ΕΘΝΙΚΟ ΜΕΤΣΟΒΙΟ ΠΟΛΥΤΕΧΝΕΙΟ
ΣΧΟΛΗ ΝΑΥΠΗΓΩΝ ΜΗΧΑΝΟΛΟΓΩΝ ΜΗΧΑΝΙΚΩΝ
ΤΟΜΕΑΣ ΘΑΛΑΣΣΙΩΝ ΚΑΤΑΣΚΕΥΩΝ

Η μεταλλική κατασκευή των πλοίων μεταφοράς χημικών προϊόντων
(Structural design of modern chemical tankers)

ΔΙΠΛΩΜΑΤΙΚΗ ΕΡΓΑΣΙΑ

ΣΚΟΥΦΑΣ ΚΩΝΣΤΑΝΤΙΝΟΣ

Επιβλέπων : Πέτρος Καρύδης
Αναπληρωτής καθηγητής Ε.Μ.Π.

Αθήνα, Μάιος 2015

Η σελίδα αυτή είναι σκόπιμα λευκή.

ΕΘΝΙΚΟ ΜΕΤΣΟΒΙΟ ΠΟΛΥΤΕΧΝΕΙΟ

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Αθήνα, Μάιος 2015

(Υπογραφή)

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ΣΚΟΥΦΑΣ ΚΩΝΣΤΑΝΤΙΝΟΣ

Φοιτητής Ναυπηγός Μηχανολόγος Μηχανικός Ε.Μ.Π.

Preface

This diploma thesis is made as a completion of my education in Naval Architecture and Marine Engineering at the National Technical University of Athens.

My intension, by developing this thesis, is to introduce the reader to the concept of chemical tanker vessels, and especially to their modern structural design. However, this thesis may also be proved useful to readers who are already experienced in the field of seaborne chemical transportation and such type of vessels.

I would like to thank my supervisor, Mr. Piero Caridis, for his support, time and guidance provided during the development of this thesis, as well as for his excellent collaboration.

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Finally, I would like to thank my family and friends, and especially my parents Stelios and Christina, for being helpful and supportive during the whole period of my studies.

Abstract

Chemical tankers are highly sophisticated commercial vessels which are used for the transportation of liquid chemical products in bulk. They are, in general terms, similar to other types of tanker vessels, such as oil tankers, or liquefied gas tankers. However they present some unique characteristics, such as a relative small size, a large number of cargo tanks, and a wide variety of cargo handling and treatment systems.

The structural design of chemical tankers is affected in a great way by the chemical products that the vessel is expected to curry. Because of their nature, chemical products are extremely hazardous, and may pose potential threat to human or to the environment. For that reason, the design of a chemical tanker is governed by a wide set of rules and regulations which make sure that a sufficient safety level and strength of the construction are obtained. In addition, the design of a chemical tanker follows also the conventional structural design process and methods that are used for all types of ocean going vessels.

In this diploma thesis, the basic concepts of the modern structural design of chemical tankers are explained and discussed. The thesis has two main targets: a) to present the typical structure of chemical tankers, by means of vessel’s arrangements, structural configuration and components, and cargo operation systems, and b) to analyze all the factors that may influence the design procedure of a chemical tanker.

The **first chapter** of this thesis tries to familiarize the reader with the concept of chemical tanker vessels. In this respect, a brief description of all types of tankers is given, in order of the reader to be able to distinguish chemical, from different types of tanker vessels. Additionally, the term chemical tanker is defined as adopted by the MARPOL Annex II.

Subsequently, an effort has been made to look back at the genesis and evolution of this type of vessels, reaching back to the beginning of the 20th century, when the first chemical tankers appeared in order to fulfill the demands for chemical products’ transportation that were born from the continuously expanding chemical industry. This section tries to analyze the development of chemical tankers in line with the development of their environment and the demands of the society, and to focus on individual vessels that have made a great impact due to innovational breakthroughs that were applied on them.

This rapid evolution of the chemical tankers, has led to a development of a series of regulations that govern their design, constructional and operational principals. It is of highest importance for

someone who wants to deal with this type of vessel, to be familiar and have a solid knowledge of these rules. For that reason these regulations are also presented in this chapter.

Finally, some additional details, such as classification ways, market trends, and fleet analysis are given to the reader as a tool, in order of him to be able to better understand and evaluate what he will come up to in the chapters to follow.

In the **second chapter** of this thesis an effort has been made to familiarize the reader with chemical tankers' cargoes, their properties, and their potential hazards. As the structural design process of a chemical tanker is directly related to the cargoes she is intended to carry, it would serve no useful purpose to begin presenting design and structural configurations, without first discussing the cargo itself.

First of all, a classification of cargoes is been made, according to their origin, chemical composition, and the pollution threat they pose to the environment as per MARPOL. In addition, all the physical properties that characterize a chemical material are listed and defined, as these properties play a significant role in the selection and design process of various cargo systems that we will meet in next chapters.

Subsequently, a brief presentation of hazards related to chemical cargoes, and the chemicals' behavior when they released to the marine environment has been made. Although there is no direct influence of this information to the design process, it is of vital importance that anyone who is in any way involved with chemical tankers and the cargoes they carry, is well informed of these hazards.

As a matter of fact, each cargo has its own characteristics, potential hazards and special requirements for treatment. All these information are conveyed to the people handling these chemical cargoes through the Cargo Information Data Sheet, which is presented at the end of this chapter.

Finally, an attempt has been made to explain as simple as possible the effect of the chemical products to the design procedure of chemical tankers. For the transportation of each product, some specific structural requirements must be met. These requirements are listed in Chapter 17 of the IBC code. This chapter aims to analyze Chapter 17 of the IBC code and investigate how individual products may affect the design process.

In the **third chapter**, the general arrangement of typical chemical tankers is described and analyzed. Arrangement of spaces in chemical tankers should be designed in accordance with class regulations and rules, so as to eliminate problems and difficulties that a non-effective arrangement of spaces may occur, as well as to ensure that no hazards for the crew, the environment, or the vessel itself arise at any time.

At first point, the arrangement of cargo tanks will be analyzed. Cargo tank's arrangement and size are directly related to the type of vessel. A chemical tanker is categorized as of type I, II, or III, depending on the cargo she is intended to carry. The three types of chemical tanker vessels, as well as the effect the Ship Type has on the location of the cargo tanks, are presented in this chapter.

Due to their hazardous nature, chemical cargoes require special consideration regarding their segregation from other cargoes, from machinery and accommodation spaces, from heat, water and other. All the above affect the arrangement of the vessels which carry those cargoes, in ways that are described in this chapter.

Furthermore, location of cofferdams, fuel oil tanks, cargo pump rooms, bilge and ballast arrangements, accommodation, machinery and service spaces, openings to accommodation and cargo spaces are considered.

Finally, reference is been made to the hazardous locations and zones of a chemical tanker, and the effect they have on the vessel's arrangement.

The scope of the **forth chapter** is to present the basic steps that are followed by the designer during the structural design process of a vessel, so that the importance and usefulness of each design stage is highlighted. The first section of this chapter summarizes the whole design procedure and aims to familiarize the reader with some basic concepts of it. Subsequently, two of the most important steps of the design process, the load analysis and the strength evaluation, are isolated and explained.

In the second section of this chapter, the loads that are predicted to be applied on the vessel, are analyzed and classified to static and dynamic loads based on their characteristics. Moreover, the ways in which these loads affect the transverse and longitudinal strength of the vessel are explained. Finally, the most commonly used methods of load calculations are presented. A brief description of impact dynamic loads, such as sloshing and slamming is also included.

The strength evaluation process is analyzed in the last section of the chapter, where reference is made to the main types of structural failure. The strength evaluation flow, conventional analytical methods as well as modern computational methods, such as the finite element method are also described here.

This chapter is not focused on chemical tankers exclusively, but it addresses to almost all types of commercial vessels, as they follow more or less the same design process. Special references in chemical tankers are made though, wherever appropriate.

The scope of the **fifth chapter** is to explain which are the most common materials used for the construction of cargo tanks in chemical tankers, why they are used, and which are the selection criteria.

The most important parameter when it comes to the selection of cargo tank materials, is these materials to be able to withstand the corrosive effect of the chemical cargoes. For that reason, the mechanism and the most common types of corrosion that take place in chemical tankers are explained.

The most commonly used materials for the construction of cargo tanks nowadays, are the stainless steel and the mild steel. Mild steel, when it is used, should be sufficiently coated in order to withstand the corrosive effect of the cargo. Firstly, the two main types of stainless steel are presented: austenitic stainless steel and duplex stainless steel. Their microstructure and their basic characteristics are analyzed and compared. Additionally, the enhanced resistance of stainless steels against corrosion is explained.

When it comes to mild steel, the selection of the proper coating is of vital importance. Each type of coating has its own characteristics, advantages and disadvantages. The most commonly used coatings are presented, and several information are given regarding their properties.

Finally, a reference is been made to the selection procedure and analysis of the correct material for cargo tank construction.

The **sixth chapter** of this thesis tries to explain and analyze the structural configuration of typical chemical tankers and of their structural components. For easier comprehension, several drawings of actual vessel constructions are included.

Before the analysis of the structural configuration takes place, some general design characteristics of the hull form of chemical tankers are presented, such as the typical block coefficient range and the common stem and stern arrangements. Furthermore, the effect on the design, of the specific gravity and the temperature of the cargo, and of the potential loading conditions, are mentioned.

Then, the structural configuration of the cargo tanks is explained, and the types of cargo tanks a chemical tanker may have are presented. Scantling methods and calculations as per classification societies for each tank type are also given. Additionally, special reference is been made to the saddle supports of the independent cargo tanks.

Subsequently, the structural configuration of the deck structure and the transverse and longitudinal bulkheads is analyzed. The analysis focus on corrugated bulkheads as this is the most common type used in chemical tankers. Design parameters of corrugated bulkheads and their effect in the design, types of corrugated bulkheads, scantlings, and other notes on the design are all included in this chapter.

Finally, a brief reference to the double hull and double bottom construction is been made.

What differentiates modern chemical tankers from product and crude oil tankers, is the amount of sophisticated cargo systems that are installed on board, for the handling and monitoring of the several cargoes, and these systems are discussed in the **seventh chapter** of this thesis. A vessel’s cargo system, together with its cargo tank arrangement and safety systems determines the cargoes that a vessel can or cannot carry. The scope of this chapter is to present these cargo systems, and the potential impact they may have on the vessel’s structural design.

First, a review is been made to the cargo piping and cargo manifolds arrangements. The method to calculate the piping scantlings is also provided, as per the IBC Code’s minimum thickness requirements. Additionally, piping joining details are highlighted and the three types of flanges which are most commonly used in chemical tankers are presented.

Subsequently, an analysis of the cargo pumps used in chemical tankers takes place. More specifically, the analysis focuses on deepwell cargo tanks, as they are the most commonly used type of pumps in chemical tankers. The two types of deepwell pumps, the hydraulically driven ones and the electrically driven ones, are explained, together with their basic functions and operational requirements. Their structural components, such as the deck trunk, the intermediate and bottom supports, the section well, and the pipe stack are also presented, and some useful information about their characteristics are given.

Finally, all other cargo systems that are used on board a chemical tanker, such as tank cleaning systems, tank venting systems, cargo monitoring and control systems, and cargo environmental control systems, are mentioned, and their basic functions are explained.

Finally, in the **eighth chapter** of this thesis, some alternative designs for chemical tankers are examined.

Due to the nature of the cargoes they carry, which may be extremely hazardous and require special care during their transportation, modern chemical tankers are characterized by increased technological sophistication. They are complex and expensive ships, and a lot of experience and know-how has been gathered over recent decades and used for their further technological development. This have led the present generation of double hull chemical tankers, equipped with several cargo systems, to be regarded as state-of-the-art vessels in matters of design and safety.

Therefore, future design philosophy is more focused on how to further improve the current design, rather than to develop new alternative design models. Improved coatings for cargo tanks, advanced steels for cargo tanks manufacturing, and several improvements of the cargo systems are some of the areas of development.

The design of chemical tankers in the future, will be influenced by the following two factors: Elimination of pollution from slops, by trying to reduce the amount of water used for the washing of cargo tanks via innovative tank design, and obtainment of high quality standards equal to those used in the food industry. It is also highlighted, that a general revolution that takes place in the design principles of all kind of vessels, which focuses more on the engineering part rather than on the rules-based part of the design, will also affect the design of chemical tankers in the future.

In this chapter, two already existing designs; the combination of duplex stainless steel and clad stainless steel for the construction of cargo tanks, and the development of a 75,000 DWT chemical tanker, are presented. In addition, an alternative design of a chemical tanker with cylindrical tanks which has not yet though been applied, is reviewed.

Εισαγωγή

Τα δεξαμενόπλοια μεταφοράς χημικών προιόντων είναι ιδιαίτερα ανεπτυγμένα τεχνολογικά πλοία τα οποία χρησιμοποιούνται για τη μεταφορά χημικών προιόντων σε υγρή μορφή χύδην. Τα πλοία αυτά μοιάζουν, σε γενικές γραμμές, με άλλους τύπους δεξαμενοπλοίων, όπως είναι τα πετρελαιοφόρα και τα πλοία μεταφοράς υγροποιήμενου αερίου. Παρουσιάζουν ωστόσο και κάποια μοναδικά χαρακτηριστηκά, όπως είναι το σχετικά μικρό τους μέγεθος, ο μεγάλος αριθμός δεξαμενών φορτίου, καθώς και μία μεγάλη ποικιλία συστήματων που αφορούν στο φορτίο.

Η δομή της μεταλλικής κατασκευής των δεξαμενόπλοιων μεταφοράς χημικών προιόντων επηρεάζεται σε μαγάλο βαθμό από τα χημικά προιόντα τα οποία το πλοίο προορίζεται να μεταφέρει. Τα χημικά προιόντα είναι εκ φύσεως ιδιαίτερα επικύνδυνα και μπορεί να αποτελέσουν απειλή τόσο για τους ανθρώπους όσο και για το περιβάλλον. Για το λόγο αυτό, η σχεδίαση των δεξαμενόπλοιων μεταφοράς χημικών προιόντων διέπεται από ένα μεγάλο εύρος κανονισμών οι οποίοι διασφαλίζουν την απαραίτητη ασφάλεια και αντοχή της κατασκευής. Επιπροσθέτως, η σχεδίαση τους ακολουθεί επίσης τις συμβατικές μεθόδους σχεδίασης που χρησιμοποιούνται για όλους τους τύπους εμπορικων πλοίων.

Σε αυτή τη διπλωματική εργασία, εξηγούνται και αναλύονται οι βασικές αρχές κατά τη σχεδίαση ενός δεξαμενόπλοιου μεταφοράς χημικών φορτίων. Η διπλωματική αυτή εργασία έχει δύο στόχους: α) Να παρουσιάσει την τυπική δομή ενός δεξαμενόπλοιου μεταφοράς χημικών φορτίων, δηλαδή τις διατάξεις του πλοίου και τα δομικά του στοιχεία, και β) να αναλύσει όλους τους παράγοντες που μπορεί να επιδράσουν στη σχεδίαση ενός τέτοιου τύπου πλοίου.

Το **πρώτο κεφάλαιο** αυτής της διπλωματικής εργασίας θέλει να εξοικιώσει τον αναγνώστη με την έννοια του δεξαμενόπλοιου μεταφοράς χημικών φορτίων. Σε αυτή τη λογική γίνεται μία συνοπτική περιγραφή όλων των τύπων δεξαμενόπλοιων έτσι ώστε ο αναγνώστης να είναι σε θέση να διακρίνει ένα δεξαμενόπλοιου μεταφοράς χημικών φορτίων από τους υπόλοιπους τύπους δεξαμενοπλοίων. Επιπλέον, δίνεται ο ορισμός του δεξαμενόπλοιου μεταφοράς χημικών φορτίων, όπως αυτό ορίζεται στο MARPOL Annex II.

