Design and Construction of Oil Tankers

Prepared for:

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1 INTRODUCTION

Interveners have filed evidence regarding the design and construction of double hull oil tankers. Among the interveners filing this evidence are:

- Coastal First Nations
- Forest Ethics
- Gitxaala Nation
- Living Oceans Society
- Raincoast Conservation Foundation

This report replies to certain aspects of the intervener evidence referenced above and explains the common structural rules and how oil tankers are designed to operate in the weather conditions experienced on the BC North Coast. The report also discusses tanker construction, the materials used and oversight of the construction process.

This report reviews current design and construction practices for oil tankers, with reference to how these standards have evolved. It focuses on ship structure and the various standards and practices that have been implemented to reduce the likelihood that structural failure will lead to a release of oil into the environment.

Over 50,000 cargo ships are engaged in international trade. Approximately one quarter of these vessels are oil tankers, designed for the carriage of crude oil and/or petroleum products. Independent shipowners control a majority of the tanker tonnage. These owners tend to build versatile vessels that are less likely to become obsolete as markets and conditions change. This practice has led to a commonality in sizes and configurations. This commonality enables shipyards to build large series of the same design, which significantly reduces the cost of construction.

1.1 The Tanker Fleet

Table 1 shows the capacity of the world tanker fleet by size of vessel. Aframax, Suezmax and VLCC's are generally arranged for shipping of crude oil only, whereas Panamax and smaller vessels can generally carry a variety of petroleum products.

	Size DWT tonnes	Fleet Capacity million DWT		Orderbook million DWT
Panamax and smaller	less than 80,000	95.9	22%	13.3
Aframax	80,000 - 120,000	98.3	22%	8.9
Suezmax	120,000 - 200,000	67.8	15%	15.9
VLCC	200,000 - 320,000	177.9	40%	34.5
		439.9		72.6

Table 1 Tanker Fleet (Capacity and Orderbook as of February 2012)
source: RS Platou [ref. 1]

New orders for tankers began expanding in the late 1990's and then again in 2006. Over the last five years, the average age for tankers has declined from 15 years to 8 years.

1.2 The Changing Regulatory Environment

The grounding of the Exxon Valdez was a watershed event, triggering fundamental changes in the way oil tankers are managed, operated and maintained. The regulatory bodies recognized a need for continuous improvement in environmental performance, and many new regulations have been introduced over the last two decades. Some of the more significant regulatory actions include: (1) double hull requirements for cargo tanks and subsequently for fuel tanks, (2) cargo tank subdivision requirements intended to mitigate outflow in the event of a collision or grounding, (3) requirements for the coating of ballast tanks and the tops/bottoms of cargo tanks to minimize corrosion, (4) new structural design rules common across classification societies, and (5) requirements for enhanced surveys to maintain structural integrity.

Because of the high level of shipbuilding activity in recent years, a significant portion of the world tanker fleet is designed and maintained to these enhanced standards. Many of these new regulations became de facto industry practice well before the International Maritime Organization (IMO) regulations were officially adopted and implemented. For example, single-tank-across cargo tank arrangements have not been employed on large tankers since the early 1990's even though the accidental outflow regulation was not mandated until 2010. Similarly, the tops and bottoms of cargo tanks on most double-hulled tankers are coated even though the cargo tank coating regulation is not yet in force. The reason for the early adoption of these practices is the desire of ship owners to meet the expectations of future charterers, to control maintenance costs, and to reduce risk of oil spillage.

2 DESIGN OF TANKERS

2.1 The Regulatory Process

The rules and regulations applied for the design and construction of oil tankers are primarily developed by the IMO and the classification societies.

IMO is an agency of the United Nations, charged with developing a regulatory framework that promotes maritime safety and environmental protection. Most of IMO's regulations pertaining to tanker design and construction are contained in the International Convention for the Safety of Life at Sea (SOLAS) and the International Convention for the Prevention of Pollution from Ships (MARPOL 73/78 and subsequent amendments). IMO regulations focus on the arrangements and outfitting of the vessel as it pertains to safety and environmental performance. For example, these regulations cover load line (freeboard) requirements, intact and damage stability, firefighting and lifesaving equipment. In 2006 IMO adopted regulations on the coating of ballast tanks, and requirements for coating cargo tanks on newbuildings will become effective in 2013. In 2010, "goal-based standards" (GBS)[ref. 2][ref. 3] were adopted by IMO covering the structural design of oil tankers and bulk carriers. This regulation establishes performance standards for structural integrity in the intact and damage condition over the design life of the vessel, and outlines the process for auditing the rules of organizations (likely the classification societies) for compliance with the goal-based standards.

