main dimensions
- Operating range
- Carrying capability (cargoes, passengers)

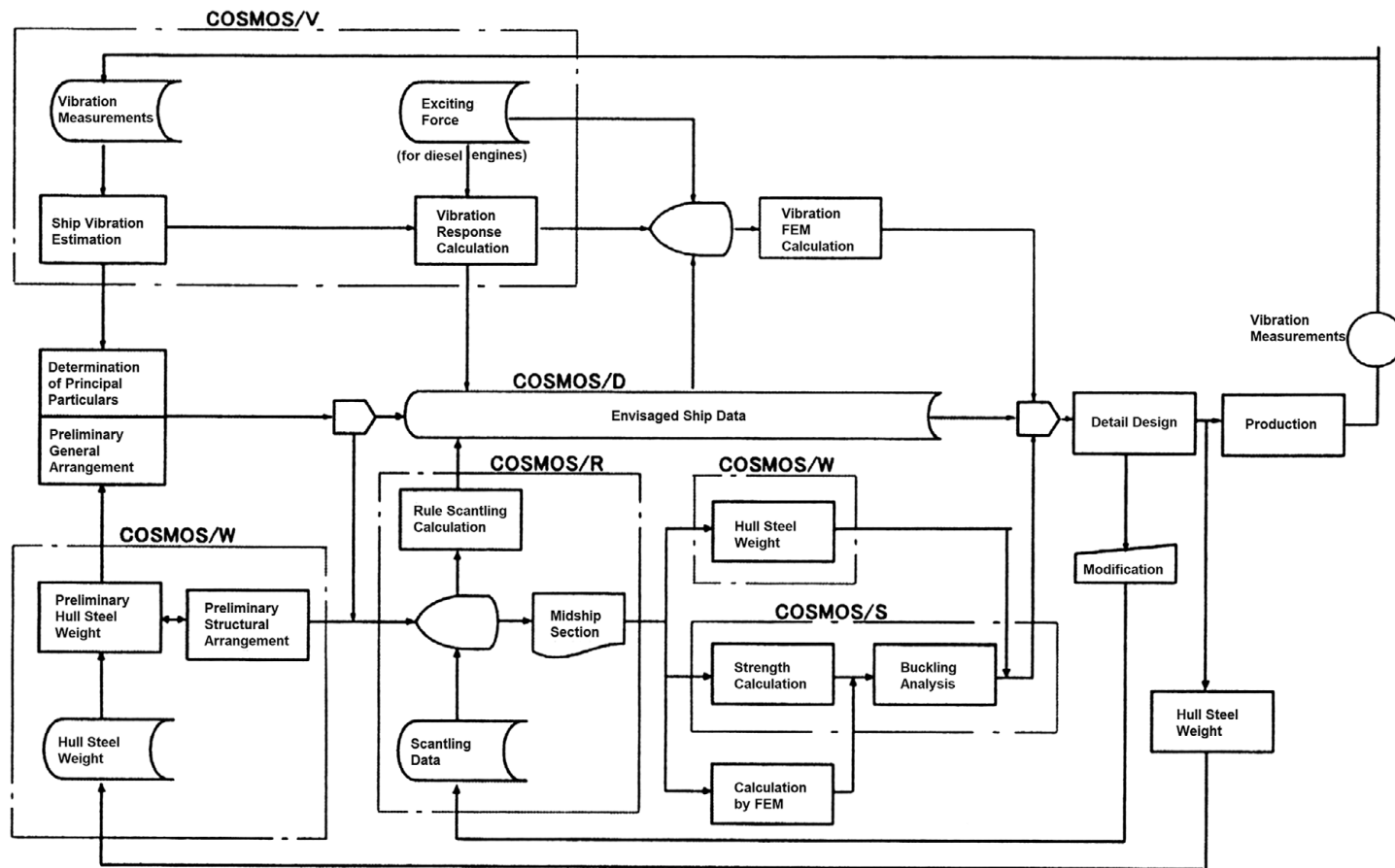
As the design proceeds, the structural design group will interact with the other members of the design team so that it becomes necessary to introduce corrections. The tools that are available to the structural designer vary in accuracy and complexity, so a judicious use of methods at every stage of the design is necessary in order to devote available resources efficiently. Figure 1.16 shows how information flows in ship structural design in the design office of a major shipyard [18].

To illustrate how this question is faced by practitioners we shall give a brief account of the design procedure followed by a ship design bureau experienced in passenger and cruiseship design [23]. Structural design represents one component of the design process. In order to initiate structural calculations for a new design project, it is necessary to have an idea of the general arrangement, functions and capacities of the proposed ship. The design team relies on

- A reference ship design
- Available open literature and design studies
- In-house similar designs and studies

in order to initiate proposals.

1. The first task is to decide on space allocations, and this is done by preparing a rough, first-stage general arrangement. An important question is then to decide on the type of stiffening system to be used for each part of the section, following which the frame spacing is selected. These decisions are based on the reference vessel. The general arrangement plan can then be adjusted accordingly. For passenger ships and cruiseships, which have a multiple deck arrangement with complicated piping and other systems, it is convenient to use a transverse stiffening system for the side shell structure whereas the bottom structure and decks are longitudinally stiffened.



**Figure 1.16** Data flow between structural design modules of the COSMOS software procedure [18].

2. The spacing between web frames is chosen and is a multiple of the ordinary frame spacing. The positions of pillars and supporting bulkheads are then selected. Transverse bulkheads are arranged in place of web frames. Pillars are positioned below beams and/or longitudinal girders.
3. Deck longitudinal girders are introduced to reduce the unsupported deck area and are arranged in place of longitudinal stiffeners.
4. The watertight bulkhead system is selected bearing in mind subdivision requirements and the spacing of web frames.
5. Longitudinal bulkheads can then be introduced bearing in mind the spacing of deck longitudinal stiffeners and girders.
6. Finally, fire division bulkheads are arranged in accordance with the watertight bulkhead system.

Once this stage has been reached, it is possible to prepare a general arrangement plan. As is evident, it is necessary to introduce matters relating to the structural arrangement early on in the ship design process. In this way serious revisions of the general arrangement plan that would otherwise be needed are avoided.