Επιπλέον, γίνεται μία προσπάθεια να ανατρέξουμε πίσω στη γέννηση και την εξέλιξη αυτού του τύπου πλοίων, ξεκινώντας από τις αρχές του $20^{ου}$ αιώνα, όταν έγινε η πρώτη εμφάνιση των δεξαμενόπλοιων μεταφοράς χημικών προιόντων για να καλύψουν τις ανάγκες τις αγοράς για χημικά προιόντα που δημιουργούσε η συνεχώς αναπτθσόμενη χημική βιομηχανία. Σε αυτό το τμήμα της διπλωματικής εργασίας γίνεται μία προσπάθεια να εξεταστεί η ανάπτυξη των δεξαμενόπλοιων μεταφοράς χημικών προιόντων σε σχέση με τις συνθήκες και τη ζήτηση της εποχής, καθώς και να παρουσιαστούν συγκεκριμένα πλοία τα οποία αποτελούν σημείο αναφοράς λόγω των τεχνολογικών καινοτομιών οι οποίες εφαρμόστηκαν σε αυτά.

Η ταχεία εξέλιξη των δεξαμενόπλοιων μεταφοράς χημικών προιόντων οδήγησε στην ανάπτυξη μίας σειράς κανονισμών οι οποίοι διέπουν τη σχεδίαση τους τόσο σε κατασκευαστικά όσο και σε λειτουργικά θέματα. Είναι πολύ σημαντικό για κάποιον ο οποίος θα ήθελε να ασχοληθεί με αυτόν τον τύπο πλοίων να είναι εξοικειωμένος και να γνωρίζει αυτούς τους κανονισμούς. Για αυτό το λόγο αυτοί οι κανονισμοί παρουσιάζονται επιγραμματικά σε αυτό το κεφάλαιο.

Τέλος, κάποια επιπλέον στοιχεία όπως οι τρόποι κατηγοριοποίησης, οι τάσεις της αγοράς, και η ανάλυση του παγκόσμιου στόλου δίνονται στον αναγνώστη σαν εργαλείο έτσι ώστε να τον βοηθήσουν να καταλάβει και να αξιολογήσει καλύτερα τα κεφάλαια που θα ακολουθήσουν.

Στο **δεύτερο κεφάλαιο** αυτής της διπλωματικής εργασίας γίνεται μία προσπάθεια να εξοικειωθεί ο αναγνώστης με τα φορτία τα οποία μεταφέρουν τα δεξαμενόπλοια μεταφοράς χημικών προιόντων, τις ιδιότητές τους και τους πιθανούς κινδύνους που σχετίζονται με αυτά. Καθώς ο σχεδιασμός της μεταλλικής κατασκευής ενός δεξαμενόπλοιου μεταφοράς χημικών προιόντων συνδεέται άμεσα με τα προιόντα τα οποία το πλοίο πρόκειται να μεταφέρει, θα ήταν άσκοπο να παρουσιάσουμε τη διαδικασία σχεδίασης του και τη διάταξη των δομικών του στοιχείων χωρίς πρώτα να εξετάσουμε τα προιόντα αυτά.

Αρχικά γίνεται μία κατηγοριοποίηση των χημικών προιόντων με βάση την προέλευσή τους, τη χημική τους σύσταση, καθώς και τη πιθανή μόλυνση που μπορούν να επιφέρουν στο περιβάλλον σύμφωνα με τη MARPOL. Στη συνέχεια παρουσιάζονται όλες οι φυσικές ιδιότητες που χαρακτηρίζουν τα χημικά προιόντα, καθώς αυτές μπορούν να παίξουν καθοριστικό ρόλο στην επιλογή και τη σχεδίαση των συστημάτων φορτίου όπως θα συναντήσουμε και στα επόμενα κεφάλαια.

Στη συνέχεια γίνεται μία σύντομη παρουσίαση των κινδύνων που προκύπτουν από τα χημικά προιόντα, καθώς και της συμπεριφοράς αυτών όταν αφεθούν στο θαλάσσιο περιβάλλον. Παρόλο που δεν υπάρχει άμεση συσχέτιση των πληροφοριών αυτών με τη διαδικασία σχεδίασης, είναι κομβικής σημασίας όποιοσδήποτε σχετίζεται με οποιοδήποτε τρόπο με τα δεξαμενόπλοια μεταφοράς χημικών προιόντων να είναι σωστά ενημερωμένος για τους κινδύνους αυτούς.

Κάθε χημικό προιόν λοιπόν έχει τα δικά του ιδιαίτερα χαρακτηριστικά, πιθανούς κινδύνους που μπορεί να εγκυμονεί, και χρίζει ιδιαίτερης μεταχείρησης. Όλες οι παραπάνω πληροφορίες μεταβιβάζονται στους ανθρώπους που χειρίζονται αυτά τα προιόντα μέσω του Cargo Information Data Sheet, το οποίο παρουσιάζεται σε αυτό το κεφάλαιο.

Τέλος, γίνεται μία προσπάθεια να εξηγηθεί όσο πιο απλά γίνεται η επίδραση που έχει το είδος των χημικών προιόντων στη διαδικασία σχεδίασης της μεταλλικής κατασκευής των δεξαμενόπλοιων μεταφοράς χημικών φορτίων. Η μεταφορά κάθε χημικού προιόντος συνοδεύεται από κάποιες ελάχιστες απαιτήσεις. Οι απαιτήσεις αυτές καταγράφονται στον κεφάλαιο 17 του IBC Code. Στο κεφάλαιο αυτό γίνεται μία προσπάθεια να αναλυθεί το κεφάλαιο 17 του IBC Code και να εξεταστεί πως συγκεκριμένα προιόντα μπορούν να επηρεάσουν τη σχεδίαση της μεταλλικής κατασκευής.

Στο **τρίτο κεφάλαιο** αυτής της διπλωματικής εργασίας περιγράφεται και αναλύεται η τυπική γενική διάταξη των δεξαμενόπλοιων μεταφοράς χημικών προιόντων. Η διάταξη των χόρων σε αυτόν τον τύπο πλοίων πρέπει να σχεδιάζεται σύμφωνα με τους αντίστοιχους κανονισμούς, έτσι ώστε να αποφεύγονται προβλήματα και δυσκολίες που μπορεί να προκύψουν από μία μη αποδοτική σχεδίαση χόρων, καθώς και να εξαλειφθούν πιθανοί κίνδυνοι τόσο για το πλήρωμα όσο και για το περιβάλλον αλλά και για την κατασκευή του πλοίου.

Σε πρώτη φάση εξετάζεται η διάταξη των δεξαμενών φορτίου. Η διάταξη και το μέγεθος των δεξαμενών φορτίου συνδέεται άμεσα με τον τον τύπο του πλοίου. Ανάλογα με τον τύπο του φορτίου που πρόκειται να μεταφέρουν τα δεξαμενόπλοια μεταφοράς χημικών φορτίων κατηγοριοποιούνται σε Τύπου Ι, ΙΙ ή ΙΙΙ. Οι τρείς τύποι των χημικών δεξαμενοπλοίων, καθώς και η επίδραση που έχει ο Τύπος Πλοίου στη διάταξη των δεξαμενών φορτίου εξετάζονται σε αυτό το κεφάλαιο.

Εξαιτίας της επικίνδυνης φύσης τους τα χημικα φορτία χρήζουν ιδιαίτερης μεταχείρησης όσο αναφορά το διαχωρισμό τους από άλλα φορτία, από τους χόρους μηχανοστασίου και ενδιαίτησης, αλλά και από τη ζέστη, το νερό και άλλα. Όλα τα παραπάνω επηρεάζουν τη διάταξη του πλοίου, με τρόπους που περιγράφονται σε αυτό το κεφάλαιο.

Επιπλέον εξετάζονται η διάταξη των κενών χόρων, των δεξαμενών καυσίμων, των δωματίων αντλιών, των δεξαμενών έρματος, των χώρων ανδιαίτησης και μηχανοστασίου, καθώς και τα ανοίγματα των υπερκατασκευών και των χόρων φορτίου.

Τέλος γίνεται μία αναφορά στις επικίνδυνες ζώνες των χημικών δεξαμενοπλοίων και την επίδραση που αυτές έχουν στην διάταξη των πλοίων.

Ο σκοπός του **τέτατρου κεφαλαίου** είναι να παρουσιάσει τα βασικά βήματα που ακολουθεί ένας ναυπηγός κατά τη διαδικασία σχεδίασης ενός πλοίου, έτσι ώστε να επισημανθεί η σημασία και η χρησιμότητα του κάθε σκέλους της σχεδίασης. Στο πρώτο μέρος αυτού του κεφαλαίου συνοψίζεται η συνολική διαδικασία της σχεδίασης. Επιλέον απομονώνονται και εξετάζονται δύο από τα πιο σημαντικά στάδια της σχεδίασης, η ανάλυση των φορτίσεων και η εκτίμηση της αντοχής του πλοίου.

Στο δεύτερο μέρος αυτού του κεφαλαίου γίνεται μία ανάλυση των φορτίσεων που αναμένεται να ασκηθούν στην μεταλλική κατασκευή του πλοίου, οι οποίες αναλύονται σε στατικές και δυναμικές με βάση τα χαρακτηριστικά τους. Επίσης εξηγείται ο τρόπος με τον οποίο οι φορτίσεις αυτές επιδρούν στην εγκάρσια και τη διαμήκη αντοχή του πλοίου. Τέλος παρουσιάζονται οι πιο συνηθισμένες μέθοδοι υπολογισμού των ασκούμενων φορτίων.

Η διαδικασία εκτίμησης της αντοχής του πλοίου αναλύεται στο τελευταίο τμήμα αυτού του κεφαλαίου, ώπου και γίνεται αναφορά σε διάφορους τύπους δομικής αστοχίας. Επίσης εξηγούναι οι συμβατικές αναλυτικές μέθοδοι εκτίμησης της αντοχής όπως είναι η Μέθοδος Πεπερασμένων Στοιχείων.

Το κεφάλαιο αυτό δεν αφορά μόνο τα δεξαμενόπλοια μεταφοράς χημικών φορτίων αλλά απευθύνεται σχεδόν σε όλους τους τύπους πλοίων καθώς ακολουθούν σχεδόν την ίδια διαδικασία σχεδίασης. Ωστόσο γίνονται συγκεκριμένες αναφορές στα χημικά δεξαμενόπλοια όπου αυτό είναι εφικτό.

Ο σκοπός του **πέμπτου κεφαλαίου** αυτής της διπλωματικής θέσης είναι να εξηγήσει ποια είναι τα υλικά που χρησιμοποιούνται περισσότερο συχνά για την κατασκευή των δεξαμενών φορτίου των δεξαμενόπλοιων μεταφοράς χημικών φορτίων, γιατί χρησιμοποιούνται αυτά τα υλικά, και ποια είναι τα κριτήρια επιλογής.

Όταν αφορά την επιλογή των υλικών κατασκευής των δεξαμενών φορτίου, η πιο σημαντική παράμετρος είναι τα υλικά αυτά να είναι ικανά να αντισταθούν στη διαβρωτική επίδραση των χημικών φορτίων. Για αυτό το λόγο ο μηχανισμός και οι πιο συνηθισμένοι τύποι διάβρωσης εξηγούνται σε αυτό το κεφάλαιο.

Τα υλικά που χρησιμοποιούνται πιο συχνά για την κατασκευή των δεξαμενών φορτίων στα χημικά δεξαμενόπλοια είναι ο ανοξείδωτος χάλυβας και ο απλός χάλυβας. Ο απλός χάλυβας, όταν χρησιμοποιείται, θα πρέπει να είναι βαμμένος κατάλληλα έτσι ώστε να αντέχει τη διαβρωτική επίδραση του φορτίου. Αρχικά εξετάζονται οι δύο βασικοί τύποι ανοξείδωτου χάλυβα: ο ωστενιτικός ανοξείδωτος χάλυβας και ο διπλός ανοξείδωτος χάλυβας. Η μικροδομή τους και τα βασικά χαρακτηριστικά τους αναλύονται και συγκρίνονται. Επιλπέον, εξηγείται η ενισχυμένη αντοχή του ανοξείδωτου χάλυβα έναντι διάβρωσης.

Όταν χρησιμοποιείται απλός χάλυβας, η επιλογή της κατάλληλης βαφής είναι κομβικής σημασίας. Κάθε τύπος βαφής έχει τα δικά της χαρακτηριστικά, πλεονεκτήματα και μειωνεκτήματα. Στη συνέχεια παρουσιάζονται οι πιο συνηθισμένοι τύποι βαφής και δίνονται πληροφορίες σχετικά με τις ιδιότητες τους.

Τέλος γίνεται αναφορά στη διαδικασία επιλογής των κατάλληλων υλικών για την κατασκευή των δεξαμενών φορτίου.

Το **έκτο κεφάλαιο** αυτής της διπλωματικής εργασίας προσπαθεί να εξηγήσει και να αναλύσει τη δομή της μεταλλικής κατασκευής των τυπικών δεξαμενόπλοιων μεταφοράς χημικών προιόντων, καθώς και τα δομικά τους στοιχεία. Αρκετά σχέδια από υπάρχοντα πλοία παρατείθονται για ευκολότερη κατανόηση.

Πριν από την ανάλυση της δομής της μεταλλικής κατασκευής παρατείθονται μερικά γενικά χαρακτηριστικά σχεδίασης της γάστρας, όπως είναι το εύρος του συντελεστή πληρότητας γάστρας, και οι τυπικες πρωραίες και πρυμναίες διαταξεις. Επίσης μελετάται η επίδραση της θερμόκρασίας, της πυκνότητας του φορτίου, και των διάφορων καταστάσεων φόρτωσης στη σχεδίαση.

Στη συνέχεια επεξηγείται η δομή της μεταλλικής κατασκευής των δεξαμενών φορτίων καθώς και οι διάφοροι τύποι τους. Για κάθε τύπο δεξαμενής δίνονται οι μέθοδοι διαστασιολόγησης όπως προκύπτουν από τους κανονισμούς των νυογνωμόνων. Ειδική αναφορά γίνεται στα στηρίγματα των ανεξάρτητων δεξαμενών φορτίου.

Στη συνέχεια επεξηγείται η δομή του καταστρώματος και των εγκάρσιων και διαμήκων φρακτών. Ιδιαίτερη έμφαση δίνεται στις πτυχωτές φρακτές καθώς είναι ο πιο διαδεδομένος τύπος φρακτών που χρησιμοποιείται στα χημικά δεξαμενόπλοια. Στο κεφάλαιο αυτό επίσης περιλαμβάνονται σχεδιαστικές παράμετροι των πτυχωτών φρακτών καθώς και η επίδρασή τους στη σχεδίαση, τύποι πτυχωτών φρακτών, διαστασιολόγηση κ.α. Τέλος γίνεται μία αναφορά σε διατάξεις διπλού πυθμένα και διπλών τοιχωμάτων.

Αυτό που διαφοροποιεί τα δεξαμενόπλοια μεταφοράς χημικών προιόντων από τα πετρελαιοφόρα δεξαμενόπλοια είναι τα προηγμένα συστήματα φορτίου που είναι εγκατεστημένα στο πλοίο για τον έλεγχο και τον χειρισμό των διάφορων φορτίων. Αυτά τα συστήματα παρουσιάζονται στο έβδομο κεφάλαιο αυτής της διπλωματικής εργασίας. Τα συστήματα φορτίου ενός πλοίου, σε συνδιασμό με τη διάταξη των δεξαμενών του και τα συστήματα ασφαλείας, καθορίζουν ποιά προιόντα μπορεί το πλοίο να μεταφέρει. Ο σκοπός αυτού του κεφαλαίου είναι να παρουσιάσει τα βασικότερα συστήματα φορτίου και την επίδραση τους στη σχεδίαση του πλοίου.

Αρχικά γίνεται μία αναφορά στα συστήματα σωληνώσεων και τη διάταξη των στομίων. Η μέθοδος διαστασιολόγησης των σωληνώσεων φορτίου δίνεται σύμφωνα με τον IBC Code. Επιπλέον, δίνονται στοιχεία για τις ενώσεις των σωληνώσεων και παρουσιάζονται οι τρεις βασικοί τύποι φλατζών που χρησιμοποιούνται.

Στη συνέχεια λαμβάνει χώρα μία ανάλυση των αντλιών φορτίου που χρησιμοποιούνται στα δεξαμενόπλοια μεταφοράς χημικών φορτίων. Πιο συγκεκριμένα, η ανάλυση επικεντρώνεται στις βυθισμένες αντλίες φορτίου καθώς είναι αυτ΄ς που χρησιμοποιούνται συνηθέστερα στα χημικά δεξαμενόπλοια. Οι δύο τύποι βυθισμένων αντλιών φορτίου - δηλαδή οι ηλεκτρικές και οι υδραυλικές αντλίες – παρουσιάζονται, εξηγούνται οι λειτουργίες τους και αναλύονται τα δομικά τους μέρη.