Classification societies develop technical rules and guides for the design and construction of ships, perform plan review to confirm that the design is in conformance with their rules, and

survey vessels during construction and trials (commissioning). The classification societies also perform periodic surveys during the life of the vessel to verify continued compliance with the rules and regulations. A Certificate of Class is usually a necessary condition for obtaining insurance. National authorities generally require that a vessel be maintained in class as a condition for national registry.

The classification societies verify the structural integrity of the hull and the functionality of propulsion and other essential systems through development and verification of compliance with their own rules. The classification societies began producing rules for the structural design and survey of ships in the 1800's. These rules were primarily in the form of experience-based empirical formulas. With the advent of more sophisticated tools for determination of loads and the assessment of structural response, the rules became predominantly first principle-based although still heavily influenced by experience.

The classification societies are also called upon to verify compliance with national and international regulations on behalf of the flag state administrations. The International Association of Classification Societies (IACS), whose membership consists of the 13 larger classification societies covering over 90% of the world's tonnage, serves as a central knowledge base and research instrument for the classification societies. IACS publishes "unified requirements" and "unified interpretations" of the IMO regulations which provides a level of uniformity across classification societies.

IACS has developed a comprehensive set of rules establishing minimum requirements for the structural design of double-hull oil tankers and bulk carriers known as the Common Structural Rules (CSR). The CSR for tankers was developed by a project team assembled from three of the leading classification societies, the American Bureau of Shipping (ABS), Det Norske Veritas (DNV), and Lloyds Register (LR). Their project plan called for evaluating each of their existing rules and "taking the best from each". The CSR applies to all oil tankers built on or after 1 April 2006. IACS members are required to apply the CSR without reservation. The CSR for tankers will likely be the first set of rules audited for compliance with the IMO goal-based standards.

As compared to prior rules, the CSR resulted in a redistribution of steel weight to critical structural elements, as well as an overall increase in steel weight of 2% to 8% [ref. 4][ref. 5]. The increase in steel weight is in part due to the longer assumed design life as compared to prior rules (25 years vs. 20 years), the application of the latest North Atlantic environmental conditions, and more stringent corrosion allowances. Although primarily patterned after the existing well-proven rules of ABS, DNV and LR, the CSR introduced some new procedures and requirements such as the requirement to assess the ultimate strength of the hull girder (refer to Section 2.3) and the use of net scantlings and corrosion allowances (refer to Section 2.6). The size of structural members or the thicknesses of plate are collectively referred to as scantlings. *Gross scantlings* are the required thickness of material at construction. *Net scantlings* is the term applied in the CSR to describe the remaining thickness after the corrosion allowance is deducted.

2.2 The Design Process

Ships are designed at ship design offices or at the design offices in shipyards, by naval architects, marine engineers, and other engineers and technicians. These design professionals develop the arrangement and hull form of the tanker, and apply the CSR and engineering design principles

and techniques to determine the ship's scantlings. The classification society rules serve as a minimum standard. Ship owners may specify increased scantlings with the intent that maintenance costs will be reduced over the vessel's life.

The loads on a ship structure include static loads (weight of structure, sea pressure, tank pressure, etc.), dynamic loads (forces arising from the ship's motions), sloshing loads (forces due to the motion of liquids within tanks), and impact loads (e.g. wave impact loads and bow slamming). The CSR describes in detail how loads are to be determined and the phase relationship between loads. Prescriptive formulas are provided dictating minimum scantlings that must be satisfied. Scantlings are then verified applying finite element analysis to confirm that stresses, deflections and resistance to buckling are within specified criteria. Critical details are evaluated for fatigue with respect to the 25 year design life.

The finite element analysis involves the modeling of the ship's structure including plating, girders and stiffeners, and then application of a series of static and dynamic loadings which simulate the variety of conditions the ship may encounter. The CSR calls for evaluation of a three cargo hold coarse mesh model (refer to Figure 1) and more refined local models (refer to Figure 2). The larger model is applied so that interactions between primary structural members are properly accounted for. The fine mesh models allow the designer to evaluate high stress regions in greater detail.