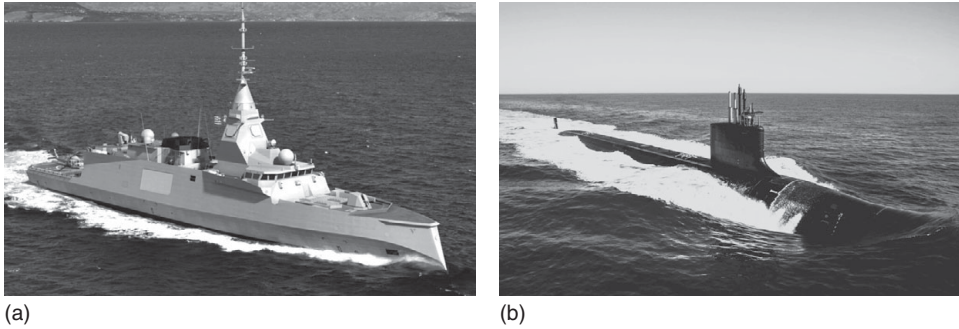
The process described up to this point consists essentially of a series of decisions concerning the structural arrangement of a new layout using a successful existing design as a basis. It is what we can term the *synthesis* of the design. Up to this point no calculations have been carried out. From this point on, however, it will be necessary to introduce calculations so that structural members are sized and their weight estimated. The weight distribution is important from the overall ship design perspective, since stability, trim and sea-keeping characteristics are directly affected. Apart from technical issues, weight also has a bearing on the cost of construction, a matter that is understandably of primary importance to the shipyard and the owner.

Weight reduction has a direct effect on material costs but not on labour costs. Construction cost depends on the type of structure, the degree of automation introduced in the fabrication process and the number of structural components. Structural arrangements ought to be simple, standardised as much as possible and with continuity. A successful general arrangement is one that permits a simple vessel to be constructed; a simple vessel is easy to repair and less prone to wear and tear.

During the initial design stage, weight estimation is carried out using a standard list of systems and items included (steel structure, outfitting, machinery, etc.). The first weight estimate is based on the general arrangement plan, the midship section plan and the ship specifications. These are used to perform direct calculation of areas and volumes, and together with data on existing designs, an initial weight estimate is obtained.

### 1.4.2 Warship Structural Design

Naval vessels are designed and built in order to replace older vessels that have exhausted their useful working life, become technologically obsolete or no longer serve the purpose



**Figure 1.17** Warship designs. (a) Belh@rra frigate (France). (b) Los Angeles class submarine (USA).

for which they were originally conceived. The opportunity is taken to incorporate in a new design lessons learnt from past practice as well as new technologies. However, a very important aspect of naval design is that it offers the opportunity to innovate by considering competing proposals that may differ radically from one another (Figure 1.17). This is not common practice in merchant shipbuilding. Innovation can touch upon all aspects of a new design, including structural arrangements and materials used.

This, however, has resulted in a much more complicated design and production process that has brought with it increased cost and time. Efforts have been made to manage design and production in more efficient ways. The US Navy has introduced project management techniques that have proven successful in a commercial environment, in an effort to reduce development time and cost. These are grouped under *systems engineering*, which, according to the International Council on Systems Engineering (*INCISE*), is defined as follows:

Systems engineering is an interdisciplinary approach that focuses on defining customer needs and required functionality early in the development cycle. It involves documenting requirements, then proceeding with design synthesis and system validation while considering the complete problem. By integrating all disciplines and specialty groups into a team effort, a structured development process is formed that proceeds from concept to production to operation [13].

Systems engineering is thus not a specific technique but a general approach that may be implemented using a number of methods. Of these the most relevant to ship design has proven to be *Concurrent Engineering* and *Integrated Product and Process Development (IPPD)* [6]. Systems engineering techniques have proven successful when the particular characteristics of the case to which they are to be applied have been correctly identified. Examples of successful application of concurrent engineering are the car industry, whereas IPPD has been used in the aerospace industry. Both of these industries are involved in the design and production of complex engineering products.

In order to implement a systems engineering approach in the maritime sector it is necessary to identify *stakeholders* that may be bodies or groups of individuals that will

be directly or indirectly involved with the ship and thereby in its operation and performance throughout its working life. In the case of merchant ships, stakeholders are owners, designers, shipyards, crews, charterers, passengers and insurers. Bodies that can also be considered as stakeholders are classification societies, flag states and port authorities. In the case of naval ships, stakeholders are the naval command that extends from the vessel's commanding officer to the Joint Chiefs of Staff, crew, designers, shipbuilding yard, subcontractors, equipment manufacturers and suppliers, and so forth.

The functional requirements of stakeholders are expressed in non-technical terms, such as needs and expectations. Systems engineers then transform stakeholders' requirements into technical requirements. The most important issues that differentiate a systems engineering approach are that all stakeholders' requirements are addressed early on – that is, from the initial design stage – which is most amenable to radical changes and also that the entire life cycle of the product is addressed.

Systems engineering approaches thus offer advantages in the case of novel designs and can be effective in an environment in which there is structured interaction between stakeholders. The traditional (design spiral) approach is suitable in the case of parametric-based design studies.

A comparison of the naval with the merchant ship structural design procedure shows that the techniques used are similar but not the same (Figures 1.18 and 1.22). One important difference in the design specification concerns the load profiles of these two categories of ships. Warships have to be able to operate under severe weather conditions without any reduction in operational ability. Other differences are:

- Their speed profile is significantly more demanding than that of merchant ships.
- Hydrodynamic loading is different due to differences in hull form.
- They need to have an acceptable standard of survivability under military threats.
- Warships have to be able to be replenished at sea from other ships and also rely on vertical replenishment using helicopters.

It should be added, however, that warship designers are now drawing upon the expertise of the merchant shipbuilding industry. Until recently, merchant ship and naval ship design standards developed in parallel. An important difference between them is that in the first case rules focus on standard ship types whereas in the second they focus on applications to specific cases, especially with regard to loading, as mentioned earlier. Navies are now collaborating with classification societies and have drafted rules for the construction and maintenance of warships. This is in contrast to past practice, in which they retained in-house technical expertise that relied on their own research, the most advanced ship design methods available as well as their own operating experience. The improvements in the theoretical basis of the rules as well as merchant ship design practice means that a large part of the design effort can be carried out using commercially available expertise. This has enabled governments to cut costs and at the same time to expand the activities of entities such as classification societies, designers, commercial shipyards and so forth. Needless to say, there remain many technical and operational aspects that are of exclusive interest to naval designers.