Τέλος παρούσιάζονται όλα τα υπόλοιπα συστήματα φορτίου που μπορεί να υπάρχουν σε ένα δεξαμενόπλοιο μεταφοράς χημικών φορτίων, όπως τα συστήματα καθαρισμού των δεξαμενών, τα συστήματα εξαερισμού των δεξαμενών, τα συστήματα ελέγχου του φορτίου κ.α.

Τέλος, στο **όγδοο κεφάλαιο** αυτής της διπλωματικής εργασίας παρουσιάζονται κάποιες εναλλακτικές σχεδιάσεις δεξαμενοπλοίων μεταφοράς χημικών φορτίων.

Εξαιτίας της φύσης των φορτίων τα οποία μεταφέρουν, τα οποία μπορεί να είναι ιδιαίτερα επικίνδυνα, τα σύγχρονα δεξαμενόπλοια μεταφοράς χημικών προιόντων είναι ιδιαίτερα προηγμένα τεχνολογικά. Είναι περίπλοκα και ακριβά πλοία για την εξέλιξη των οποίων έχουν χρησιμοποιηθεί την τελυταία δεκαετία συνδιασμένες γνώσεις και εμπειρία. Αυτό έχει οδηγήσει την τωρινή γενιά χημικών δεξαμενόπλοιων διπλής γάστρας τα οποία είναι εξοπλισμένα με περίπλοκα συστήματα φορτίου να θεωρούνται το επιστέγασμα της τεχνολογικής εξέλιξης των πλοίων από άποψη σχεδίασης και ασφάλειας.

Για αυτό το λόγο οι μελλοντικές σχεδιάσεις επικεντρώνονται περισσότερο στο πως να βελτιώσουν τις ήδη υπάρχουσες σχεδιάσεις και λιγότερο στο να αναπτύξουν εναλλακτικά σχεδιαστικά μοντέλα. Βελτιώμενες βαφές για τις δεξαμενές φορτίου, βελτιωμένοι χάλυβες για την κατασκευή τους, και διάφορες βελτιώσεις στα συστήματα φορτίου είναι κάποιοι από τους τομείς της εξέλιξης.

Η σχεδίαση των δεξαμενόπλοιων μεταφοράς χημικών φορτίων στο μέλλον θα επηρεάζεται βασικά από δύο παράγοντες: Την απαλοιφή της ρύπανσης από τα απόβλητα, προσπάθοντας να μειωθεί το νερό το οποίο χρησιμοποιείται για την απόπλυση των δεξαμενών, και τη διασφάλιση υψηλής ποιότητας ισάξιας με αυτή που υπάρχει στη βιομηχανία φαγητού.

Σε αυτό το κεφάλαιο τελος, παρουσιάζονται δύο ήδη υπάρχουσες σχεδιάσεις: ο συνδιασμός διπλού ανοξείδωτου χάλυβα και απλού ανοξείδωτου χάλυβα για την κατασκευή των δεξαμενών φορτίου, και η σχεδίαση ενός δεξαμενόπλοιου μεταφοράς χημικών προιόντων μεταφορικής ικανότητας 75000 τόνων. Επιπλέον, παρουσιάζεται μία εναλλακτική σχεδίαση χημικου δεξαμενόπλοιου με κυλινδρικές δεξαμενές φορτίου.

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Chapter 1

Introduction to chemical tankers

1.1 Introduction

The first chapter of this thesis sets as target to familiarize the reader with the concept of chemical tanker vessels. In this respect, a brief description of all types of tankers is given, in order of the reader to be able to distinguish chemical, from different types of tanker vessels. Additionally, the term chemical tanker is defined as adopted by the MARPOL Annex II.

Subsequently, an effort has been made to look back at the genesis and evolution of this type of vessels, reaching back to the beginning of the 20th century, when the first chemical tankers appeared in order to fulfill the demands for chemical products' transportation that were born from the continuously expanding chemical industry. This section tries to analyze the development of chemical tankers in line with the development of their environment and the demands of the society, and to focus on individual vessels that have made a great impact due to innovational breakthroughs that were applied on them.

This rapid evolution of the chemical tankers, has led to a development of a series of regulations that govern their design, constructional and operational principals. It is of highest importance for someone who wants to deal with this type of vessel, to be familiar and have a solid knowledge of these rules. For that reason these regulations are also presented in this chapter.

Finally, some additional details, such as classification ways, market trends, and fleet analysis are been given to the reader as a tool, in order of him to be able to better understand and evaluate what he will come up to in the chapters to follow.

1.2 Classification of tankers by type of cargo[1]

A tanker is, in a wide sense, a general term for a cargo ship carrying liquid cargoes in bulk, and in a narrow sense, a term for a vessel carrying petroleum oils and their products. Liquid cargoes carried in bulk by tankers include petroleum oils, petroleum products, liquefied gases, many kinds of liquid chemicals, slurry substances, etc.

The classification of tankers in terms of carrying cargoes is as follows:

- Oil tanker: An oil tanker is a tanker carrying petroleum oil and petroleum products. They are subdivided into crude oil tankers, product tankers and crude oil/product tankers according to their purpose respectively.

Figure 1.1 – Oil tanker (VLCC)

- Product tanker: A product tanker is an oil tanker carrying petroleum products and they are generally divided into two types: clean product tankers, which transport light petroleum products and dirty product tankers, which transport heavy petroleum products.

Figure 1.2 – Product tanker

- Chemical tanker: A chemical tanker is a tanker carrying chemicals and usually they are divided into two types: parcel chemical tankers, which are capable of transporting many kinds of chemical cargoes including petroleum products, and exclusive chemical tankers, which transport very limited kinds of chemical cargoes.

Figure 1.3 – Chemical Tanker

- Liquefied gas tanker: A liquefied gas tanker is a tanker transporting liquefied gases in pressurized and/or refrigerated conditions. They are subdivided into LPG carriers and LNG carriers.

Figure 1.4 – LPG carrier

Figure 1.5 – LNG carrier

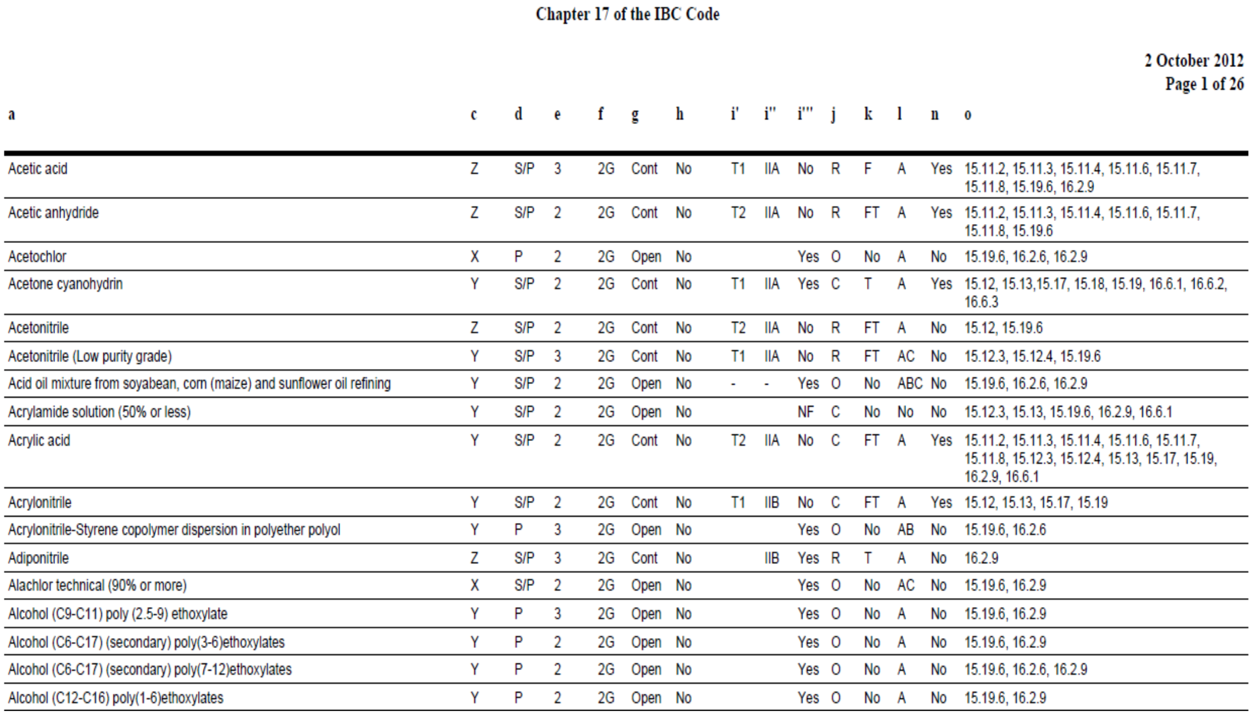
- Combination carrier: A combination carrier is a cargo ship which transports ore or solid cargo and crude oil alternatively. They are subdivided into ore/oil carriers and ore/bulk/oil carriers (OBOs).

Figure 1.6 – Ore/oil carrier

1.3 Definition of the term Chemical tanker

According to the International Maritime Organization (IMO), as defined in the MARPOL Annex II[2], a chemical tanker is a ship constructed or adapted and used for the carriage in bulk of any liquid product listed in chapter 17 of the International Bulk Chemical code (IBC code).

Chapter 17 of the IBC code contains a list of all the chemicals covered by the code. The IMO publishes annually a Provisional Categorization of Liquid Substances list to provide guidance on new products that are to be covered under the IBC code. The provisional categorization list is valid until the next revision of the IBC code is published.[3]



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a	c	d	e	f	g	h	i'	i''	i'''	j	k	l	n	o
Acetic acid	Z	S/P	3	2G	Cont	No	T1	IIA	No	R	F	A	Yes	15.11.2, 15.11.3, 15.11.4, 15.11.6, 15.11.7, 15.11.8, 15.19.6, 16.2.9
Acetic anhydride	Z	S/P	2	2G	Cont	No	T2	IIA	No	R	FT	A	Yes	15.11.2, 15.11.3, 15.11.4, 15.11.6, 15.11.7, 15.11.8, 15.19.6
Acetochlor	X	P	2	2G	Open	No			Yes	O	No	A	No	15.19.6, 16.2.6, 16.2.9
Acetone cyanohydrin	Y	S/P	2	2G	Cont	No	T1	IIA	Yes	C	T	A	Yes	15.12, 15.13,15.17, 15.18, 15.19, 16.6.1, 16.6.2, 16.6.3
Acetonitrile	Z	S/P	2	2G	Cont	No	T2	IIA	No	R	FT	A	No	15.12, 15.19.6
Acetonitrile (Low purity grade)	Y	S/P	3	2G	Cont	No	T1	IIA	No	R	FT	AC	No	15.12.3, 15.12.4, 15.19.6
Acid oil mixture from soyabean, corn (maize) and sunflower oil refining	Y	S/P	2	2G	Open	No	-	-	Yes	O	No	ABC	No	15.19.6, 16.2.6, 16.2.9
Acrylamide solution (50% or less)	Y	S/P	2	2G	Open	No			NF	C	No	No	No	15.12.3, 15.13, 15.19.6, 16.2.9, 16.6.1
Acrylic acid	Y	S/P	2	2G	Cont	No	T2	IIA	No	C	FT	A	Yes	15.11.2, 15.11.3, 15.11.4, 15.11.6, 15.11.7, 15.11.8, 15.12.3, 15.12.4, 15.13, 15.17, 15.19, 16.2.9, 16.6.1
Acrylonitrile	Y	S/P	2	2G	Cont	No	T1	IIB	No	C	FT	A	Yes	15.12, 15.13, 15.17, 15.19
Acrylonitrile-Styrene copolymer dispersion in polyether polyol	Y	P	3	2G	Open	No			Yes	O	No	AB	No	15.19.6, 16.2.6
Adiponitrile	Z	S/P	3	2G	Cont	No		IIB	Yes	R	T	A	No	16.2.9
Alachlor technical (90% or more)	X	S/P	2	2G	Open	No			Yes	O	No	AC	No	15.19.6, 16.2.9
Alcohol (C9-C11) poly (2.5-9) ethoxylate	Y	P	3	2G	Open	No			Yes	O	No	A	No	15.19.6, 16.2.9
Alcohol (C6-C17) (secondary) poly(3-6)ethoxylates	Y	P	2	2G	Open	No			Yes	O	No	A	No	15.19.6, 16.2.9
Alcohol (C6-C17) (secondary) poly(7-12)ethoxylates	Y	P	2	2G	Open	No			Yes	O	No	A	No	15.19.6, 16.2.6, 16.2.9
Alcohol (C12-C16) poly(1-6)ethoxylates	Y	P	2	2G	Open	No			Yes	O	No	A	No	15.19.6, 16.2.9

Figure 1.7 – First Page of Chapter 17 of the IBC 2012

1.4 Historical evolution

The chemical tanker as a ship type has its origins in the late 1940s and early 1950s. The first chemical tankers were developed to meet the needs of a growing petrochemical industry on the Gulf coast of the United States.[3]

Prior to the 1920s – and in fact afterwards as well – chemical manufacturers relied upon traditional raw materials such as animal and vegetable matter. However, the significant use of hydrocarbons as raw materials for the synthesis of organic chemicals began in the USA around this time. Cracker gases, rich in olefins (ethylene, propylene and butylene) were initially regarded as by-products of oil refining, but from the 1920s onwards it was realized that they could be profitably used as feedstock for chemical manufacture. For instance, by the 1930s, natural gas had largely replaced coke gases as feedstock for the synthesis of ammonia.

Initially, shipments from chemical plants were transported in drums and in portable tanks by road on the US Interstate highway system, as well as by rail tank cars to the US Atlantic coast. Individually packaged chemicals had also been transported in glass carboys, drums and tank containers on conventional ships, by river and sea.

Throughout the 1950s demand for chemicals increased rapidly and more sophisticated means of transport were required. For a while the deep tank on board dry cargo ships were able to supplement existing methods of transportation, but the emergence of hazardous new chemicals which had to be shipped in large parcels made it clear that a new type of ship was required.

The surplus of wartime T2 tankers ensured an ample supply of ships that could be converted for the large-scale carriage of bulk chemicals. Conversion of such vessels was not technologically demanding, but necessary so as to enable cargo segregation. Conversion work usually included adding bulkheads to provide more and smaller tanks, extending the line system and installing additional cargo pumps.[4]

By realizing the significance of cargo segregation, the tank layouts in the earliest of these conversions enabled the simultaneous carriage of several hazardous and incompatible cargoes. The first of the new breed was the 9,073 GT R.E. Wilson, converted for Union Carbide and Carbon Corp. In 1948, this ship was fitted with a double bottom and deepwell pumps, unique for such ships at that time. Her center tanks enabled the carriage of nine different chemicals while petroleum products of moderate density, such as kerosene, could be carried in the wing tanks. The ship entered service in January 1949 and shuttled regularly from the Gulf Coast ports to New York. She was scrapped in 1971.[5]

In addition to these converted, relatively large chemical carriers, smaller tankers specially designed and constructed for the carriage of "acids" – e.g. sulfuric acid, were built during the early 1950s, the cargo tanks of which were made of special alloy steel, strengthened for cargo densities up to 2.0 kg/l.

In the Netherlands, the Broere brothers put their first chemical tanker of only 400 dwt into service in October 1949 delivering US cargoes to North Sea ports. This ship was followed by the 2,880 dwt Elizabeth Broere in 1954. These small ships could not compete against the economies of scale that the much larger converted oil tankers could offer.

The chemical parcel tanker trades were created with the introduction of the converted cargo ships and oil tankers. The essence of this trade was that it enabled a variety of shippers of small lots of liquid chemicals - or parcels - to enjoy the economies of scale of larger size tanker operation and regularity of service. Parcels could have a size extending from a few hundred to a few thousand tonnes each; they could be any of a multitude of products; and they could be loaded and/or discharged at any one of a number of ports along an established route.

As the redundant wartime T2 tanker and the C4 cargo vessels had been the trigger for the conversion into chemical tankers, a new impetus came from another regional war that resulted in the closure of the Suez Canal in 1957. The petroleum products tankers of that time were made uncompetitive by larger and newer vessels, which had better economies for sailing round the Cape of Good Hope. Owners of this redundant tonnage were willing to invest in conversions in order to avoid lay-up and assure employment. The conversion of the tankers usually entailed adding a few bulkheads to provide smaller tanks, coating some of the tanks with zinc silicate, installing additional pumps and pipelines to provide segregation and, if necessary, adding a second pump room.