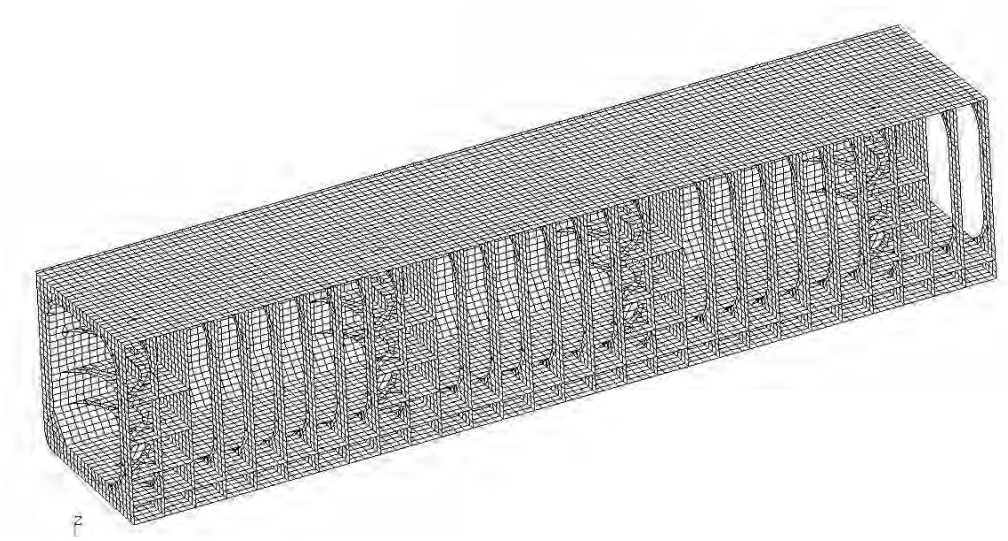

Figure 1 Three Hold Finite Element Model

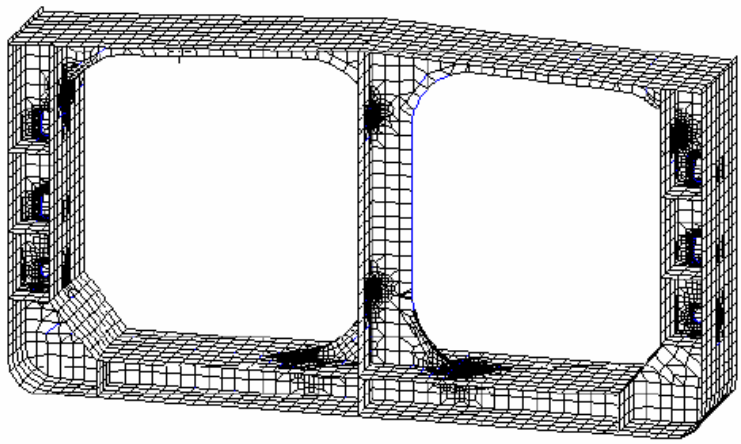

Figure 2 Fine Mesh Model

2.3 The Strength of Ships in Waves

The downward force due to the weight of the hull steel, machinery and equipment, and cargo is counterbalanced by an upwards force equal to the weight of the displaced seawater (known as buoyancy). When the distribution of weights over the length of the ship differs from the distribution of buoyancy forces, the ship is subject to bending. In calm water, this bending moment is referred to as the still-water bending moment.

When the weights are concentrated towards the middle of the ship, the ship will tend to deflect down in the middle and up at the ends. The bending moment is referred to as a sagging moment, which is the typical condition for an oil tanker fully laden with cargo oil (refer to Figure 3). Conversely, the distribution of weights towards the ends of the ship induces a hogging moment. A hogged ship deflects up in the middle and down at the bow and stern. This is the typical condition for an oil tanker in ballast.