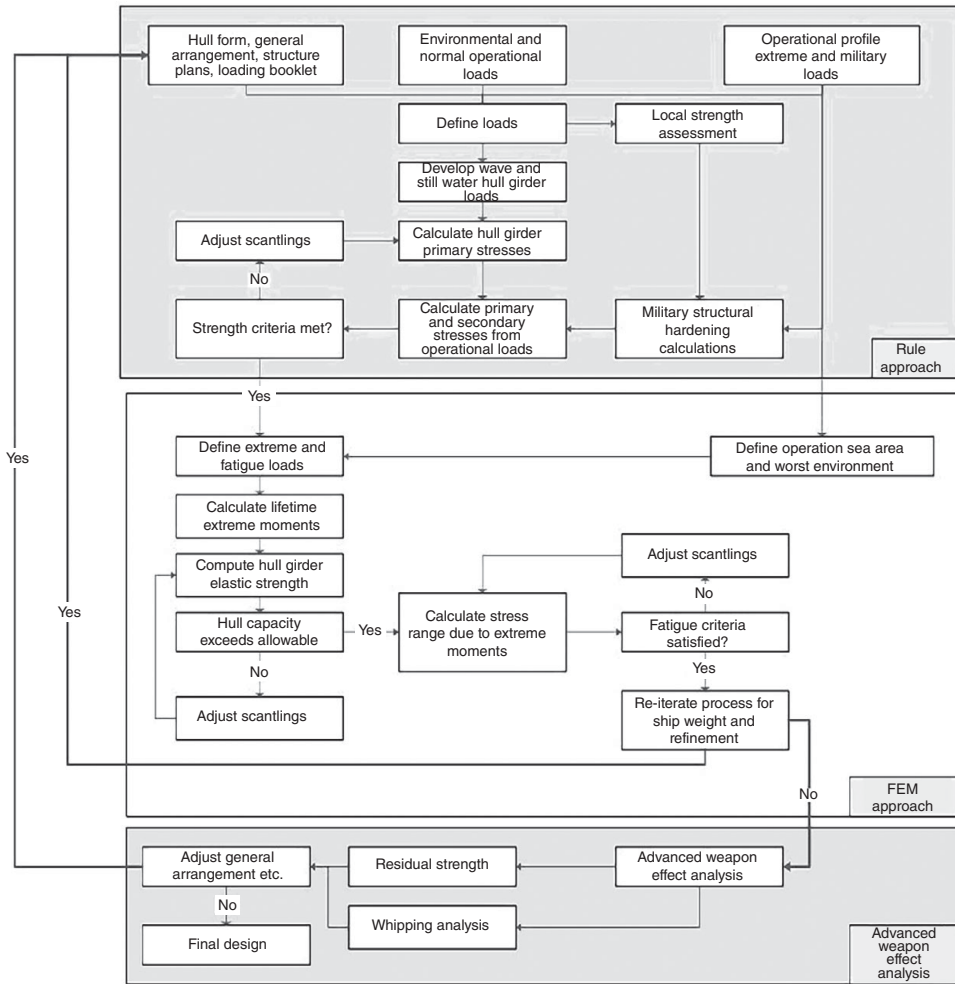
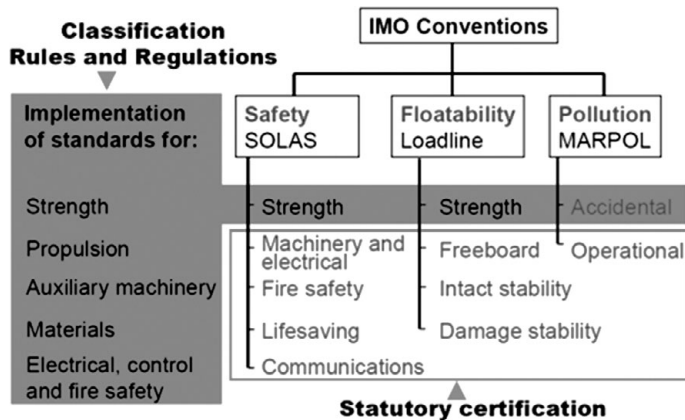


Figure 1.18 Warship structural design procedure [1].

### 1.4.3 Classification Societies and Their Evolving Role

For the overwhelming majority of merchant ships the structure is designed and constructed in accordance with the rules of classification societies. It is useful to reflect at this point on the role of the class society today, which is not as clear as it may appear at first glance. To appreciate the changes that have occurred over time it is necessary to go back to the beginning. How Lloyd's Register started out is well known; in the late 18th century, insurers who wished to provide cover needed to know the quality and seaworthiness of individual ships in order to assess the risk involved in each case [20]. The Register Society was thus formed (later Lloyd's Register of Shipping) and was allocated the task of grading the condition of ships and of granting them a class. Originally five classes were available: A, E, I, O and U



**Figure 1.19** Relationship between class and statutory requirements [8]. Reprinted courtesy of Elsevier.

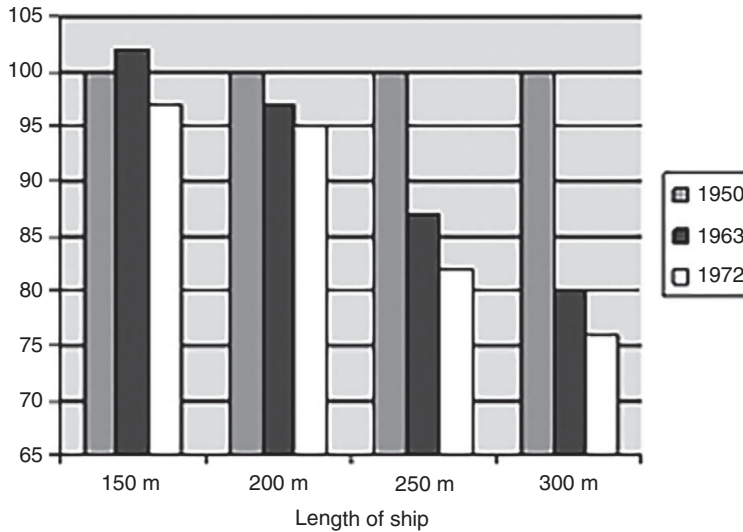
with a numeral indicating the number of years that a ship would remain in that class. For example, the *Cutty Sark* was granted *16A1* in 1869 [24].