The first tanker to be specially designed to carry chemicals in bulk was the Marine Dow-Chem, a twin-screw steam turbine ship built in 1954 in the USA.[6] The vessel had double bulkheads to separate the tanks, each with separate transfer systems, pipes and connections. She was used to carry eleven chemical cargoes, each with their own different characteristics, from Dow's Texas plants to US ports, the Caribbean and Central and South America. At 168 meters in length the Marine Dow Chem was capable of transporting 16,000 long tons of chemicals in her specially designed hold.[4]

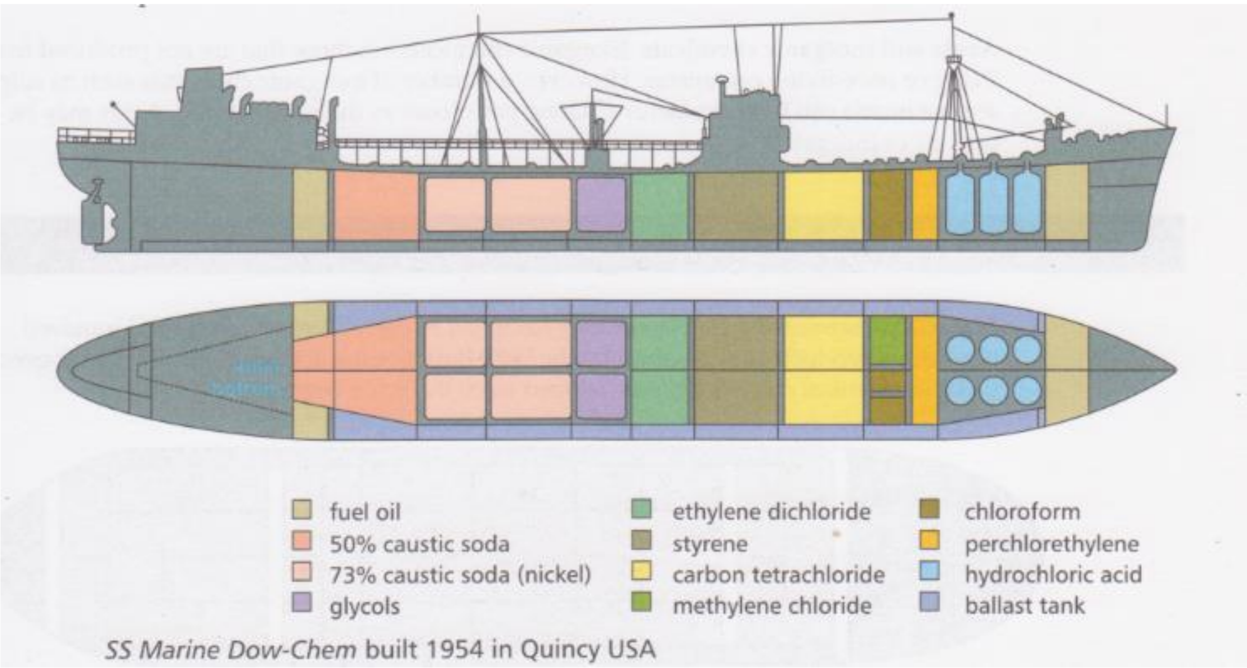

Figure 1.8 – SS Marine Dow-Chem

Parcel tankers incorporated all of the characteristics of the early tankers plus a few more. More bulkheads were included to give each ship more than 40 tanks. Apart from coatings, stainless steel tanks were fitted in many ships, enabling them to carry corrosive cargoes or cargoes requiring a high degree of product purity.

Stainless steel tanks were expensive, but offered relatively easy cleaning and enabled the transport of a number of cargoes that could not be shipped in conventional, coated mild - steel tanks. The first tanker equipped with stainless steel cargo tanks was the Norwegian M/T Lind, delivered in 1960.

Over the next forty years the chemical transportation industry continued to expand and evolve. The innovations and developments were fueled by the needs of the shippers and their cargoes as well as by the desire of the shipowners to operate more efficient vessels. These innovations and technologies were developed by a joint effort by chemical tanker shipowners and operators, ship designers, equipment manufacturers, shipbuilders and classification societies. The growing body of international regulations on ship design and operations provided additional impetus.[7]

In the early 1970s international control of the bulk shipments of chemicals had been *de facto* addressed by the United Nations-backed International Maritime Consultative Organization (IMCO). IMCO had promulgated a Bulk Chemical Code for the construction and equipment of ships carrying dangerous chemicals in bulk. The Code was applicable to all ships built or converted after April 1972. Moreover, after a six- year grace period, the Code would be extended to include all chemical carriers in operation.

The Code forced the chemical tankers to adopt many technological innovations in respects of safety and environmental protections. As a matter of fact, modern chemical tankers were equipped with cargo tank vetting and gas freeing systems, environmental control of cargoes, electrical installations, fire protection and extinction. [4]

The size of chemical tankers usually varies between small ones (5,000 dwt or less) to bigger ones (over 40,000 dwt), which is considerably smaller than an average crude oil or product tanker because of the usually smaller quantities of chemical cargo and the sometimes much smaller ports where the ship loads or unloads.[8] However larger ships have also been built in recent years. The larger chemical tanker yet known is the Bow Pioneer[9] delivered in April 2013 in Daewoo, Korea. The 75,000 dwt Bow Pioneer represents a new development within the chemical tanker industry, and is a considerably larger chemical tanker than ever built before.

Figure 1.9 – Bow Pioneer

1.5 International Regulations

As described in “Ship Design and Construction, Volume 2”, Chemical tanker design and operation is principally governed by three documents issued by the International Maritime Organization (IMO). The first and most specific to chemical tankers is *The International Code for the Construction and Equipment of Ships Carrying Dangerous Chemicals in Bulk* (IBC Code)[*]. The *International Conversion for the Safety of Life at Sea, 1974, as amended* (SOLAS)[**] includes more general regulations governing commercial vessel design. Finally, *The International Convention for the Prevention of Pollution from Ships, 1973, and Protocol of 1978 (MARPOL 73/78)*[***] provides regulations that affect the design and operation of chemical tankers with regard to pollution prevention. These international regulations are the foundation for the majority of the flag state regulations and classification society rules relating to the design of chemical tankers.

1.5.1 SOLAS

The purpose of SOLAS is to provide regulations governing the design, construction, and operation of commercial vessels with a focus on maximizing safety. Chemical tankers are required to meet many of the generic safety regulations included in SOLAS that are applicable to all types of vessels, such as radio and navigation equipment. The SOLAS regulations specific to chemical tanker design and operations are located in Chapter VII part B, titled *Construction and Equipment of Ships Carrying Dangerous Liquid Chemicals in Bulk.* This section does not contain specific technical requirements or a list of cargoes to which it applies, but rather differs from the IBC code. The section requires that all chemical tankers built after 1 July 1986 comply with the requirements of the IBC code as well as with the applicable survey requirements spelled out in Chapter I of SOLAS. The text of the chapter also requires that the chemical tankers built after 1 July 1986 be surveyed and certified as per the IBC code.

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[*] International Code for the Construction and Equipment of Ships Carrying Dangerous Chemicals in Bulk (IBC Code) as amended by MEPC.225(64) and MSC.340(91)- International Maritime Organization, London, June 2014

[**] SOLAS Consolidated Edition, 2009 Consolidated text of the International Convention for the Safety of Life at Sea, 1974, and its Protocol of 1988: articles, annexes and certificates

[***] Articles, Protocols, Annexes, Unified Interpretations of the International Convention for the Prevention of Pollution from ships, 1973 as modified by the Protocol of 1978, Consolidated Edition 2002,International Maritime Organization, London ,2001

1.5.2 IBC code

The IBC code contains the IMO regulations that specifically govern the design, construction, and outfitting of newly built or converted chemical tankers. The IBC code was adopted by the IMO's Maritime Safety Committee (MSC) in 1983 and by the IMO's Maritime Environmental Protection Committee in 1985. The IBC replaced the *Code for the Construction and Equipment of Ships Carrying Dangerous Chemicals in Bulk* (BCH code), which applies to chemical tankers built or converted before 1 July 1986. The purpose of the IBC code as stated in its preamble is:

"…to provide an international standard for the safe carriage, in bulk by sea, of dangerous chemicals and noxious liquid substances listed in chapter 17 of the Code. The Code prescribes the design and construction standards of ships, regardless of tonnage, involved in such carriage and the equipment they shall carry to minimize the risk to the ship, its crew and the environment, having regard to the nature of the products involved."

The IBC code applies to any size vessel that is engaged in the carriage of dangerous or noxious liquid chemical substances in bulk, not including petroleum or similar products. The substances covered by the code are defined as:

- Products having significant fire hazards in excess of those of petroleum products or similar flammable products, and
- Products having significant hazards in addition to or other than flammability.

Based on these definitions, most petroleum products such as gasoline, kerosene, diesel, and solvent naphtha are not required to be carried on chemical tankers as defined by the IBC code. The products covered by the IBC code are also defined as possessing a vapor pressure equal to or less than 2.8 bar absolute at a temperature of 37.8° C. This guideline excludes liquefied gases from the auspices of the IBC code as they are covered by *The International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk* (IGC code).

The cargo hazards other than flammability that are considered by the IBC code include health hazards, reactivity hazards, and water, air, and marine pollution hazards. Specific health hazards considered are the toxic, irritant, and sensitizing effects of the material. With regards to reactivity, the materials reactivity with itself, water, and other products are considered. In terms of water pollution the hazards considered are human toxicity, water solubility, the odor and taste, and material relative density. The air pollution hazards taken into account include toxicity, vapor pressure, vapor density, solubility in water, and relative density of the product. The marine pollution hazards takes into account the bioaccumulation risks, the damage to living resources, the hazard to human health, and the reduction of amenities.

The IBC code defines three ship types, ST1, ST2, and ST3. The ship type determines the type of cargoes, with regard to safety and environmental hazards, that a vessel may transport, based on the vessel's design and equipment. A list of cargoes that can be carried by a chemical tanker is included in Chapter 17 of the IBC code. For each of the chemicals included in this list, the code assigns one of three ship types. A chemical assigned to ST1 in Chapter 17 is deemed to present the greatest combined threat to safety and the environment. As the ship type number increases the overall threat that the chemical presents, the rules governing the ship design become less stringent.

For each ship type there are specific design criteria that must be met, such as double bottom height and double side width. The list included in Chapter 17 also identifies eleven different categories of requirements that must be incorporated into a ship's design and/or operation so that it may carry a given cargo. These requirements range from tank gauging systems to requirements for construction material. Therefore, the ship type alone does not qualify a ship to carry a specific cargo. In addition to the ship type the vessel must also be outfitted with the equipment that the IBC code requires for the specific cargo. Included in the list in Chapter 17 are product hazard categories and pollution category designations. The pollution categories (A, B, C, D) are derived from the regulations set forth in MARPOL 73/78, Annex II. Since the total hazard, that includes both safety and environmental, is considered when assigning a ship type to a cargo, there is no direct correlation between ship type and the MARPOL pollution category.

Chapter 18 of the IBC code includes a list of the products for which the code does not apply. The code does not apply to these cargoes as it has been determined that they do not present sufficient hazard to warrant their inclusion. This does not imply that there are no special carriage or handling requirements related to the cargo but rather because of the nature of the cargo, the rules governing their carriage is left to the discretion of the flag states and the classification societies.

The IBC code includes regulations that govern the following areas of chemical tanker design:

- Intact stability and freeboard
- Damage stability
- Location of cargo tanks
- Vessel arrangements
- Cargo containments
- Cargo transfer
- Construction materials
- Cargo tank venting and gas freeing
- Environmental control of cargoes
- Electrical installations
- Fire protection and extinction
- Mechanical ventilation in cargo area
- Instrumentation
- Personnel protection
- Operation Requirements

Finally, the IBC code requires two pieces of documentation unique to chemical tankers. The first document is the International Certificate of Fitness for the Carriage of Dangerous Liquid

Chemicals in Bulk or COF. The COF provides a list of all the chemical cargoes that the vessel is approved to carry, based on its design and equipment on board. In order for a vessel to carry any particular cargo that is listed in Chapter 17 of the IBC code or any cargo that is designated as pollution category D and is listed in Chapter 18 of the IBC code it must be listed on the vessel's COF. The COF is typically issued and maintained by the classification society on behalf of the vessel's flag state. The COF is an internationally accepted document that indicates that a vessel meets the requirements of the IBC code. The second piece of documentation required by the IBC ode is the vessel's Procedures and Arrangement (P&A) Manual whose purpose and required format is outlined in the MARPOL 73/78 Annex II regulations.

1.5.3 MARPOL 73/78

The stated purpose of the MARPOL convention is:

"to achieve the complete elimination of intentional pollution of the marine environment by oil and other harmful substances and the minimization of accidental discharge of such substances."

Annexe II of the convention are the "Regulations for the Control of Pollution by Noxious Substances in Bulk" and applies to design and operation of chemical tankers. The Annex provides specific regulations aimed at preventing pollution from the discharge of both chemical cargo residues and cargo tank washings. These regulations address both the operational procedures and the unloading arrangements of vessels. The regulations are applies based on a cargo categorization system. This system places each noxious liquid cargo into one of four categories (A, B, C and D) based on the threat that the cargo poses to the marine environment.

The Annexe includes regulations regarding the amount of cargo residues that may remain in a tank after discharging is complete. This requirement affects the design of the vessels cargo tanks cargo piping and pumping systems. To promote this requirement the Annexe calls for testing of the system to be carried out and approved by the flag state. The test procedure and associated calculation methods are included in the appendix to the Annexe II regulations. Requirements for the locations and size of the underwater discharge ports for tank washings are also stipulated by the Annexe.

The Annexe requires that each vessel carrying noxious liquid substances carry certain documentation that proves compliance with regulations. Each vessel is required to maintain a Cargo Record Book that lists all cargo-related activities that are carried out on an individual cargo tank basis. Activities that are required to be listed include the loading, transferring, and discharge of cargoes, tank cleaning, disposal of residues to shore, and discharging of tank washings at sea. The Annexe requires that each vessel be provided with a Procedures and Arrangement Manual (P&A Manual) that provides specific guidance on how the vessel is to be operated to ensure compliance with the regulations set forth in the Annexe. This manual is a design document that is produced by either the vessel designer or shipbuilder and approved by the flag state. Typically the vessel’s class society will review and approve the P&A manual on behalf of the flag state administration. The Annexe also requires that chemical tankers be provided with Shipboard Marine Pollution Emergency Plan (SMPEP), which provides guidance to the vessels’ operators in the event of a pollution incident.

It should be noted that most chemical tankers are designed so that they can carry petroleum products as well as chemicals. These vessels must meet the applicable requirements of both Annexe I and Annexe II of MARPOL 73/38.

1.6 Chemical tankers classification

1.6.1 Size categorization

Chemical tankers can be categorized in a number of different ways. Unlike oil and product tankers there is no universally accepted size categorization of chemical tankers, however modern vessels typically fall into one of the following three categories:

- **Inland Chemical Tankers:**
  500 to 4,000 tons DWT. Typically in the form of self - propelled barges. Commonly used in the river systems of northwestern Europe to load cargo from larger tankers or coastal terminals and transport the material to inland industrial facilities.
- **Coastal Chemical Tankers:**
  3,000 to 10,000 tons DWT. These small tankers, also referred to as short sea tankers, are used to transport chemicals coastwise and to transship cargoes into ports and terminals where larger tankers are unable to call because of any number of restrictions. These tankers may load or discharge cargo from a shore terminal or directly from a larger vessel. These vessels are commonly used in the intra - Europe, intra - southeast Asia, and the north - central south American markets.
- **Deep Sea Tankers:**
  10,000 to 50,000 tons DWT. These ocean going vessels typically have a large number of segregations and have either stainless steel or coated tanks. These vessels operate on the major trade routes between North and South America, Europe, the Middle East and Asia.