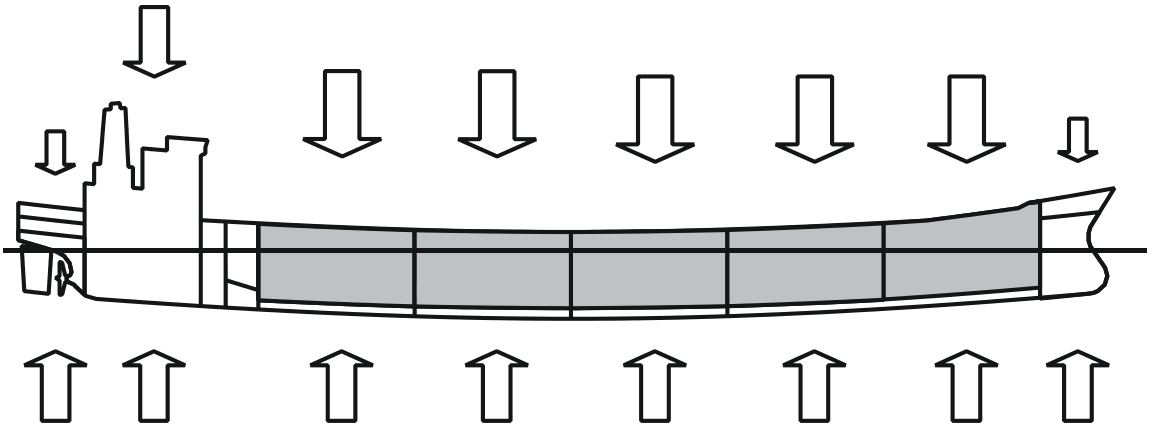

Figure 3 Still-Water Sagging Moment (Oil Tanker in Laden Condition)

The loading on the ship's hull girder (the longitudinally continuous structural members) changes as a ship encounters a wave. When the wave crest is amidships (at the mid-point of the vessel's length), the change in bending moment due to the redistribution of buoyancy towards the middle of the ship is referred to as the wave hogging moment. When the wave trough is amidships, the bending moment is called a wave sagging moment. The wave bending moments increase with

the height of the wave, and are highest when the wave length is approximately equal to the ship's length. The still-water bending moment plus the wave bending moment is the total bending moment. Figure 4 shows the laden oil tanker encountering a wave with the trough amidships. The additional sagging moment increases the hull girder deflection and consequently the primary hull girder stresses.

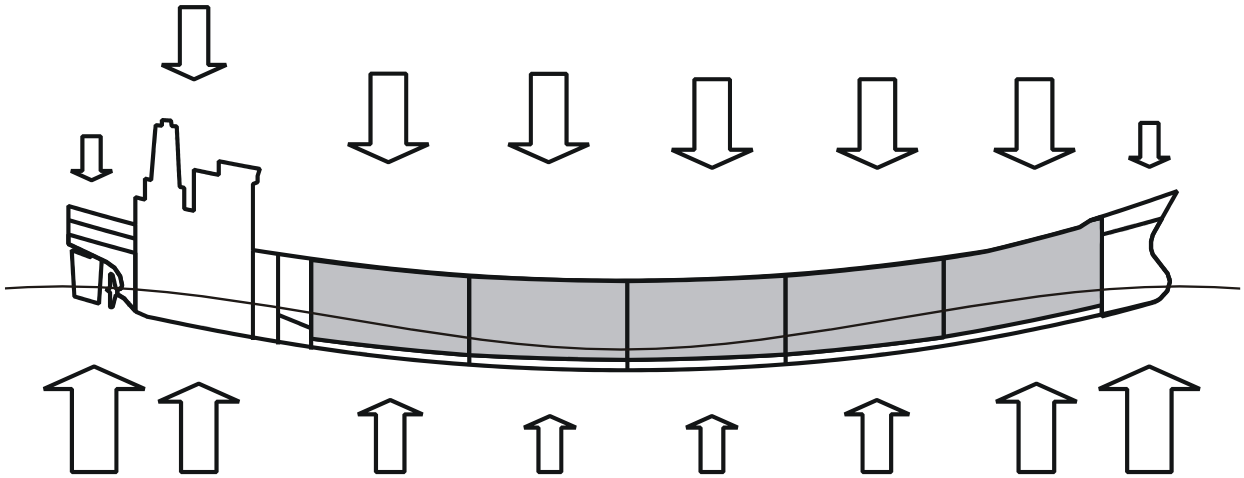

Figure 4 Wave Sagging Moment (Wave Trough Amidships)

The calculation of the still-water bending moment is a straightforward mathematical exercise, once the weight distribution of the tanker, the arrangement of the tanks, and the shape of the hull are known.