Rules for ship construction and maintenance were first issued by Lloyd's Register in 1834 in order to enforce acceptable quality standards. At no time was there involvement of any governmental authority, and thus classification remained a purely commercially oriented activity, carried out by a not-for-profit organisation. During the 19th century a number of other classification societies were founded. Their number has steadily increased so that at the beginning of the 21st century there are approximately 50 societies in as many countries around the world.

In 1870, the reference by Lloyd's Register to specific terms in each class was withdrawn for iron ships and the use of the character *100A1* was introduced as the highest class for iron vessels. Thus the classification system whereby a ship was assigned to a particular class was replaced by acceptance or failure to attain a certain standard, so that in a sense, the term 'classification' became a misnomer. Insurers nowadays will rarely be willing to cover a ship that does not have valid class certificates. Risk (and hence premium) is quantified on the basis of other, non-technical factors such as insured value, type of vessel, owner's track record, fleet size and age profile.

In 1835, Lloyd's Register introduced rules concerning the minimum freeboard of ships, the so-called Lloyd's Rule. In 1876, this became a statutory requirement for UK-flagged merchant ships. Over time, national administrations began to delegate survey and certification tasks to classification societies, and this number has continued to grow. In this way the role of class societies has expanded a great deal. At the same time statutory requirements have also increased, making it necessary for both parties to ensure compatibility between rules and statutory requirements (Figure 1.19). The SOLAS regulations require that all ships be classed, so that classification is now also a statutory requirement. Class, in turn, also requires ships to have valid statutory certificates.

Since the middle of the 19th century, technological advances have changed the face of shipping. Classification societies have had to be at the forefront of developments in order to



**Figure 1.20** Percentage reduction in oil tanker section modulus requirement over time [18].

be in a position to assess the quality of construction and thus of inherent safety. To succeed in this they have expanded their research and development activities to such an extent that they nowadays retain a large concentration of technological expertise, with which the majority of owners and individual yards cannot compete. As a result, they play an increasingly important role in technological innovation in the maritime industry. There have been a number of fields in which even the largest shipowning companies do not possess suitable resources or expertise.

It is also necessary to note that the original purpose of construction and classification rules was to ensure safety of the ship, and as such they were not intended to play the role of ‘design manuals’, for use by yards and consultancies. However, the scale and complexity of the design and construction process in conjunction with the rapid technological developments that have taken place over the past two centuries have made it difficult for builders and owners to maintain a fully independent viewpoint with respect to design and construction practice. As a result, the influence that rules have had has extended beyond ensuring the safety of seafarers and cargoes.

In recent years, there has been intense competition between classification societies. Throughout this period, advances in structural analysis and ship design permitted reductions in scantlings (Figure 1.20). This fact, in conjunction with a number of ship losses, led owners to question whether their ships were being built as robustly as before. The reduction in scantlings meant that yards could build ships at a lower cost. At the same time the fees paid by yards to class societies reduced as a result of market competition. The end result was that class societies did not have the resources to devote to plan approval and new construction supervision as before. Transfers of class also took place in the case of aged ships which were in need of costly repair work, since the standards of acceptance varied, and continue to do so, between different class societies. A number of environmental

disasters occurred, and the publicity they received in the media created political pressure for change. The maritime industry responded to this situation primarily through initiatives of the IMO and IACS, and in 2003 the Maritime Safety Committee approved the introduction of *Goal-Based Standards (GBS)*. The aim of GBS is to ensure safety at sea through a multi-level (tier) system that addresses not only construction standards but also safety of seafarers and passengers (*SOLAS*). In principle, the role of class societies in preparing rules for construction remains intact, although the rules themselves are assessed against the safety objectives set by the IMO. The activities of the International Association of Classification Societies (IACS), members of which currently are 10 societies, have been all-important, in that the society has already introduced common structural rules for oil tankers and bulk carriers, thereby leading to a unification of minimum standards at a global level for these types of ships. Individual societies now have to introduce rules that are in compliance with agreed standards laid down by their own umbrella organisation; they also have to be in compliance with IMO requirements.

When it comes to everyday activities such as periodical surveys and other types of inspections, it has to be remembered that classification societies assume their historical role, which is to limit themselves to assessing the condition of the ship. The responsibility for any mishap or incident lies solely with the owner, as the classification society does not assume any liability. We thus see that, on the one hand, class has an overwhelming influence on ship design, construction and the standard of maintenance, and on the other it is the owner who is responsible in the case of any untoward event.

#### 1.4.4 IMO Goal-Based Standards

Safety at sea, in a general sense, is the most important concern of the International Maritime Organisation (IMO). In 2004, a proposal was submitted to the IMO in which a radically new approach to ensuring safety at sea was advocated. According to this proposal, all activities related to maritime transport are integrated in such a way that safety at sea is served. The fundamental shift in the approach to safety from the status quo consisted of a process of integration of rules and regulations through the establishment of GBS (Figure 1.21). These do not specify the means of achieving compliance but set goals that allow alternative ways of achieving compliance.