1.6.2 General type categorization

A modem chemical tanker is primarily designed to carry some of the several hundred hazardous products now covered by the IMO Bulk Chemical Codes. The following general types of chemical carriers have developed since trade began:[13]

- **Sophisticated parcel chemical tankers:**
  Typically up to 40,000 tonnes deadweight with multiple small cargo tanks - up to 54 - each with an individual pump and a dedicated pipeline, to carry small parcels of high grade chemicals. These ships have a significant proportion of the cargo tanks made with stainless steel, allowing maximum flexibility to carry cargoes that need their quality safeguarded.
- **Product / chemical tankers:**
  Of similar size to parcel tankers but with fewer cargo tanks, mostly of coated steel rather than stainless, and less sophisticated pump and line arrangements. Such ships carry the less difficult chemicals, and also trade extensively with clean oil products.
- **Specialized chemical carriers:**
  Small to medium sized ships, often on dedicated trades and usually carrying a single cargo such as an acid, molten sulfur, molten phosphorus, methanol, fruit juice, palm oil and wine. Cargo tanks are coated or stainless steel according to the trade.

1.6.3 Ship type categorization as per IBC code

Chemical tankers can be also grouped by the level of cargo containment designed into the vessel, known as Ship Type (ST).

The IBC code defines three specific ship types, with ST 1 providing the greatest level of containment for the transportation of the most hazardous cargoes. Conversely, ST 3 provides minimal containment for carriage of the least hazardous cargoes covered by the IBC code. Chemical tanker designs typically fall in one of three ship type arrangements:

1. ST 1/2
2. ST 2
3. ST 2/3

1.7 Fleet Analysis

According to data taken from Odfjell[11], chemical tankers account for 8 percent of global tankers fleet by numbers, as is shown in the following diagram.

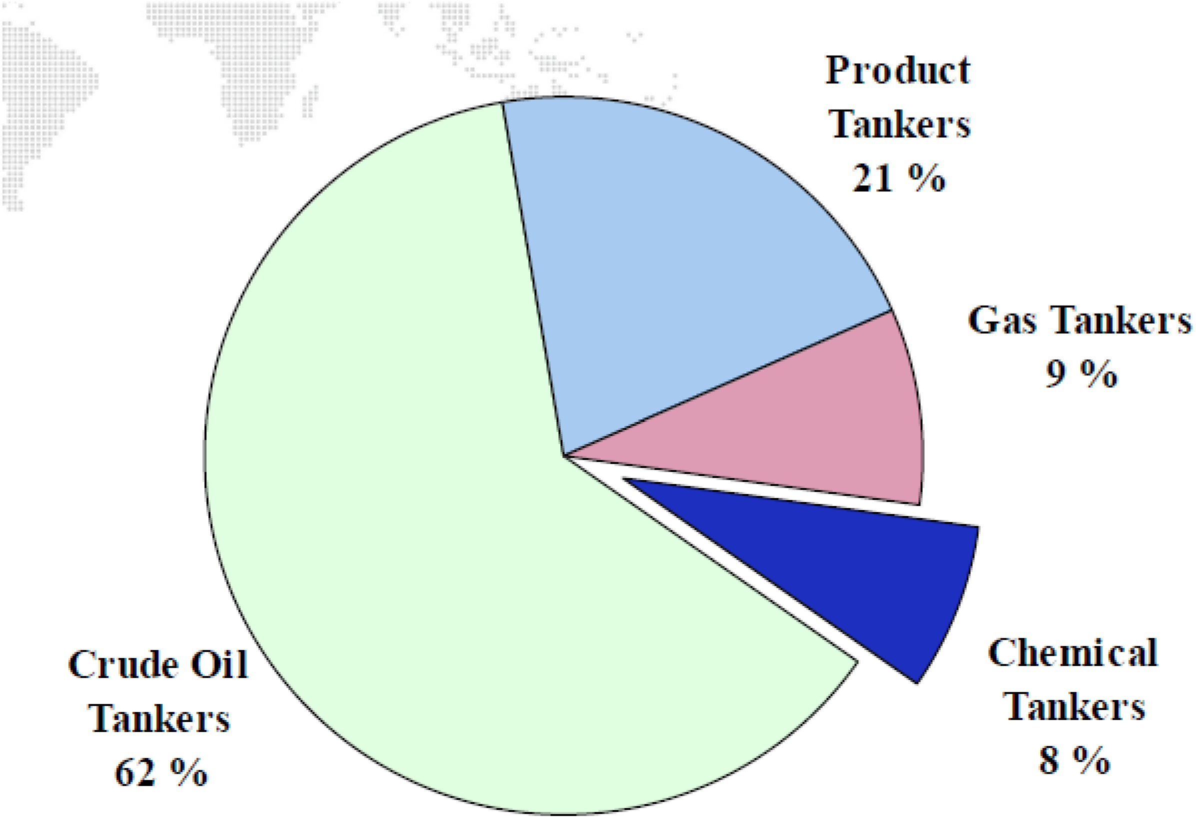

Figure 1.10 – Tankers fleet distribution (2015)

Ship owners acquire chemical tankers either through the contracting of one or a series of new buildings or by the purchase of one or several vessels in the second hand market. When new buildings are delivered, the global fleet or supply increases, likewise when a tanker is scrapped, the global fleet or supply decreases. The growth rate of supply in the chemical tanker market can therefore be determined by the balance between deliveries and scrapping of chemical tankers in the market.[12]

The global chemical fleet has grown by 25 % between 2008 and 2011, however the rate of fleet growth continues to slow with 4,651,058 DWT and 3,358,465 DWT added in 2011 and 2012 respectively. The reason for this may be the large average age of the fleet, as at the end of 2012, 5.9 million DWT or 8 % of the global fleet was 20 years or older. This leaves scope for further scrapping to take place if steel prices remain firm.[13]

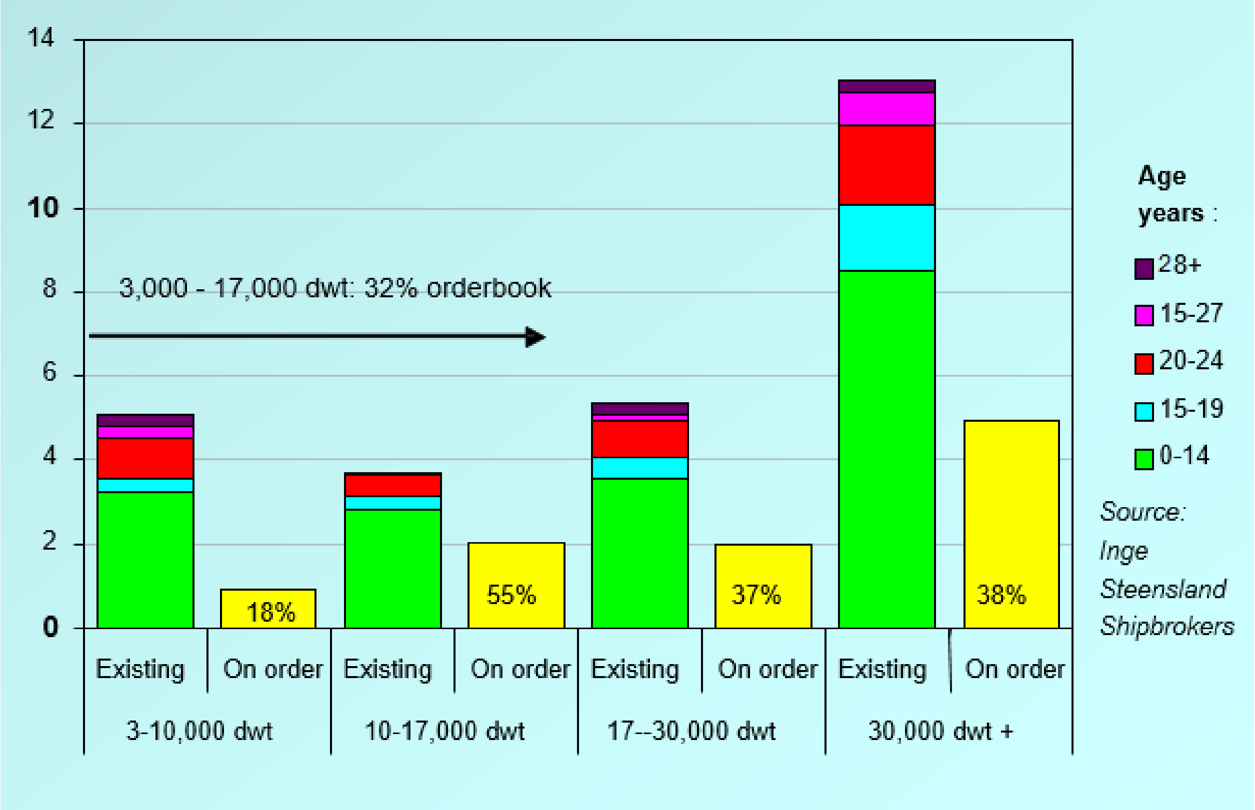

Figure 1.11 – Age and size distribution of chemical tanker fleet (2006)[14]

In a shipping market review delivered by Danish Skibskredit in October 2012[15], the chemical tanker fleet was expected to grow only 3% in 2012. Deliveries were at the lowest level in ten years, as a result of cancelations, only 49% of the expected deliveries actually were delivered.

About 40% of the vessels delivered were highly specialized chemical tankers with either stainless steel or marineline coated tanks. The remaining 60% were vessels with less than 13 sophisticated tanks, coated either with zinc or epoxy. Scrapping activity remained fairly high compared to previous years. During the first eight months of 2012 scrapping amounted to 0.5 million dwt. with an average scrapping age of 27 years.

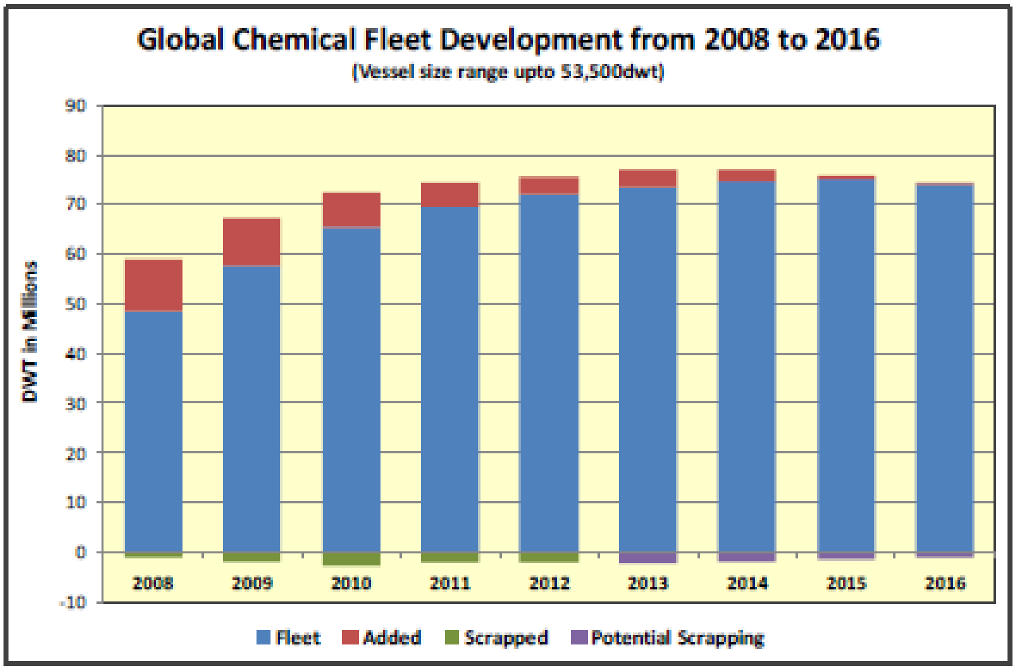

Figure 1.12 – Global Chemical Fleet Development

Eighty of the total 151 ships on the orderbook were delivered in 2012, all coming from yards in China, including several that were thought to have been cancelled. Of these 80 ships, 68 are below 20,000 dwt and most are in the 5,000 to 10,000 dwt class, with many now trading Palm Oil. Korean yards delivered 28 ships; all but one being above 37,000 dwt. Japanese yards delivered 24 ships in sizes ranging from 1,231 dwt to over 50,000 dwt.

The average dwt of the ships on order is now 32,015 tons against 23,934 tons a year ago. New ordering activity of late is gravitating towards larger sizes of 38,000 dwt or above for deliveries spread into 2016. The move towards MRs and Handysize tankers has been prompted by better fuel efficiency and more environmentally friendly main propulsion engines.[16]

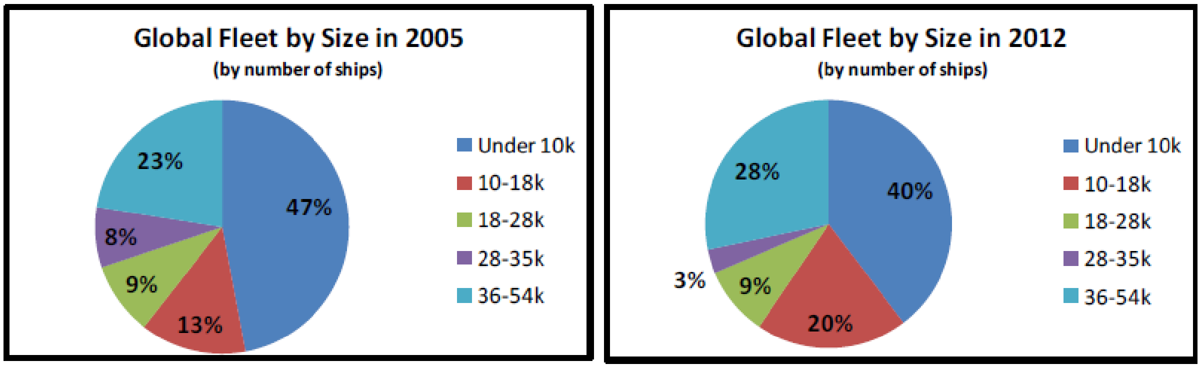

Figure 1.13 – Chemical Tankers size distribution

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Chapter 2

Chemical Cargoes

2.1 Introduction

In the second chapter of this thesis an effort has been made to familiarize the reader with chemical tankers' cargoes, their properties, and their potential hazards. As the structural design process of a chemical tanker is directly related to the cargoes she is intended to carry, it would serve no useful purpose to begin presenting design and structural configurations, without first discussing the cargo itself.

First of all, a classification of cargoes is been made, according to their origin, chemical composition, and the pollution threat they pose to the environment as per MARPOL. In addition, all the physical properties that characterize a chemical material are listed and defined, as these properties play a significant role in the selection and design process of various cargo systems that we will meet in next chapters.

Subsequently, a brief presentation of hazards related to chemical cargoes, and the chemicals' behavior when they released to the marine environment has been made. Although there is no direct influence of this information to the design process, it is of vital importance that anyone who is in any way involved with chemical tankers and the cargoes they carry, is well informed of these hazards.

As a matter of fact, each cargo has its own characteristics, potential hazards and special requirements for treatment. All these information are conveyed to the people handling these chemical cargoes through the Cargo Information Data Sheet, which is presented at the end of this chapter.

Finally, an attempt has been made to explain as simple as possible the effect of the chemical products to the design procedure of chemical tankers. For the transportation of each product, some specific structural requirements must be met. These requirements are listed in Chapter 17 of the IBC code. This chapter aims to analyze Chapter 17 of the IBC code and investigate how individual products may affect the design process.

2.2 Chemical cargoes classification

2.2.1 Classification based on chemical composition

The cargoes transported by chemical tankers can be classified in several different ways. The cargoes may be divided based on their chemical composition, such as inorganic and organic compounds.

- **Organic compound:**
  any of a large class of chemical compounds in which one or more atoms of carbon are covalently linked to atoms of other elements, most commonly hydrogen, oxygen, or nitrogen.