The calculation of the design wave bending moment is more complex. The CSR formula for design wave bending moment is based on a determination of the most probable largest wave bending moment to be encountered over the ship's service life. Over its 25 year life, a ship will encounter approximately 100 million (10^8) waves. When determining the extreme waves, IACS applies wave statistics for the particularly severe North Atlantic wave environment. Although it is recognized that few vessels spend their entire service life transiting the North Atlantic, an assumption of continuous service in this severe environment is used for the design of oceangoing ships approved for unrestricted ocean service.

The CSR defines the various combinations of static and dynamic loads to be analyzed in the design of a new ship. The designer applies these loads in the finite element analysis to determine the deformation and stress levels of the various structural components. The CSR specifies yielding and buckling acceptance limits with safety margins to account for uncertainty and the possibility that the design loads could be exceeded.

Recognizing that the lighter main deck structure achievable with higher strength steels may reduce the hull girder ultimate strength capacity, IACS included a simplified hull girder ultimate strength assessment requirement in the CSR. The ultimate strength capacity is the load at which collapse of the hull girder (catastrophic failure) occurs. Previously, the classification rules only considered elastic-based assessment. Similar to other strength assessments defined in the CSR, the ultimate strength assessment accounts for expected corrosion over the service life.

2.4 Large Waves and Steep, Rogue Waves

The CSR dynamic loads were determined through hydrodynamic calculations using linear seakeeping software. The statistical basis for the analysis is the "IACS Recommendation No. 34 wave scatter diagram for the North Atlantic"[ref. 6], which is derived from global wave statistics published by British Maritime Technology and updated in year 2000. The scatter diagrams give the number of occurrences in 100,000 observations, of different significant wave height and wave period combinations. According to this data, the likelihood that a sea state encountered in the North Atlantic will exceed 12 meter significant wave height is about 1 in 10,000. The 'height' is the distance from crest to trough.

The significant wave height H_S is the mean wave height of the highest one-third of the waves. The highest 1 in 100 waves is 1.67 times H_S, and the highest 1 in 1000 is 1.83 x H_S. Thus, for a 12 meter significant sea state the highest third of the waves average 12m in height and there is a 1/100 likelihood of the wave height exceeding 20 meters and a 1/1000 likelihood of the wave height exceeding 22 meters. Large, storm-driven seas are, generally, confused and irregular leading to the significant variation in wave heights. The occasional large wave in such an event is expected and should not be confused with a rogue wave.

In rare circumstances, waves have been observed that are even larger than those expected from such statistical assessments. They are referred to as rogue waves or freak waves. Current ship design rules and practices do not include direct evaluation of rogue waves – at this time considering current knowledge, such extreme events can only be accommodated through safety factors. The safety factors defined in the CSR vary depending on type of load. For example, heavy weather loads are determined based on a once in 25 year probability assuming operation in the North Atlantic environment. After reducing plate thickness for assumed corrosion, the calculated stress in the primary members is limited to 85% of the yield stress of the steel. The yield stress is the minimum stress at which steel will not behave elastically (i.e. will experience some level of permanent deformation).

The generation of rogue waves is a non-linear phenomenon, believed to be associated with the interaction of ocean currents and the wave field. Although not fully understood, progress is being made in modeling rogue waves, but these models are not of sufficient robustness to be applied in the design process. Rogue waves are extremely steep, and are primarily a concern with regards to bottom slamming and green water impact on the forecastle, deck and superstructure.

2.5 Materials for Ship Construction

All modern oil tankers are of welded steel construction. Ordinary strength steel (also referred to as mild steel) with a minimum yield stress of 235 N/mm^2 together with higher strength steels up to yield stress of 355 N/mm^2 are commonly applied. Notch resistant steels are applied for thicker plates in critical stress regions.

Higher strength steels are used to reduce the weight of the vessel and to reduce construction cost. The two common grades of higher strength steel are HT32 (minimum yield stress of 315 N/mm^2) and HT36 (minimum yield stress of 355 N/mm^2). The use of higher strength steels varies considerably – there are smaller tankers constructed of 100% mild steel and larger tankers with

up to 80% HT36 steel. Common practice is 30% to 60% HT32 steel, with this higher strength steel primarily allocated to the upper and lower longitudinally continuous hull girder structure.