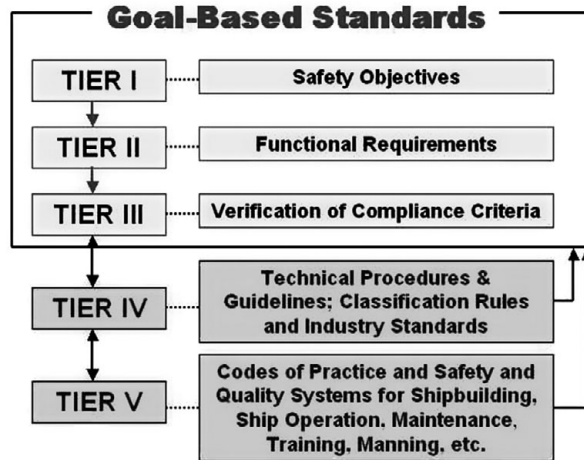
An example will serve to illustrate this approach. Consider the requirements for bulk carrier deck plate thickness. In a prescriptive regulation an expression of the type

$$t = f(L, s, z_s, \dots) + t_k \quad (mm) \quad (1.1)$$

is usually given, whereas in a goal-based regulatory environment the requirement would be given as:

“Deck plating should not fail during ship’s life of X years if operated in a Y (e.g. global) environment”

A number of equally acceptable rule formulations could be demonstrated to fulfil the specified objective, such as, for example:



**Figure 1.21** Goal-Based Standards according to IMO MSC 78/6/2. Reprinted courtesy of IACS, London.

- Minimum thickness with specified stiffener spacing, corrosion allowance and with defined inspection/repair intervals.
- A different minimum thickness without a corrosion allowance but with more frequent inspection intervals.
- A different minimum thickness with specified coating requirement, cathodic protection requirement and inspection intervals.

It is hoped, therefore, that classification societies will be able to explore in a much more free and creative manner the alternative paths to fulfil the goals that have been set, hopefully on the basis of rational analysis. This would be an improvement to current practice, which has been to compete by setting essentially different structural weight requirements, which correspond to different construction costs. These, however, rely on essentially similar strength formulations, which in the absence of transparency do not have a demonstrable scientific basis.

The implementation of GBS entails the fulfilment of the requirements of a series of levels (Tiers), as indicated in Figure 1.21. It is envisaged that such an approach will eventually encompass and integrate all activities that relate to the safety of ocean-going vessels. The upper Tiers (I, II and III) are the responsibility of the IMO whereas Tiers IV and V are implemented by classification societies, governmental authorities, etc. A compendium of relevant IMO texts is included in Appendix B.

#### 1.4.5 An Assessment of Rules and Standards

As mentioned in Section 1.4.3, there have been significant developments in the rules for ship construction. Table 1.10 summarises the methodologies used in rules published by

Table 1.10 Approaches used in selected ship structural rules for classification [15].

| Rule                  | Approach used         |                             |            |                  |                         |
|-----------------------|-----------------------|-----------------------------|------------|------------------|-------------------------|
|                       | Prescriptive          | Working stress              | LSD (LRFD) | First principles | Simulation-based design |
| <b>Merchant ships</b> |                       |                             |            |                  |                         |
| CSR                   | Min req. <sup>1</sup> | Gen. req. <sup>2</sup>      | Not used   | Optional         | Optional                |
| ABS                   | Min & gen. req.       | Req. spec vsls <sup>3</sup> | Not used   | Optional         | Optional                |
| BV                    | Min req.              | Not used                    | Gen. req.  | Optional         | Optional                |
| DNV                   | Min req.              | General req.                | Not used   | Optional         | Req. spec vsls          |
| LR                    | Min & gen. req.       | Not used                    | Not used   | Optional         | Optional                |
| <b>Naval ships</b>    |                       |                             |            |                  |                         |
| ABS                   | Min req.              | Not used                    | Not used   | Gen req.         | Optional                |
| GL                    | Min req.              | Not used                    | Gen. req.  | Optional         | Optional                |
| LR                    | Min req.              | Gen req.                    | Not used   | Optional         | Optional                |

<sup>1</sup> Minimum requirements: Scantlings (and strength) are to be at least equal to those required.

<sup>2</sup> General requirements: Requirements are to be satisfied as stipulated.

<sup>3</sup> Required for specific vessels: Tankers, bulk carriers and containerships with  $L > 150$  m.

several classification societies. It has to be said that changes are continuous and that there is a gradual shift away from prescriptive to first principles and simulation-based design.

Some brief comments regarding the approaches mentioned in the table are pertinent.

*Prescriptive* requirements stipulate that scantlings and strength requirements, generally expressed in terms of member thickness and section moduli, have to exceed specified minimum values. As such, a strength standard is guaranteed for each component of the structure. In fact, all rules are based on relatively simple concepts of structural engineering (beam theory, frame behaviour). In the *working stress* approach, scantlings are selected so that under normal operating conditions the stress that arises in each component does not exceed a specified value. Both of these approaches have a history of application in ship structures. *Limit state design (LSD)* or *load resistance factor design (LRFD)*, on the other hand, has been used in civil engineering applications and has only recently been introduced in ship structural design, although it has been in use in the offshore industry. It has a probabilistic basis and makes use of partial safety factors so that a consistent failure probability of all structural components is assured. A *first principles approach* aims at modelling structural response using rational criteria on the basis of certain simplifying assumptions with regard to load application (quasi-static wave loading etc). The stresses that result in a structural member are obtained using mechanics of materials theory.

*Simulation-based design* essentially consists of the development of a finite element model of a large part of the structure or of the entire structure. A series of specified load conditions are then applied to it, which permits the response to be assessed at a global, intermediate or local level for each load condition. It may involve interaction with environmental loads, in which case computational fluid dynamics software may also be used.

In this text we shall consider the response of the entire hull girder and in doing so will apply structural engineering concepts to analysis and design. Reference will also be made to probabilistic approaches (Chapters 9, 11 and 12). This will enable us to carry out a first-principles approach and also develop an understanding of the theoretical basis of classification society rules.

Rules and standards for the construction of engineering structures in general and ships in particular need to include, either explicitly or implicitly:

- An idealisation approach (structural model)
- A definition of loads (model or idealisation of loads)
- A definition of response
- Suitable safety factors

In [15] the comparison of rules included an assessment of the following:

1. Wave pressure loading, since this is the most important component of external loading and is subject to different interpretations and treatment. In general, the load on a structural member is based on adding hydrostatic pressure to wave pressure
2. Required minimum scantlings
3. Corrosion additions
4. Ultimate strength capacity of the hull girder

With regard to wave pressure loading, it was found that the design wave pressure:

- Varies between class societies
- Varies or may be constant over the flat of bottom
- Varies in way of the design draught waterline

Furthermore it was found that the safety factor is low throughout: that is, the applied pressure can be exceeded for deeper draught conditions. Results from this comparison study are summarised in Table 1.11.

The required minimum scantlings are prescriptive and based on load-stress-based rules. They are not related to load calculations and they overrule other requirements if necessary. An example comparison showed that for the thickness of the bottom plating of a 150-m ship with 800-mm frame spacing, requirements vary from 11 mm to 13 mm.