- **Inorganic compound:**
  any substance in which two or more chemical elements other than carbon are combined, nearly always in definite proportions. Compounds of carbon are classified as organic except for carbides, carbonates, cyanides, and a few others.[1]

2.2.2 Classification based on origin

As described in *Chemical Tankers: The quiet evolution* [2], the chemical cargoes may be divided into the following four groups based on their origin, and a specific heavy group:

- **Petrochemical products:**
  Carbon compounds exist naturally in abundance. Those which cannot be put to use as soon as extracted and purified provide starting materials for other useful compounds. The traditional bulk liquid "product" cargoes are the paraffins, obtained from crude oil by fractional distillation. These are the "saturated" hydrocarbons. Chemically, they are relatively unreactive and do not constitute the most suitable starting materials for making other substances. These compound do, however, burn readily, some explosively when vaporized and mixed with air, which is the basis of their value as fuels.
  Thermal and catalytic "cracking processes" are used to obtain more volatile fuel compounds from the residual heavy fuel fractions of primary distillation and many hydrocarbon gases are also produced. The latter are principally the unsaturated hydrocarbons, which are of higher chemical reactivity than their saturated counterparts and which form the basis of the rapidly expanding petrochemical industry.
  The typical olefin hydrocarbon, ethylene, which is produced in great quantity during cracking, is such a compound. It can react by "addition" of atoms, a property which is extremely important in the formation of polymers, (substances which are composed of

giant molecules formed by the union of a considerable number of simpler molecules). Rubber obtained by tapping the Hevea Brasiliansis tree is a natural polymer as are plant fibers such as cotton, which consists of the polymer cellulose, animals' hair, horn, nails, wool, etc. which consist of giant molecules of protein. The three familiar forms of synthetic polymer are plastics, man-made rubbers and fibers. An example of the plastics variety is polythene which is manufactured by heating ethylene at high pressures in the presence of catalysts, so that its molecules add to themselves, or "polymerize". Ethylene is now also a major source of ethanol (ethyl alcohol) which is used as a fuel and an industrial solvent.

P.V.C. (poly vinyl chloride) is produced by polymerization of vinyl chloride monomer, which can be obtained by chlorination of ethylene or derived from acetylene – another unsaturated hydrocarbon. The engineering uses of the gas acetylene are, of course, already well known to shipbuilders.

It is now also possible to convert large quantities of methane into methanol (otherwise known as methyl alcohol, methyl fuel or wood alcohol) for transportation in bulk as an alternative to shipment as a liquefied gas.

- **Coal tar products:**
  The other industrial source of hydrocarbons is the residual coal tar derived when coal is carbonized to produce coal gas. The aromatic compounds benzene, toluene and xylene, from which are derived some very important commodities, can be obtained as coal tar products. Carbolic acid (phenol) was the first antiseptic, although not in direct use today. The substances which are used, however, are mostly derived from phenol or similar compounds, as are numerous disinfectants, detergents, dyestuffs and selective weed-killers. Phenol is also used in the manufacture of certain of the nylon types and pharmaceuticals and it was with "Bakelite", the hard, synthetic resin produced by reaction of phenol and formaldehyde that the plastics industry really originated.

- **Carbohydrate derivatives:**
  These include molasses and alcohols produced by fermentation. The latter, of course, are associated with the brewing industry and ships which transport the end products (e.g. wine) in bulk are, in fact, specializing chemical tankers. The most common alcohols are ethanol and, mainly from the petrochemical industry, methanol and propanol. Alcohols can be oxidized to aldehydes and then to carboxylic acids, with which they also react to form esters. In this way, acetic acid is derived from ethanol for use as a solvent and, by reaction with ethanol, to produce ethyl acetate. Cellulose acetate, familiar as a thermoplastic moulding compound (telephones, packaging, film and buttons), as a man-made fiber (Tricel) and as a lacquer, is an ester formed by cellulose and acetic acid.

- **Animal and vegetable oils:**
  Esters occur in nature in the form of vegetable or animal oils and fats. Their composition is quite different from that of petroleum (mineral) oils which are almost completely composed of hydrocarbons. Although the oils are liquid at room temperature and the fats are solid, both are, in general esters of an alcohol called glycerol and a variety of organic acids known as "fatty acids" (e.g. palmitic, stearic, oleic).
  The animal and vegetable oils which are used in the manufacture of such widely varying commodities as soap, detergent, margarine, etc. , have been carried in ships for many years, the main problem being this of maintaining cargo quality.

- **Heavy chemicals:**
  Heavy chemicals are common chemicals that are widely produced for use in a variety of industries. The term heavy results from the high specific gravities of the chemicals. Examples of heavy chemicals include: sulphuric acid, caustic soda, caustic potash, phosphoric acid, nitric acid and sulphur.

2.2.3 Pollution categories

MARPOL Annex II *Regulations for the control of pollution by noxious liquid substances in bulk*[3] sets out a pollution categorization system for noxious and liquid substances. The four categories are:

- **Category X:**
  Noxious Liquid Substances which, if discharged into the sea from tank cleaning or deballasting operations, are deemed to present a major hazard to either marine resources or human health and, therefore, justify the prohibition of the discharge into the marine environment.

- **Category Y:**
  Noxious Liquid Substances which, if discharged into the sea from tank cleaning or deballasting operations, are deemed to present a hazard to either marine resources or human health or cause harm to amenities or other legitimate uses of the sea and therefore justify a limitation on the quality and quantity of the discharge into the marine environment.

- **Category Z:**
  Noxious Liquid Substances which, if discharged into the sea from tank cleaning or deballasting operations, are deemed to present a minor hazard to either marine resources or human health and therefore justify less stringent restrictions on the quality and quantity of the discharge into the marine environment.

- **Other Substances:**
  Substances which have been evaluated and found to fall outside Category X, Y or Z because they are considered to present no harm to marine resources, human health, amenities or other legitimate uses of the sea when discharged into the sea from tank cleaning of deballasting operations. The discharge of bilge or ballast water or other residues or mixtures containing these substances are not subject to any requirements of MARPOL Annex II.

2.3 Physical properties of chemicals

It is crucially important to know the physical properties of the chemicals transported in ships. A brief explanation of these properties is given below, as defined in the IBC code[4], and as found in other sources[5,6,7,8]:

- **Specific gravity:**
  Cargo tanks on a chemical tanker are normally designed to carry cargoes of a higher specific gravity than an oil tanker. Sometimes the design strength even differs between tanks on the same ship.
  The information regarding tank strength may be found on the classification society's certification of the ship, and the master must be familiar with any restrictions that may be imposed on loading heavy cargoes. Especially important is the risk of slack loading a tank because this can lead to sloshing forces that may cause damage to the tank structure or its equipment. Likewise, the tank's design capacity must be strictly observed: exceeding is dangerous. Note that the cargo's specific gravity and its vapour pressure must be considered together.

- **Flashpoint:**
  The flash point of a liquid is the lowest temperature at which the liquid will give off sufficient vapour to form a flammable gas mixture with air, near the surface of the liquid.

- **Saturated vapour pressure:**
  The process of evaporation in a closed container will proceed until there are as many molecules returning to the liquid as there are escaping. At this point the vapour is said to be saturated, and the pressure of that vapour (usually expressed in mmHg) is called the saturated vapour pressure.

- **Vapour pressure / boiling point:**
  At any given temperature every liquid exerts a pressure called the vapour pressure. The liquid will boil when its vapour pressure equals the external atmospheric pressure.
  In a closed cargo tank a liquid will boil when the vapour pressure is equal to the external vapour pressure plus the pressure setting of the pressure / vacuum (P/V) valve. The tanks and vent systems are designed to withstand this pressure, plus the hydrostatic pressure of the cargo. Cargoes that exceed the normal atmospheric pressure plus at 37.8°C (100°F) should not be loaded into a tank that is not specially designed for that duty. Where P/V valve set point can be varied, the correct setting should be confirmed. Vent line systems must be checked for correct operation at regular intervals, as structural damage can easily result from malfunction or blockage due to freezing of cargo vapour, polymer build-up, atmospheric dust or icing in adverse weather conditions. Flame screens are also susceptible to blockage, which can cause similar problems.
  The higher the vapour pressure the more vapour will be released, a fact that may require use of personal protective equipment.

- **Cubic expansion:**
  Liquids will expand as temperature rises, or contract when temperature falls. Sufficient space must be allowed in the tank to accommodate any cubic expansion expected during the voyage.
  Vent line systems must be checked at regular intervals. Their design capacity is based on vapour flow only; structural damage may result if vent systems become full of cargo liquid due to thermal expansion.

- **Vapour density:**
  Vapour density is expressed relative to the density of air, as heavier or lighter. Most chemical cargo vapour are heavier than air. Caution must therefore be exercised during cargo operations, as vapour concentrations are likely to occur at deck level or in lower parts of cargo pumprooms.

- **Lower and Upper flammable / explosive limits:**
  The flammable (explosive limits) are the minimum and maximum concentrations of flammable gas or vapour in air between which ignition can occur. The Minimum vapour concentration is known as:

  The Lower Flammable Limit (LFL)
  The Lower Explosive Limit (LEL)
  The maximum vapour concentration is known as:

The Upper Flammable Limit (UFL)
The Upper Explosive Limit (UEL)

- **Auto ignition temperature:**
  The auto ignition temperature of a solid, liquid or gas is the lowest temperature at which it requires to be raised to support self-combustion.

- **Spontaneous combustion:**
  A type of combustion which occurs by self-heating (increase in temperature due to exothermic internal reactions), followed by thermal runaway (self-heating which rapidly accelerates to high temperatures) and finally, ignition.

- **Freezing point / Melting point:**
  Most liquids have a defined freezing point, sometimes described as the melting point. Some products, like lube oil additives, vegetable and animal oils, polyoils etc. do not have a defined freezing point, but rather a freezing (melting) range or none at all. The product's viscosity is instead used as a measurement for the products liquidity or handling characteristics. Products with a freezing point higher than the outside temperature in which the ship is trading will need to be heated in order to remain liquid.

- **Pour point:**
  The pour point of a liquid is the lowest temperature at which the liquid will flow. It should be noted that cargo with thixotropic properties (the properties of showing a temporary reduction in viscosity when shaken or stirred) can be pumped at temperatures well below its pour point, but at very restricted rates.

- **Viscosity:**
  Viscosity is a measure of a liquids ability to flow and is usually determined by measuring the time required for a fixed volume to flow under gravity through a thin tube at a fixed temperature. It can also be described as a measure of the internal friction of a liquid. The distinction between viscosity and pour point should be made clear. Oil ceases to flow below its pour point temperature when the wax content solidifies.
  The viscosity of a cargo determines how easy it is to pump, and the amount of residue that will be left after unloading. Viscosity is related to temperature and, in general, a substance will become less viscous at higher temperatures, but note that certain cargoes (such as luboil additives) show increased viscosity when heated. IMO standards define high and low viscosity substances, and require cargo tanks that have contained substances with a high viscosity to be pre-washed and the washings discharged to shore reception facilities.

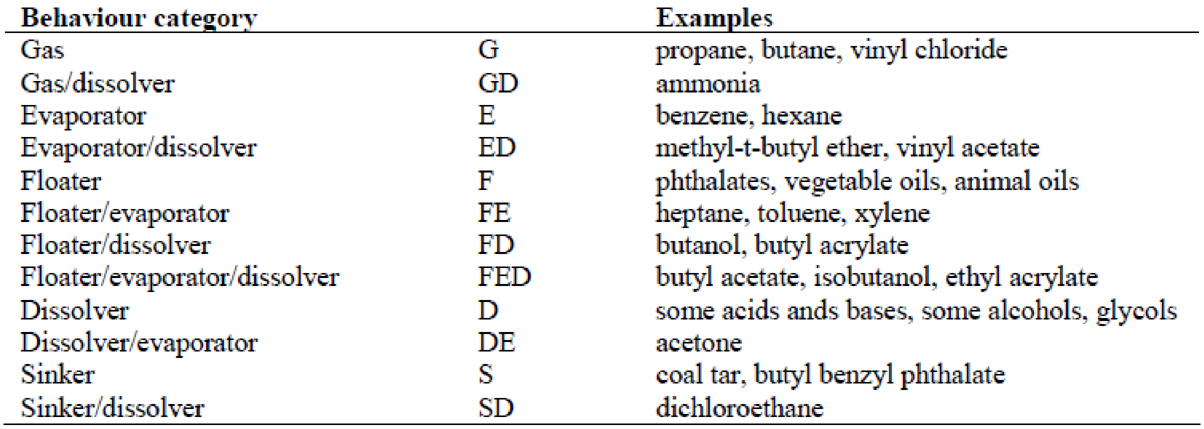
- **Electrostatic charging:**
  Certain cargoes are known as static accumulators, and become electrostatically charged when handled. They can accumulate enough charge to release a spark that could ignite a flammable tank atmosphere.

- **Solubility:**
  Solubility is expressed in different ways: either as simple as yes or no, as slight, or as a percentage, but always in relation to water. Solubility is temperature dependent. A cargo with low solubility will form a layer above or below a water layer depending on its specific gravity. Most non-soluble chemicals are lighter than water and will float on top but some others, such as chlorinated solvents, are heavier and will sink to the bottom. Chemicals that are heavier than water can cause a safety risk in pumprooms when the overlying water is disturbed, and in drip trays. Even in cargo tanks they may be trapped under water in pump wells, and pose a danger even after the tank atmosphere is tested and found safe for entry.

2.4 Behavior of chemicals in the marine environment

Different chemicals behave in different ways when released into the sea. They can evaporate, float, dissolve or sink. Behavior depends on physical properties of the chemical and also on the environmental conditions of the sea. Substances can be categorized into physical property groups by certain limits of vapour pressure, density, solubility, and viscosity. Different limits are used for substances in different physical state, in other words for gaseous, liquid, and solid chemicals. Categories help officials in a case of spillage or accident since chemicals in the same property group behave in similar ways.

In reality, substances released into water behave often in more complex manner than simply evaporate, float, dissolve, or sink. A chemical may behave in several ways simultaneously, for example evaporate into the air and dissolve into the water. There are 12 property groups named in European behavior classification system of Bonn Agreement (2006).



Behaviour category		Examples
Gas	G	propane, butane, vinyl chloride
Gas/dissolver	GD	ammonia
Evaporator	E	benzene, hexane
Evaporator/dissolver	ED	methyl-t-butyl ether, vinyl acetate
Floater	F	phthalates, vegetable oils, animal oils
Floater/evaporator	FE	heptane, toluene, xylene
Floater/dissolver	FD	butanol, butyl acrylate
Floater/evaporator/dissolver	FED	butyl acetate, isobutanol, ethyl acrylate
Dissolver	D	some acids ands bases, some alcohols, glycols
Dissolver/evaporator	DE	acetone
Sinker	S	coal tar, butyl benzyl phthalate
Sinker/dissolver	SD	dichloroethane

Figure 2.1 – Chemicals behavior categories

This simple classification system takes only one chemical into account at a time. This is problematic, because large chemical tankers carry several different chemical at the same time, and in case of an accident these chemicals may get mixed. A new compound may have totally different properties and behavior than the original, separate chemicals had. In any case, chemicals involved in an accident should be known before starting the rescue actions.[9]

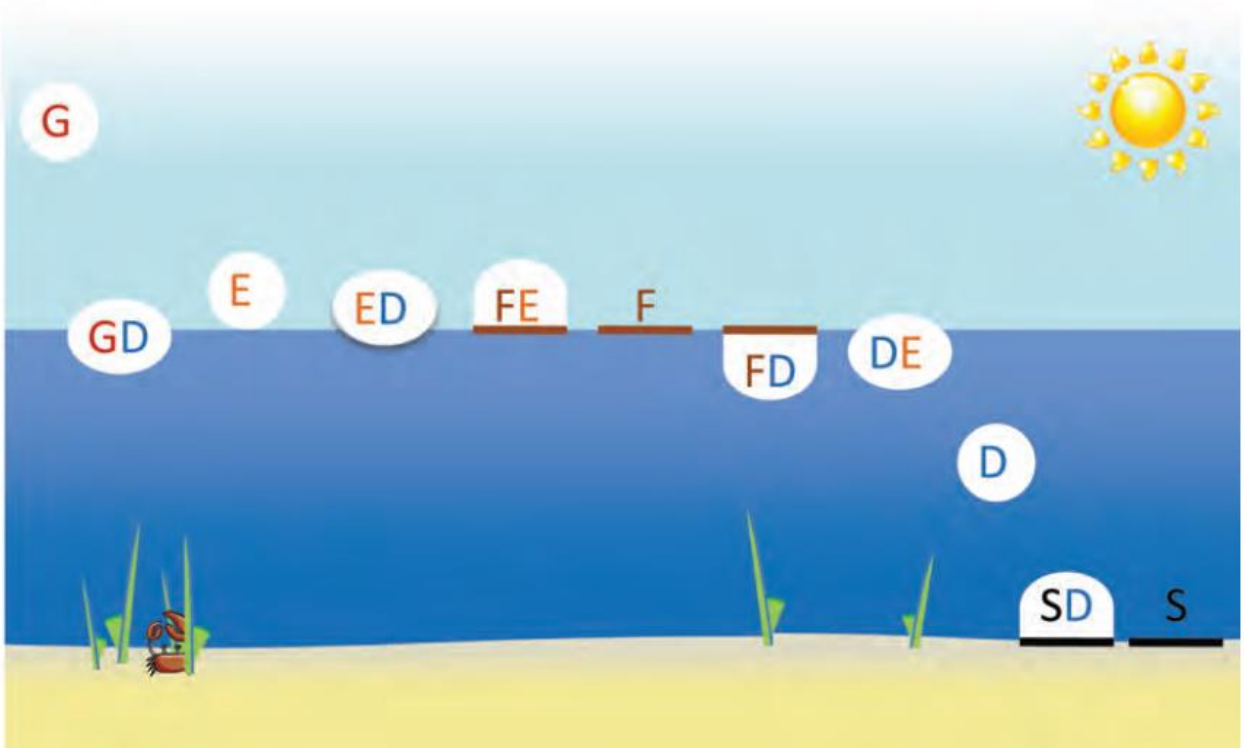


Figure 2.2 – Chemicals behavior categories

2.5 Hazards of chemicals

In the *Tanker Safety Guide Chemicals*[10], one can also find a brief description of hazards related with chemical cargoes. Knowing and understanding those hazards is very important in order for someone to eliminate them.