Although higher strength steels exhibit higher yield and ultimate strengths, their fatigue properties are comparable to ordinary strength steel. Structural details in high stress regions constructed of higher strength steels must be carefully designed to insure adequate fatigue life. In the 1970's when higher strengths steels were first widely used for ship construction and their properties were not fully understood and appreciated, the frequency of fatigue failures increased. The classification societies subsequently introduced fatigue assessment into their rules. The assumption of a 25 year design life in the CSR further strengthens fatigue assessment for new tanks. For double hull tankers which have a high degree of structural redundancy, it is very unlikely that fatigue failure will lead to catastrophic loss of hull girder structural integrity. The double hull protection also minimizes risk that fatigue fractures will result in oil spillage. However, ship owners have an interest in robust fatigue criteria as the repair of fatigue failures can be expensive due to the repetitive nature of such fractures.

2.6 Cargo Hold Structure

All tankers built since 1990 are of double hull construction. Figure 5 shows typical tankage arrangements for double hull tankers. Wing tank widths range from 2.0 meters for Panamax size tankers up to 3.0 to 4.0 meters for VLCC's. Double bottom heights are generally comparable to wing tank width.

Most Panamax, Aframax, and Suezmax tankers have two-across cargo tank arrangements. Most VLCC's have 3-across cargo tanks arrangements. In the early 1990's, a few Panamax and Aframax tankers were built with single-tank-across arrangements. It was shown that these tankers had higher expected oil outflow in the event of a casualty that breached the inner hull, and could potentially become unstable during loading operations. Since that time, IMO has adopted intact stability regulations and accidental oil outflow regulations that effectively preclude construction of such designs. The MARPOL *Intact stability* regulation entered into force in 2005 [ref. 7] followed by the *Accidental oil outflow performance* regulation in 2010 [ref. 8]. These regulations were developed and became known to industry during the 1990's and the large majority of double hull tankers built since the mid 1990's conform to these regulations.

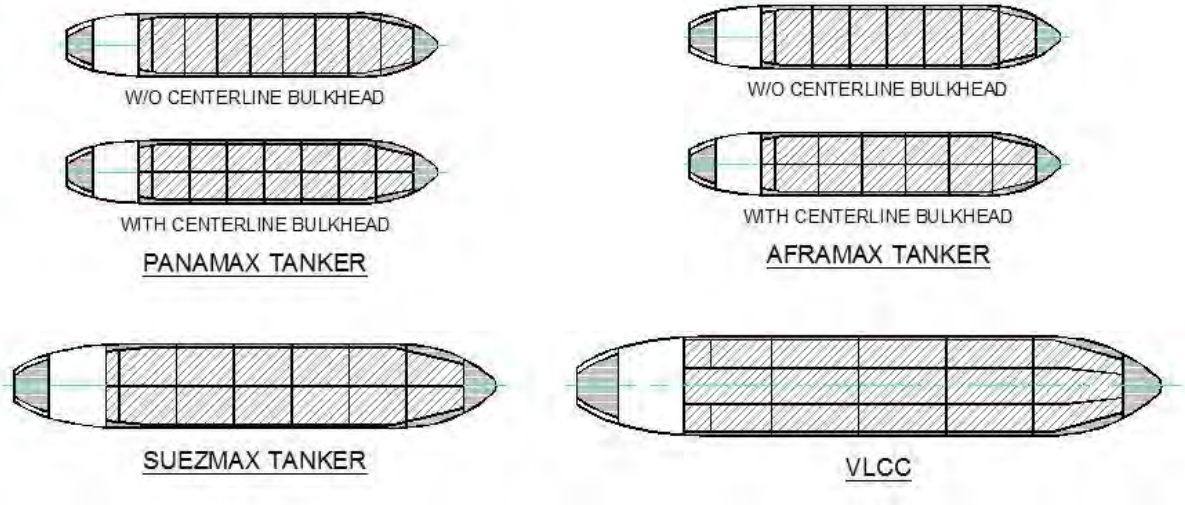

Figure 5 Typical Tankage Arrangements

The structural arrangement of a representative web frame on a VLCC is shown in Figure 6. Horizontal plates (referred to as Horizontal Girders or Stringers) are arranged in the wing tanks and walkways are arranged in the upper portion of the cargo holds to allow for close up inspection of all structure. A sloping hopper structure at the bottom of the wing tank is arranged to provide strength and rigidity at the double bottom/wing tank interface. The inner bottom plating (at the top of the double bottom structure) is maintained as clear as practical to allow for ready drainage of the cargo oil. These web frames are typically every 3.5 to 5.0 meters, depending on the tanker size. Oil tight bulkheads which subdivide the tanks are typically arranged every 20m to 30m. This configuration provides a robust structure which is readily accessible for inspection.