Corrosion additions for double bottom ballast tank plating vary from 3 mm down to 1 mm for merchant ships and 0.5 mm for naval ships. Hull girder longitudinal strength requirements were unified under IACS UR S11, and rules for bulk carriers and oil tankers have a common basis, following the publication by IACS of the Harmonised Common Structural Rules.

Of interest to the designer and the owner is the effect that the choice of rule has on the structure of a particular ship type, particularly its weight. Table 1.10 summarises findings for the application of different rules to the design of various ship types. Differences between these were found to be negligible. This is understandable, since these rules have been based on a large database of ships of these types and configurations. The Common

Table 1.11 Comparison study for the structural design of common ship types [15].

| Type of ship                        | Rules and software packages used                                 | Findings                                                                                                           |
|-------------------------------------|------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------|
| Small general cargo                 | DNV – NAUTICUS<br>GL – POSEIDON<br>BV – MARS<br>LR Naval – EXCEL | Small differences (<20%),<br>BV requirements lower than others. Corrosion addition requirements reduce differences |
| General cargo<br>$L > 90\text{ m}$  | DNV – NAUTICUS<br>GL – POSEIDON<br>LR Naval – EXCEL              | Very similar results                                                                                               |
| Bulk carriers<br>$L > 150\text{ m}$ | JBR<br>DNV – NAUTICUS<br>LR Naval – EXCEL                        | Very similar results                                                                                               |
| Oil tankers<br>$L > 150\text{ m}$   | JTR – NAUTICUS<br>GL – POSEIDON<br>BV – MARS                     | Very similar results                                                                                               |

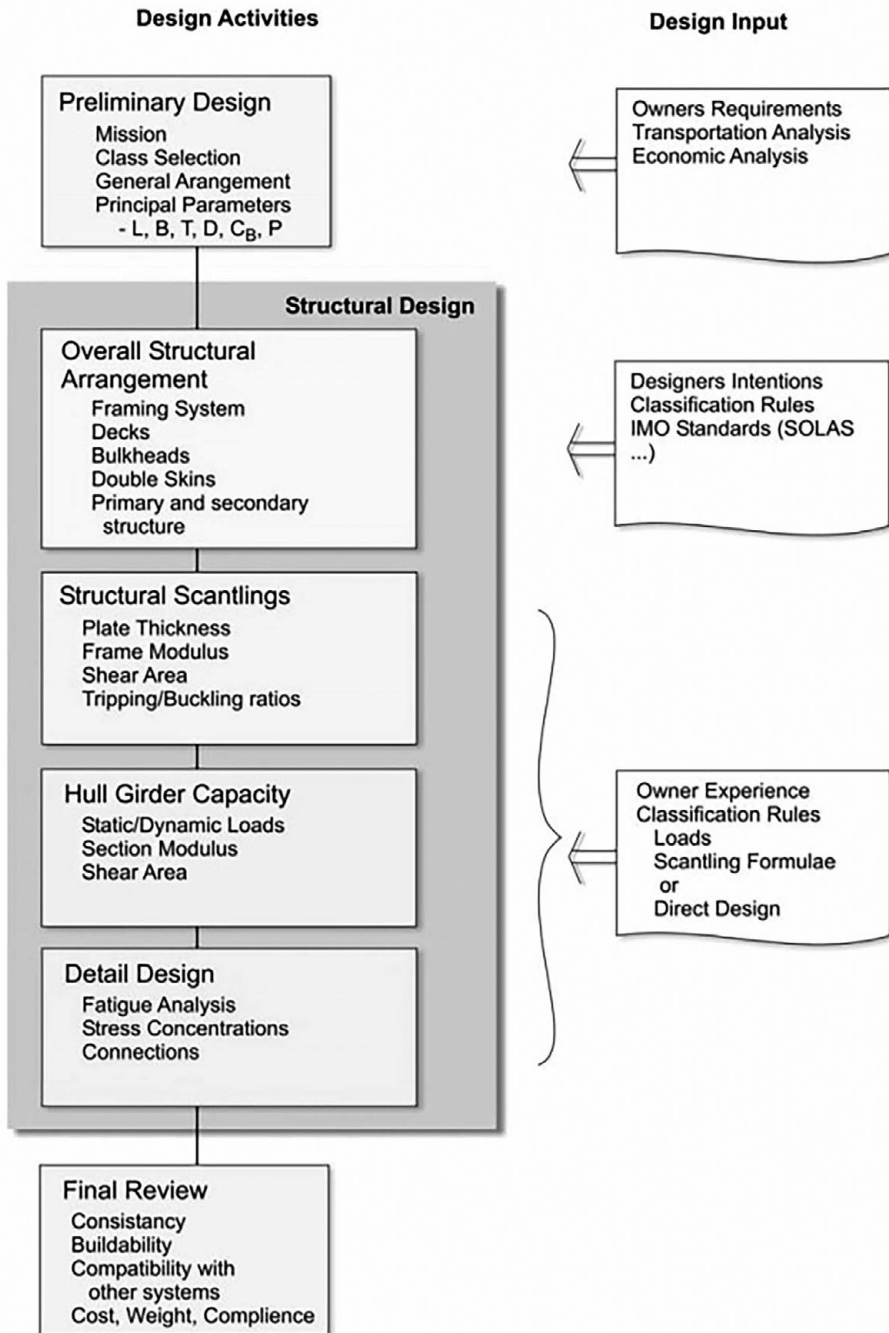
Structural Rules result in an increase in weight only through corrosion allowances – that is, scantlings requirements are essentially the same as in earlier rules. As a result, owners who wish to introduce a greater degree of *robustness*<sup>5</sup> in the structure will need to request that scantlings exceed minimum requirements or else introduce innovative arrangements and/or materials. As a final comment, it has to be said that the CSR, being particularly thorough and far-reaching, add complexity, and their interpretation requires a good understanding of structural mechanics, in contrast to the prescription-based rules of the past. The added complexity is a source of possible misinterpretations and errors, and it is up to the classification societies to publish rules that, on the one hand, comply with the CSR and, on the other, are clear and easy to apply.