2.5.1 Flammability

Vapour given off by a flammable liquid will burn when ignited provided it is mixed with certain proportions of air, or more accurately with the oxygen in air. But if there is too little or too much vapour compared to the air, so that the vapour-and-air mixture is either too lean or too rich, it will not burn. Combustion of a vapour-and-air mixture results in a very considerable expansion of gases which, if constricted in an enclosed space, can raise pressure rapidly to the point of explosive rupture.

In addition, a flammable liquid must itself be at or above a temperature high enough for it to give off sufficient vapour for ignition to occur. This temperature is known as the flash point. Some cargoes evolve flammable vapour at ambient temperatures, others only at higher temperatures or when heated. Safe handling procedures depend upon the flammability characteristics of each product. Non-combustible cargoes are those which do not evolve flammable vapour.

As mentioned, the fire risk presented by a flammable cargo depends upon the oxygen content of the atmosphere above it. By filling the ullage space in a cargo tank with an inert gas such as nitrogen or the output of an oil fired inert gas generator, the oxygen content can be reduced to a level at which the atmosphere will no longer support combustion of flammable vapour.

This is known as inerting a tank. But it is important to remember that an inerted atmosphere may become flammable again if air is admitted, for instance during routine measuring or on venting the mixture to atmosphere or during gas freeing with air.

An inert atmosphere must not be considered as being without hazard, however, as without enough oxygen it will not support life either. Any person entering a tank which has been inerted must always follow strict procedures for entry into enclosed spaces.

2.5.2 Health hazards

2.5.2.1 Toxicity

Toxic means the same as poisonous. Toxicity is the ability of a substance, when inhaled, ingested, or absorbed by the skin, to cause damage to living tissue, impairment of the central nervous system, severe illness or, in extreme cases, death. The amounts of exposure required to produce these results vary widely with the nature of the substance and the duration of exposure to it.

Acute poisoning occurs when a large dose is received by exposure to high concentrations of a short duration, i.e. a single brief exposure. Chronic poisoning occurs through exposure to low concentrations over a long period of time, i.e. repeated or prolonged exposures. Toxicity is objectively evaluated on the basis of test dosages under controlled conditions, and expressed as threshold limit values (TLVs).

Prevention of exposure is achieved through a combination of cargo containment, which prevents toxic fumes or liquid from contaminating the workplace, and the use of personal protective equipment (PPE).

2.5.2.2 Asphyxia

Asphyxia is unconsciousness caused by lack of oxygen, and means suffocation. Any vapour may cause asphyxiation, whether toxic or not, simply by excluding oxygen in air. Danger areas include cargo tanks, void spaces and cargo pump-rooms. But the atmosphere of a compartment may also be oxygen-deficient through natural causes, such as decomposition or putrefaction of organic cargo, or rusting of steel in void spaces such as cofferdams, forepeak and aft peak tanks.

2.5.2.3 Anesthesia

Certain vapour cause loss of consciousness due to their effect on the nervous system. In addition, anesthetic vapour may or may not be toxic.

2.5.2.4 Additional health hazards

Additional health hazards may be presented by non-cargo materials used on board during cargo handling. One hazard is that of frostbite from liquid nitrogen stored on board for use as atmosphere control in cargo tanks. Another hazard is that of burns from accidental contact with equipment used while handling heated cargoes.

2.5.3 Reactivity

A chemical may react in a number of ways; with itself, with water, with air, with other chemicals or with other materials.

2.5.3.1 Self-reaction

The most common form of self-reaction is polymerization. Polymerization generally results in the conversion of gases or liquids into viscous liquids or solids. It may be a slow, natural process which only degrades the product without posing any safety hazards to the ship or the crew, or it may be a rapid, exothermic reaction evolving large amounts of heat and gases, Heat produced by the process can accelerate it. Such a reaction is called a run-off polymerization that poses a serious danger to both the ship and its personnel. Products that are susceptible to polymerization and normally transported with added inhibitors to prevent the onset of the reaction.

An inhibited cargo certificate should be provided to the ship before a cargo is carried. The action to be taken in case of a polymerization situation occurring while the cargo is on board should be covered by the ship's emergency contingency plan.

2.5.3.2 Reaction with water

Certain cargoes react with water in a way that could pose a danger to both the ship and its personnel. Toxic gases may be evolved. The most noticeable examples are the isocyanates; such cargoes are carried under dry and inert condition. Other cargoes react with water in a slow way that poses no safety hazards, but the reaction may produce small amounts of chemicals that can damage equipment or tank materials, or can cause oxygen depletion.

2.5.3.3 Reaction with air

Certain chemical cargoes, mostly ethers and aldehydes, may react with oxygen in air or in the chemical to form unstable oxygen compounds (peroxides) which, if allowed to build up, could cause an explosion. Such cargoes can be either inhibited by an anti-oxidant or carried under inert conditions.

2.5.3.4 Reaction with other cargoes

Some cargoes react dangerously with one another. Such cargoes should be stowed away from each other (not in adjacent tanks) and prevented from mixing by using separate loading, discharging and venting systems. When planning the cargo stowage, the master must use a recognized compatibility guide to ensure that cargoes stowed adjacent to each other are compatible.

2.5.3.5 Reaction with other materials

The materials used in the construction of cargo systems must be compatible with the cargoes to be carried, and care must be taken to ensure that no incompatible materials are used or introduced during maintenance (e.g. by the material used for replacing gaskets). Some materials may trigger a self-reaction within the product. In other cases, reaction with certain alloys will be non-hazardous to ship or crew, but can impair the commercial quality of the cargo or render it unusable.

2.5.4 Corrosiveness

Acids, anhydrides and alkalis are among the most commonly carried corrosive substances. They can rapidly destroy human tissue and cause irreparable damage. They can also corrode normal ship construction materials, and create a safety hazard for a ship. Acids in particular react with most metals, evolving hydrogen gas which is highly flammable. The IMO Codes address this and care should be taken to ensure that unsuitable materials are not included in the cargo system. Personnel likely to be exposed to these products should ear suitable personal protective equipment.

2.5.5 Putrefaction

Most animal and vegetable oils undergo decomposition over time, a natural process known as putrefaction (going off), that generates obnoxious and toxic vapour and depletes the oxygen in the tank. Tanks that have contained such products must be carefully ventilated and the atmosphere tested prior to tank entry.

It must not be assumed that all vapour produced by cargoes liable to putrefaction will in fact be due to putrefaction; some may not be obvious, either through smell or appearance of the cargo. Carbon monoxide (CO), for instance, is colorless and odorless and can be produced when a vegetable or animal oil is overheated.

2.6 Cargo Information Data Sheet

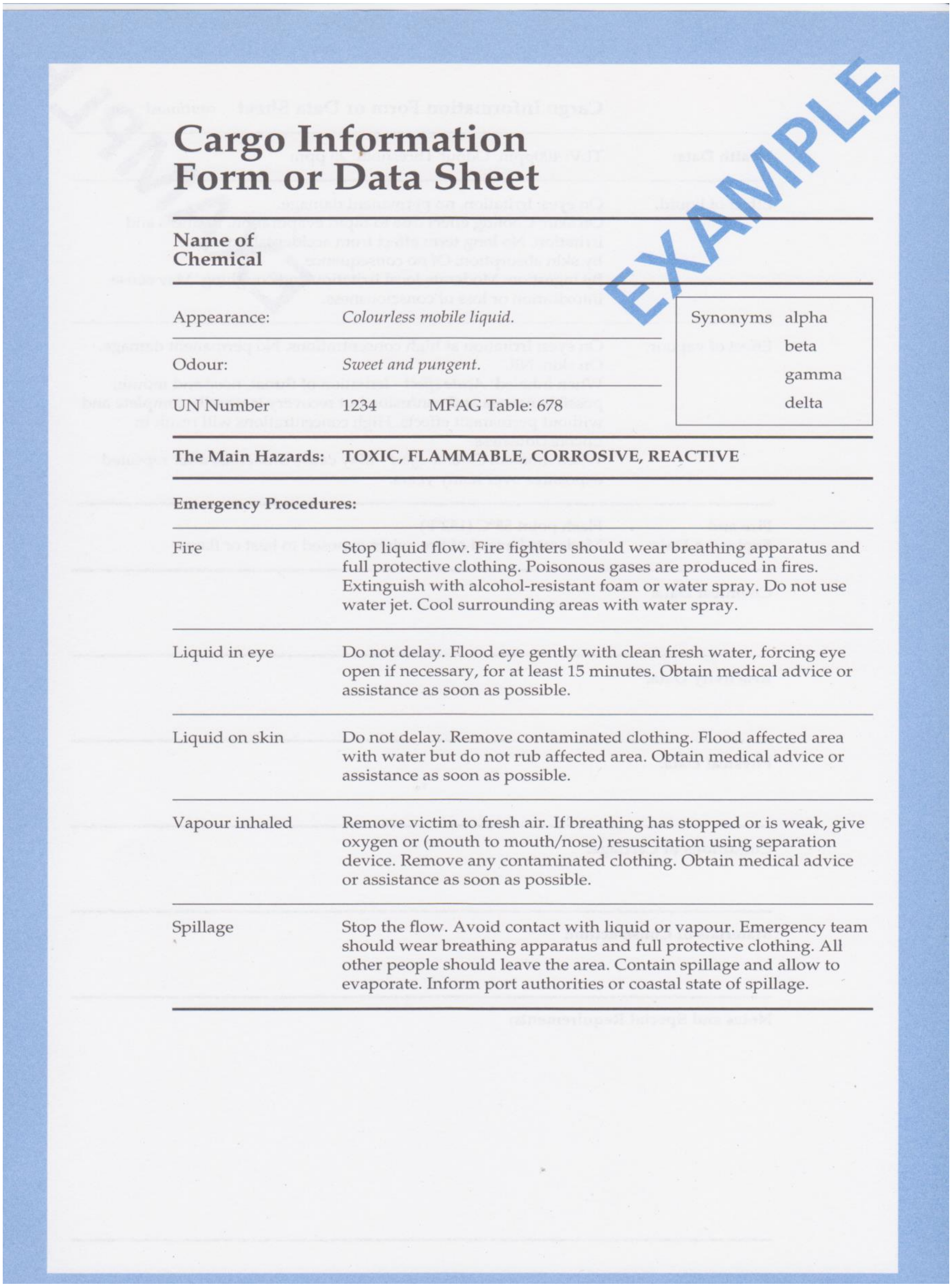
As described in *Tanker Safety Guide Chemicals*[10], it is an IMO requirement for the shipper of a liquid chemical cargo in bulk to supply a data sheet to ensure that ships have the information necessary for safe containment of the cargo, and the emergency action that should be taken in case of fire, spills, leaks or personal contact with the liquid. In the case of cargoes that are stabilized or inhibited, the ship should have sufficient details of the stabilizer or the inhibitor, and its effectiveness.

Those supplying the information should bear in mind that cargo related emergencies may occur when the ship is at sea as well as in port. It is therefore not sufficient to advise that the crew call the local fire brigade in case of fire, or send a casualty to hospital in case of personal contact. Realistic and helpful but succinct advice is needed.

Different manufacturers are likely to have different styles of presenting technical chemical data about a product, often associated with a defined market or trading region. However, it should be a priority to present ships with the essential safety guidance in a uniform manner to which one can refer to immediately in the event of an emergency.

Regulation 16.2.3.1 of the IBC Code[11] states that information shall be on board and available to all concerned, giving the necessary data for the safe carriage in bulk. Such information shall include a cargo stowage plan, to be kept in an accessible place, indicating all cargo on board, including, for each dangerous chemical carried:

1. A full description of the physical and chemical properties, including reactivity, necessary for the safe containment of the cargo.
2. Action to be taken in the event of spills or leaks.
3. Countermeasures against accidental personal contact.
4. Fire-fighting procedures and fire-fighting media.
5. Procedures for cargo transfer, tank cleaning, gas-freeing and ballasting.



Cargo Information Form or Data Sheet

Name of Chemical

Appearance:	*Colourless mobile liquid.*
Odour:	*Sweet and pungent.*
UN Number	1234 MFAG Table: 678

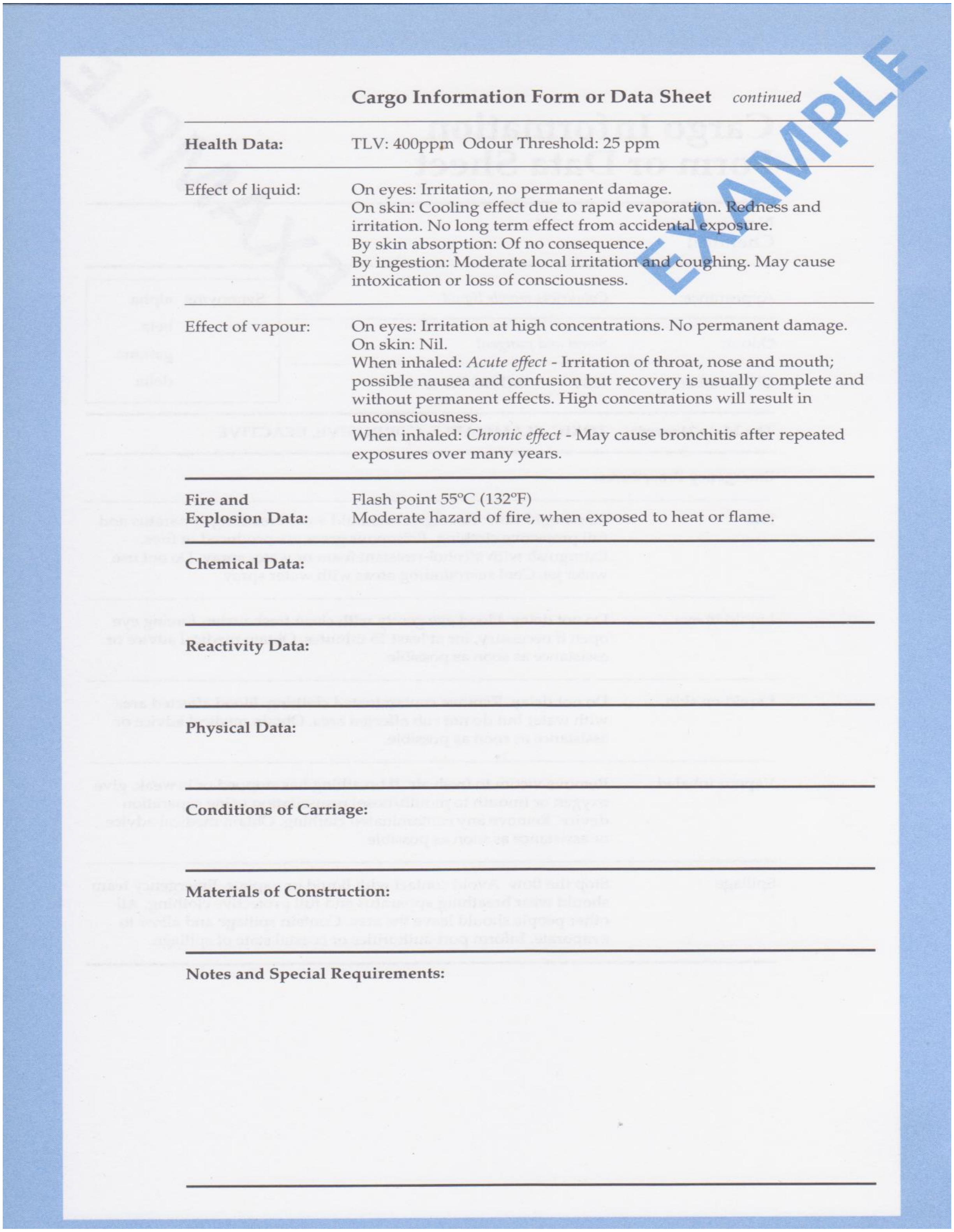
Synonyms	alpha beta gamma delta

The Main Hazards: **TOXIC, FLAMMABLE, CORROSIVE, REACTIVE**

Emergency Procedures:

Fire	Stop liquid flow. Fire fighters should wear breathing apparatus and full protective clothing. Poisonous gases are produced in fires. Extinguish with alcohol-resistant foam or water spray. Do not use water jet. Cool surrounding areas with water spray.
Liquid in eye	Do not delay. Flood eye gently with clean fresh water, forcing eye open if necessary, for at least 15 minutes. Obtain medical advice or assistance as soon as possible.
Liquid on skin	Do not delay. Remove contaminated clothing. Flood affected area with water but do not rub affected area. Obtain medical advice or assistance as soon as possible.
Vapour inhaled	Remove victim to fresh air. If breathing has stopped or is weak, give oxygen or (mouth to mouth/nose) resuscitation using separation device. Remove any contaminated clothing. Obtain medical advice or assistance as soon as possible.
Spillage	Stop the flow. Avoid contact with liquid or vapour. Emergency team should wear breathing apparatus and full protective clothing. All other people should leave the area. Contain spillage and allow to evaporate. Inform port authorities or coastal state of spillage.