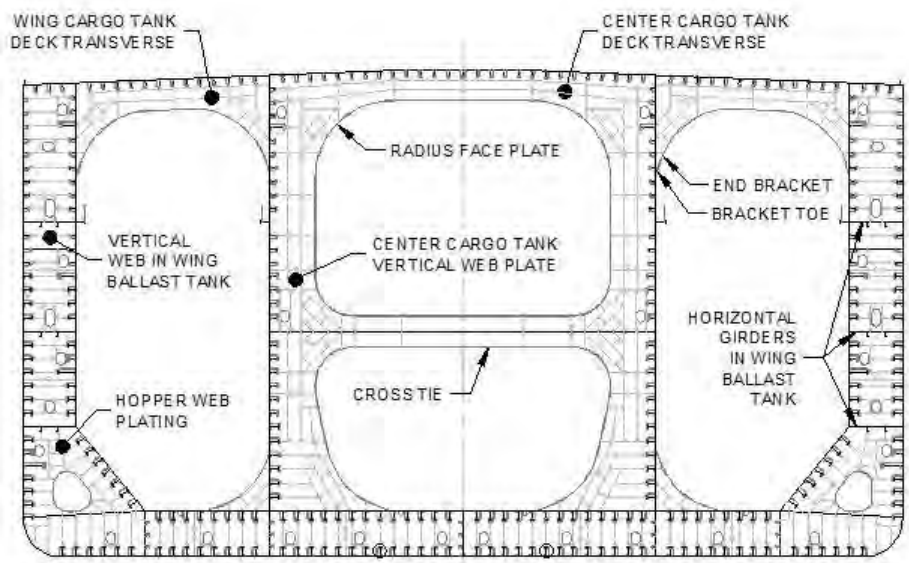

Figure 6 Tanker Structural Arrangement (typical web frame for VLCC)

Typical scantlings for a VLCC built to CSR are shown in Figure 7. As described in Section 2.7, the plate thickness of each member consists of a net scantling (the plate thickness required to carry the specified loads without exceeding acceptance criteria) and a corrosion allowance.