Ship structural design has thus been transformed in many cases into a process of rule compliance. However, it has to be said that the use of optimisation software in conjunction with operations research techniques can lead to structural designs that are competitive in terms of payload and operating (fuel) expenses. This is particular true in the case of multi-deck ships.<sup>6</sup> The fact is that with the development of clearly identifiable vessel types such as oil tankers and containerships that have more or less standardised configurations, rules can provide very detailed design guidance which, in the majority of cases, facilitates the work of the designer. Improvements in vessel structural designs will thus have to follow improvements in standards. This situation has been acknowledged as such by the maritime community and is an important reason for which GBS have been introduced.

Figure 1.22 shows the flow of calculations that a structural design team will generally need to follow. This, as discussed in Chapter 10, forms part of the ship design process.

<sup>5</sup> *Robustness* ( $\eta$ ) is a measure of insensitivity (or stability) with respect to parameters that cannot be controlled. It is defined quantitatively to be equal to the ratio of the mean of the attribute value  $\mu$  to the standard deviation  $\sigma$  resulting from uncertain parameter values. It is thus the ratio of predictability to unpredictability.

<sup>6</sup> The use of an advanced optimisation procedure in the structural design of a RoPax ship is described in Chapter 14.



**Figure 1.22** Rule-based design of merchant ships [15]. Reprinted courtesy of the Ship Structure Committee, Washington, DC.

To conclude, a structural standard in principle ought to:

1. Be based on accurate models of in-service loading and response
2. Address all response and failure mechanisms
3. Address uncertainties in all aspects of models
4. Incorporate safety factors that reflect consequences of failure

The basic steps of rule-based ship structural design are listed below. This list is complemented by the flow chart of Figure 1.22.

1. Selection of rules and other relevant regulations to comply with (IMO, classification society, national authorities)
2. Determination of structural arrangements, materials and stiffening systems (longitudinal, transverse, mixed) (synthesis)
3. Determination of scantlings by use of rules
  - 3.1 Longitudinal strength (section modulus)
  - 3.2 Application of rules to modified basis design to select spacing and stiffener section moduli for midship section
4. Check whether global strength requirements are satisfied on the basis of local strength requirements. Increase scantlings as required.
5. Extend section design beyond midship section of ship
6. Design fore and aft ends of ship
7. Design accommodation arrangements using rules and computer-based tools as required
8. Design connections, openings and transition regions (parallel body to fore and aft end)
9. Prepare initial structural drawings

#### ***1.4.6 Computer-Based Techniques in Ship Structural Design***

Ship structural design is a field that has profited from information technology to the extent that it has been reshaped by it. This is because ship structures have a complex configuration, are large and are subjected to randomly varying external loads. The development of computer-based methods has enabled the representation of complex structural arrangements, the modelling of randomly varying loads and the development of solutions that involve both of these. Furthermore, advances in optimisation theory have enabled the adoption of a broad range of criteria of acceptance in addition to purely structure-based ones. A rigorous exposition of the theory and application of these methods to marine structures would require a separate volume.<sup>7</sup> The application of the finite element method in ship structural design has now become well established and is an essential part of the

<sup>7</sup> A text that covers these subjects is [11].

most basic activity, which is plan approval. It is now impossible to seek approval without including results from finite element procedures for a variety of ship types and cases. The application of the finite element method with examples from ship structural analysis and design is discussed in Chapter 13.

#### 1.4.7 Good Practice in Ship Structural Design

In closing this chapter it is necessary to mention some points of guidance in ship structural design that experience has shown to be of value. Clearly, computer-based methods will have built-in checks so that the issues raised are taken into account, but it is important that the designer is able to have a first-hand idea of the quality of the design by referring to a brief (mental) check list.

Requirements that are demanded of the structure of a sea-going vessel in general are:

- Sufficient working strength. This is ensured by adherence to classification society rules but may need to be assessed in the case of an unconventional hull structure or arrangement.
- Requisite fatigue strength. This is also satisfied by adherence to classification society rules. Again, should extraordinary requirements be imposed, first-principles methods will have to be resorted to.
- Ultimate longitudinal strength. The designer ought to have an idea of the ultimate longitudinal strength of the hull girder and of the effect that alternative structural arrangements may have on its value, hence the true safety margin against overall collapse.
- Producibility. This is of importance to the shipyard. Shipyards are well aware of production techniques and particularities of hull girder fabrication methods.
- Inspectability and repairability. These qualities are of most importance to the owner and the classification society.

Beyond the above-listed requirements there are additional features that a well-designed structure will exhibit. *Robustness* is one such quality. We desire that the consequences of structural failure are not disproportionate to the effect that causes failure. In a robust structure, failure of a single member does not lead to the collapse of the whole structure. In order to design a structure so that it proves to be robust, it needs to have built-in *redundancy*. A redundant structure is one with additional internal load paths or external supports in excess of the minimum required for stability. An example of a structure with insufficient redundancy would be a three-legged oil platform which, if one leg collapses (as may occur should a ship collide with it), will collapse as a whole. Additional legs and braces increase redundancy, thereby leading to a more robust structure.<sup>8</sup>

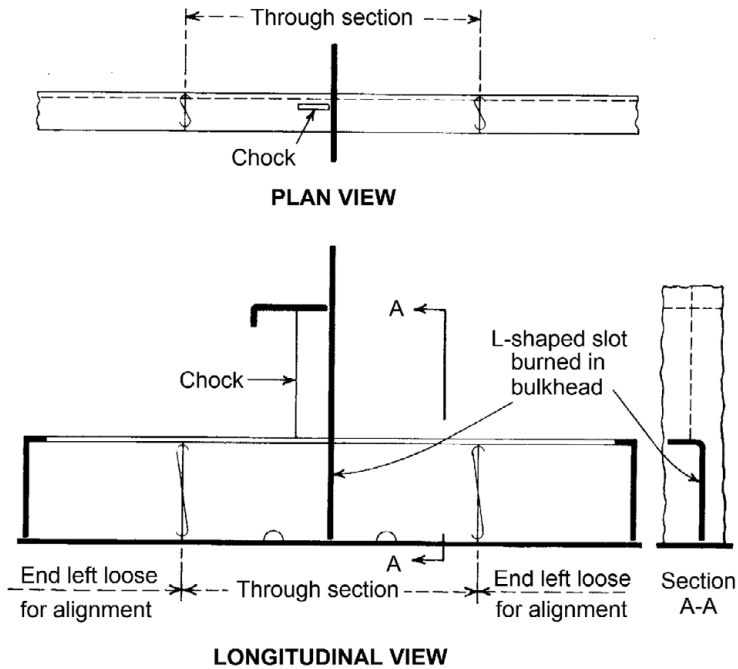
<sup>8</sup> The *Alexander L. Kjelland*, a semi-submersible oil rig operating in the North Sea, collapsed after fractures developed in one of the braces and foundered with a severe loss of life. Robustness as an explicit design aim is discussed in Chapter 12.