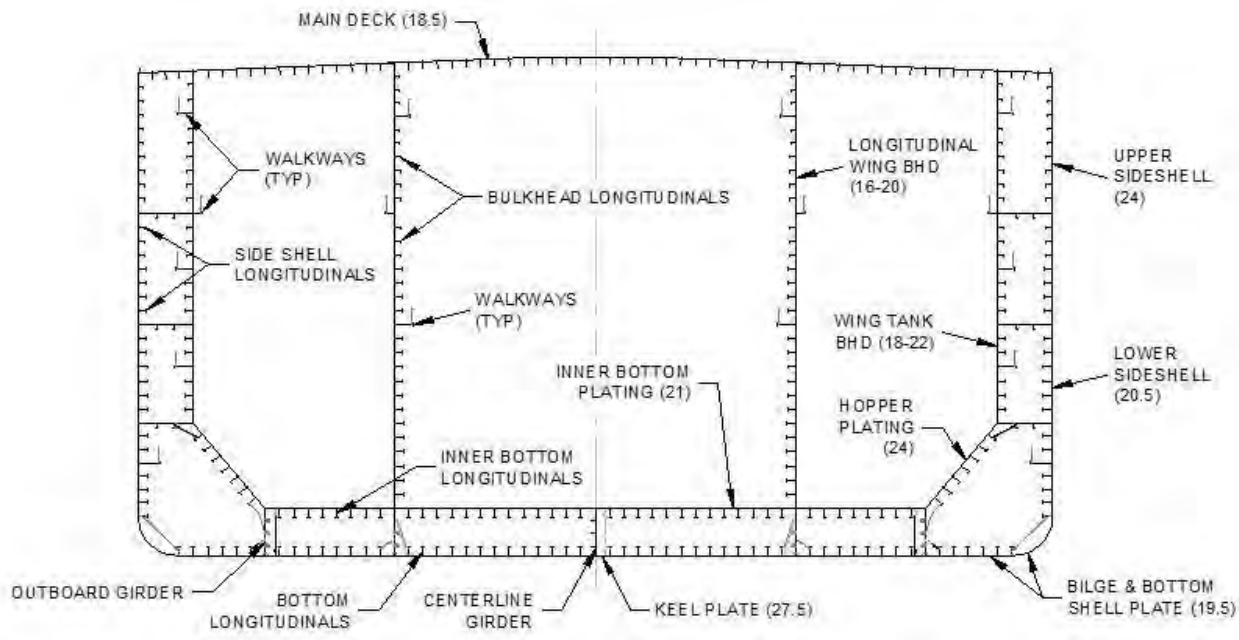

Figure 7 Typical Gross Plating Thickness (mm) for VLCC (Net thickness+ corrosion addition)

3 CONSTRUCTION OF TANKERS

3.1 The Shipbuilding Process

The successful shipyards have automated nearly all stages of production. The process begins with the cutting and, where necessary, forming of plate. The plates are then welded together and then stiffeners, web frames, and brackets are attached. These are brought together into modules and pre-outfitted with piping, machinery, wiring, etc. as far as practical. Numerical cutting, automatic welding, automatic line heating, and assembly line robotics are now widely used. Double hull construction also improves productivity, as the double bottom and wing tank units are rigid structures which facilitate handling and assembly.

The modules (commonly referred to as blocks) and major equipment (ex: the main engine) are assembled in the drydock after which the oil tanker is floated out for final outfitting and delivery trials. Minimization of time in the drydock is a key concern for shipyards as the drydock is often the critical path limiting throughput. This has been achieved through creation of larger blocks, typically 500 to 1,000 tonnes each for the efficient yards, reducing time in drydock to 3 months or less. Samsung Heavy Industries (SHI) has taken this a step further – using large floating cranes to handle blocks up to 3000 tonnes. This has allowed SHI to reduce the number of blocks required for construction of an Aframax tanker from 90 to 10, and time-in-dock to as little as 6 weeks.

3.2 Initial Inspection (During Construction)

The shipyard (through its quality assurance department), the classification society surveyors, and the ship owner site inspection team form a triumvirate, and best results are achieved when they work in concert although each group has specific responsibilities. The flag state may also have representatives at the yard, although their inspection responsibilities are normally delegated to the classification society.

The shipyard has a set of quality standards and procedures that is vetted by the owner prior to contract signing. IACS and the classification society also have standards – for example IACS has standards for new construction that include tolerances for plate thickness, weld induced distortion, and alignment of structure. The shipyard construction and quality standards augment the standards and procedures established by class and the Regulatory Bodies, providing greater specificity on the design details, tolerances, procedures and controls. Shipyard quality control engineers are expected to oversee all stages of production to insure compliance with the relevant standards.

The classification society has the following responsibilities during design and construction.

- Review of design plans, vendor equipment specifications, and other documentation for compliance with the rules.
- Survey of the ship during construction to verify that approved plans are followed and applicable standards are adhered to.
- Survey at manufacturers' facilities (including steel production and castings, and major machinery and equipment) to verify compliance with approved plans and standards.
- Attendance during dock and sea trials to confirm conformance with the rules.

After witnessing the construction and trials of the ship and determining to its satisfaction that all applicable rules are met, the classification society will issue a certificate of class.

The shipowner is ultimately responsibility for the safety and seaworthiness of the ship, and has a vested interest in insuring that the vessel is of good quality and built to the specifications agreed upon at contract signing. The shipowner will have a team onsite at the shipyard, typically consisting of at least 4 and up to 12 or more inspectors, with expertise in steel fit-up and welding, coatings, outfitting, machinery, and electrical systems. These owner's representatives will attend many of the same call-outs and tests/trials as the classification society surveyor, both at the shipyard and at manufacturers' plants where fabrication and testing is carried out. The owner's representatives confirm that the ship and its equipment are in conformance with the ship's specification and the contract, and are another set of eyes to insure compliance with all applicable rules and quality standards.

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