In ship structures, failure occurs at a local level (buckling, yielding and fracture), so that overall failure occurs when the consequences of one of these failure modes propagate in an uncontrolled manner or lead to a different failure mode. For example, a heavily corroded structure that is subjected to continuous pounding in severe seas may suffer fracture or tearing. The structure will then not be able to withstand further loading, and the fracture may propagate to the extent that one or more compartments become flooded or, in a worst-case scenario, the ship founders. Such a sequence of events is the result of one failure mode leading to a different one, thereby causing a reduction in structural redundancy.

In general, because of their configuration, ship structures have a greater degree of redundancy than do civil engineering structures. This is because they consist of thin stiffened plating, in contrast to civil engineering structures that consist of beams and frames. When failure occurs in a plated structure, loads are borne by adjoining members. In the case of beam-type structures, the degree of redundancy depends on the spatial configuration of the members, the direction of loading and the support conditions. It has to be said that redundancy is not considered explicitly in the design of marine structures in the same way that subdivision is used to ensure adequate damage stability. For example, when designed properly, frames can exhibit sufficient bending strength but also redundancy, due to secondary load paths created by axial stresses in the plate and frame. As a second example we can consider the vertical support provided to a tweendeck inside a cargo hold. In general, pillars are used to support the deck. Clearly a larger number of pillars, each bearing a smaller proportion of the total load, will lead to a more robust structure. By adopting such a standpoint a *ductile* structure will result – that is, one for which the consequences of local failure will lead to a gradual loss of strength and not to sudden unloading, which may occur in an uncontrolled manner and have much more serious consequences. The issue of redundancy is discussed further in Chapter 7 and that of robustness in Chapter 14.

We shall end this chapter by referring to the issues of *alignment* and *continuity*. These are closely linked, and it is worth to consider continuity first. Structural continuity at a global level is not under absolute control of the structural designer, as there will always be structures that end abruptly, such as superstructures. In such cases it is important to ensure that stress concentrations are avoided by suitable detail design at a local level. Past practice in which longitudinal stiffeners were ended in way of transverse bulkheads and were attached to them using various arrangements has been superseded by having them pass through the bulkhead and by being suitably attached to it (Figure 1.23). The problem that arises when a longitudinal stiffener is attached to bulkhead plating is that the bending stiffness of the two members is very different. If a stiff member is attached to a more flexible one, the latter bends about the former.<sup>9</sup> In the case of stiffener–bulkhead connections, this may give rise to cracks in

<sup>9</sup> This is termed a *hard spot*.



**Figure 1.23** Connection of a continuous longitudinal stiffener with a transverse bulkhead [3]. Reprinted courtesy of the Society of Naval Architects and Marine Engineers.

the bulkhead plating. The aim therefore is to ensure a connection in which both members will distort by approximately the same extent. One way in which this can be achieved is by increasing the bulkhead plate bending stiffness by fitting a collar plate. Another way is to align vertical stiffeners on the bulkhead with the longitudinal stiffeners of both the deck and the bottom structure, thereby forming a ring frame within each compartment. This, however, is not effective in the case of the longitudinal stiffeners that are attached to the side shell plating, and it is for this reason that many fatigue cracks arise in way of the connections of longitudinal stiffeners with web frames and transverse bulkheads.

The question of *misalignment*, on the other hand, is one in which the designer can exert much greater control. Misalignment may arise as a result of design decisions or else during fabrication. Alignment is a necessary prerequisite to proper load transfer and, when used effectively, can reduce the loads to which members may otherwise be unnecessarily subjected. Thus it pays to have supporting members such as pillars located beneath each other in successive decks.

Table 1.12 summarises some of the points raised and gives an idea of issues that are under the control of the structural designer.

Table 1.12 *Recommendations for good practice.*


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| a) General                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |
| <ul style="list-style-type: none"> <li>• Keep it simple – everything in general.</li> <li>• Incorporate feedback from in-service experience.</li> <li>• Ensure that loads are readily transferred, thereby ensuring that the structure is highly redundant (for example, by making use of multiple rather than single supports, the use of brackets at stiffener ends, the use of foot and head plates and chocks at pillar ends).</li> </ul>                                                                                                                                                                                                                     |
| b) Structural Layout                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |
| <ul style="list-style-type: none"> <li>• Ensure alignment of the structure (such as pillars supporting successive layers of decks, stiffening members on either of bulkheads and decks).</li> <li>• Ensure continuity in order to enable the satisfactory transfer of loads between adjacent members and the avoidance of stress concentrations.</li> <li>• Optimum proportions of beam.</li> <li>• Stiffness of attached members is to be of the same order of magnitude.</li> <li>• Avoid sharp corners in way of openings.</li> <li>• Strengthen openings and select positions of welds with care.</li> <li>• Facilitate access and inspectability.</li> </ul> |
| c) Structural Properties                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |
| <ul style="list-style-type: none"> <li>• Bending stiffness of adjacent members is to be similar (avoidance of hard spots).</li> <li>• Uniform reliability (rational values of safety indices).</li> <li>• Use readily available materials and sizings.</li> </ul>                                                                                                                                                                                                                                                                                                                                                                                                 |
| d) Materials and Fabrication                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |
| <ul style="list-style-type: none"> <li>• Judicious use of high-tensile steel.</li> <li>• Reduce lengths of welds to reduce the number of defects such as stress concentrations (for example, by the use of larger plate sizes or alternative structural arrangements or materials).</li> <li>• Simplify stiffening systems (for example, consider the use of the unidirectional system) as well as the connections between structural members.</li> </ul>                                                                                                                                                                                                         |

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