Figure 2.3 (a) – Cargo Information Data Sheet Sample



Cargo Information Form or Data Sheet *continued*

Health Data:	TLV: 400ppm Odour Threshold: 25 ppm
Effect of liquid:	On eyes: Irritation, no permanent damage. On skin: Cooling effect due to rapid evaporation. Redness and irritation. No long term effect from accidental exposure. By skin absorption: Of no consequence. By ingestion: Moderate local irritation and coughing. May cause intoxication or loss of consciousness.
Effect of vapour:	On eyes: Irritation at high concentrations. No permanent damage. On skin: Nil. When inhaled: *Acute effect* - Irritation of throat, nose and mouth; possible nausea and confusion but recovery is usually complete and without permanent effects. High concentrations will result in unconsciousness. When inhaled: *Chronic effect* - May cause bronchitis after repeated exposures over many years.
Fire and Explosion Data:	Flash point 55°C (132°F) Moderate hazard of fire, when exposed to heat or flame.
Chemical Data:	
Reactivity Data:	
Physical Data:	
Conditions of Carriage:	
Materials of Construction:	
Notes and Special Requirements:	

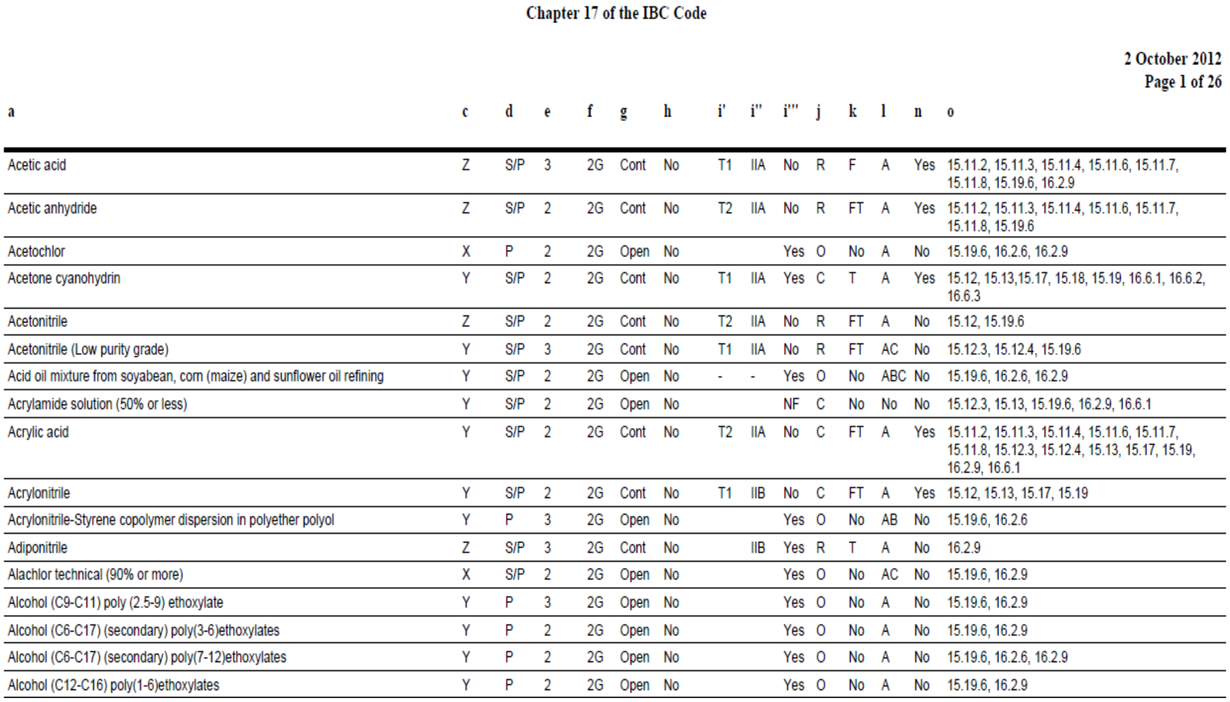
Figure 2.3 (b) – Cargo Information Data Sheet Sample

2.7 The effect of cargo in the design of chemical tankers

Chemical tankers' design and construction are – more than in any other type of vessel – strongly affected by the type of cargoes that the vessel is intended to carry. The variety of cargoes that the vessel will carry are defined by the shipowner, prior to the beginning of the design process. Then, the design of the vessel takes place based on the minimum requirements that are set for the specified products.

This procedure is very important, as it determines the operational flexibility of the vessel. Once a vessel is built for the carriage of certain products, she will be unable to carry products with higher requirements, unless sufficient modifications are made. These modifications though are not always easy to be made, and their cost may be extremely high.

Chapter 17 of the IBC Code[12] provides a list of products that, in order to be carried by a chemical tanker, the vessel shall fulfill some minimum requirements. This list is consisted of 15 columns, each of which gives information about the individual product and the requirements that need to be fulfilled. A part of this list is shown in Figure 2.4.



Chapter 17 of the IBC Code

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a	c	d	e	f	g	h	i'	i''	i'''	j	k	l	n	o
Acetic acid	Z	S/P	3	2G	Cont	No	T1	IIA	No	R	F	A	Yes	15.11.2, 15.11.3, 15.11.4, 15.11.6, 15.11.7, 15.11.8, 15.19.6, 16.2.9
Acetic anhydride	Z	S/P	2	2G	Cont	No	T2	IIA	No	R	FT	A	Yes	15.11.2, 15.11.3, 15.11.4, 15.11.6, 15.11.7, 15.11.8, 15.19.6
Acetochlor	X	P	2	2G	Open	No			Yes	O	No	A	No	15.19.6, 16.2.6, 16.2.9
Acetone cyanohydrin	Y	S/P	2	2G	Cont	No	T1	IIA	Yes	C	T	A	Yes	15.12, 15.13,15.17, 15.18, 15.19, 16.6.1, 16.6.2, 16.6.3
Acetonitrile	Z	S/P	2	2G	Cont	No	T2	IIA	No	R	FT	A	No	15.12, 15.19.6
Acetonitrile (Low purity grade)	Y	S/P	3	2G	Cont	No	T1	IIA	No	R	FT	AC	No	15.12.3, 15.12.4, 15.19.6
Acid oil mixture from soyabean, corn (maize) and sunflower oil refining	Y	S/P	2	2G	Open	No	-	-	Yes	O	No	ABC	No	15.19.6, 16.2.6, 16.2.9
Acrylamide solution (50% or less)	Y	S/P	2	2G	Open	No			NF	C	No	No	No	15.12.3, 15.13, 15.19.6, 16.2.9, 16.6.1
Acrylic acid	Y	S/P	2	2G	Cont	No	T2	IIA	No	C	FT	A	Yes	15.11.2, 15.11.3, 15.11.4, 15.11.6, 15.11.7, 15.11.8, 15.12.3, 15.12.4, 15.13, 15.17, 15.19, 16.2.9, 16.6.1
Acrylonitrile	Y	S/P	2	2G	Cont	No	T1	IIB	No	C	FT	A	Yes	15.12, 15.13, 15.17, 15.19
Acrylonitrile-Styrene copolymer dispersion in polyether polyol	Y	P	3	2G	Open	No			Yes	O	No	AB	No	15.19.6, 16.2.6
Adiponitrile	Z	S/P	3	2G	Cont	No		IIB	Yes	R	T	A	No	16.2.9
Alachlor technical (90% or more)	X	S/P	2	2G	Open	No			Yes	O	No	AC	No	15.19.6, 16.2.9
Alcohol (C9-C11) poly (2.5-9) ethoxylate	Y	P	3	2G	Open	No			Yes	O	No	A	No	15.19.6, 16.2.9
Alcohol (C6-C17) (secondary) poly(3-6)ethoxylates	Y	P	2	2G	Open	No			Yes	O	No	A	No	15.19.6, 16.2.9
Alcohol (C6-C17) (secondary) poly(7-12)ethoxylates	Y	P	2	2G	Open	No			Yes	O	No	A	No	15.19.6, 16.2.6, 16.2.9
Alcohol (C12-C16) poly(1-6)ethoxylates	Y	P	2	2G	Open	No			Yes	O	No	A	No	15.19.6, 16.2.9

Figure 2.4 – List of products and requirements

The columns of this list will be analyzed one by one, to make clear what requirements they set for the carriage of each product.

Column a – Product name

The product name is indicated here. The product name shall be used in the shipping document for any cargo offered for bulk shipments. Any additional name may be included in brackets after the product name.

Column c – Pollution category

The letter X, Y, or Z indicates the pollution category of the product under MARPOL Annex II. Categories X, Y, and Z are explained in Section 2.2.3 of this thesis.

Column d – Hazards

Indications “S” and “P”, state why the particular product is included in the Code. "S" means that the product is included in the Code because of its safety hazards; "P" means that the product is included in the Code because of its pollution hazards; and "S/P" means that the product is included in the Code because of both its safety and pollution hazards.

Column e – Ship type

Number 1, 2, or 3, indicates if the vessel that will carry the relative product shall be of Ship type 1, 2, or 3 as defined in Sections 3.3.1 and 3.3.2 of this thesis.

Column f – Tank type

Number 1 or 2, and indication “G” or “P”, give the type of tank that is required for the carriage of each product. 1 stands for independent tank and 2 stands for integral tank, when “G” stands for gravity tank and “P” stands for pressure tank. All the tank are described in Section 6.5.2 of this thesis.

Column g – Tank vents

The type of venting system that is required is declared in this column. “Cont.” indicates a controlled venting tank system, and “Open” indicates an open venting tank system, as they are described in Section 7.5 of this thesis.

Column h – Tank environmental control

This column states if the transported product requires an inert gas system, or any other environmental control system, to be installed in the tank. “Inert” indicates that an inert gas system is required, when “Pad”, “Dry”, and “Vent”, stand for a liquid or gas padding system, a drying system, and a natural or forced ventilation system respectively. “No” states that there are no special requirements regarding the tank environmental control of the particular product. All tank environmental control systems are described in Section 7.7.1 of this thesis.

Column i – Electrical equipment

Electrical installations in chemical tankers should be such as to minimize the risk of fire and explosion from flammable products. Where the specific cargo is liable to damage the materials normally used in electrical apparatus, due consideration shall be given to the particular characteristics of the materials chosen for conductors, insulation, metal parts, etc. The specifications of the electrical equipment, that are required for each type of cargo, are set in columns i' and i''. Column i' indicates the temperature class that the equipment must have, in a range from T1 to T6, when column i'' indicates the apparatus group, IIA, IIB, or IIC, in which the equipment should belong. In both columns, "-" indicates there are no requirements for the electrical installations, and if the field is left blank, that means that there are no information available for the specific product. More information regarding the temperature classes and apparatus groups are given by the International Electrotechnical Commission*.

Where electrical equipment is installed in hazardous locations, it should be of intrinsically safe type in general. For example, a flameproof type ceiling light is shown in Figure 2.5.

Figure 2.5 – Flameproof type ceiling light

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* International Electrotechnical Commission, Publication IEC 60092-502, 1999

The hazardous locations, with regard to the electrical installations, depend on the flashpoint of the carried product. Hazardous locations for chemical tankers carrying cargoes with a flashpoint not exceeding 60°C are as follows[13]:

- Cargo tanks and cargo piping
- Void spaced adjacent to, above, or below integral tanks.
- Hold spaces containing independent cargo tanks.
- Cargo pump rooms and pump rooms in the cargo area.
- Zones on open deck, or semi- enclosed spaces on deck, within 3 m of any cargo tank outlet, gas or vapour outlet, cargo pipe flange, cargo valve or entrance and ventilation opening to cargo pump rooms; cargo area on open deck over all cargo tanks and cargo tank holds, including all ballast tanks and cofferdams within the cargo tank block, to the full width of the ship, plus 3m fore and aft and up a height of 2.4m above the deck.
- Enclosed or semi-enclosed spaces in which pipes containing cargoes are located; enclosed or semi-enclosed spaces immediately above cargo pump rooms or above vertical cofferdams adjoining cargo tanks, unless separated by a gas tight deck and suitable ventilated; and compartments for cargo hoses.

Hazardous locations for chemical tankers carrying cargoes with a flashpoint exceeding 60°C are only cargo tanks and cargo piping.

The flashpoint range of each product is indicated in column i’’’. “Yes” means flashpoint exceeds 60°C, and “No” means flashpoint does not exceed 60°C. “NF” indicates that the product is not flammable.

Column j - Gauging

As described in Section 7.6, cargo monitoring can take place via open gauging devices - where the gauger may be exposed to the cargo or its vapour - for less hazardous cargoes, or via closed gauging devices – which are part of a closed system and keeps tank contents from being released – for more hazardous cargoes.

In addition, restricted gauging devices may be used, which penetrate the tank and, when in use, permit a small quantity of cargo vapour or liquid to be exposed to the atmosphere. When not in use, these devices are completely closed.

“O” in this column indicates that the product requires open gauging, “R” restricted gauging, and “C” closed gauging devices.

Column k – Vapour detection

For some hazardous products, a vapour detection system is required to be outfitted on board. “F” stands for a flammable vapour detection system, and “T” for a toxic vapour one. “No” indicates that no vapour detection system is required.

Column l – Fire protection

In this column the type of fire protection system (alcohol-resistant foam or multi-purpose foam (“A”), regular foam (“B”), water spray (“C”), or dry chemical (“D”)) that is required for each product is indicated.

Column n – Emergency equipment

The need, or not, of emergency equipment (respiratory, eye protection, etc.) to be available on board is indicated in this column.

Column o – Specific and operational requirements

For some individual products, special requirements are given by the IBC Code. In this column, a reference is been made to the section of the Code that the special requirements can be found. Most of these, are operational and cargo-handling requirements. Some of them, though, may affect the vessel’s construction. For example, cargo tanks – and associated equipment - that are intended to carry hydrogen peroxide solutions should be either pure aluminum (99.5%) or solid stainless steel. Aluminum though shall not be used for piping on deck. For cargo tanks designed to carry phosphorus, yellow or white, they shall be designed in such a way in order to minimize the interfacial area between the phosphorus and its water pad. In addition, tank heating arrangements shall be external to the tanks and have a suitable method of temperature control to ensure that the temperature of the phosphorus does not exceed 60°C. All special requirements for individual products can be found under Chapter 15 of the IBC Code.

The above requirements apply to all but few products that are transferred via chemical tankers. For some products that do not present safety or pollution hazards, there is no need for the requirements to be specified. Even for these products though, some safety precaution need to be taken, to ensure their safe transportation. The list of these products is given in Chapter 18 of the IBC Code.

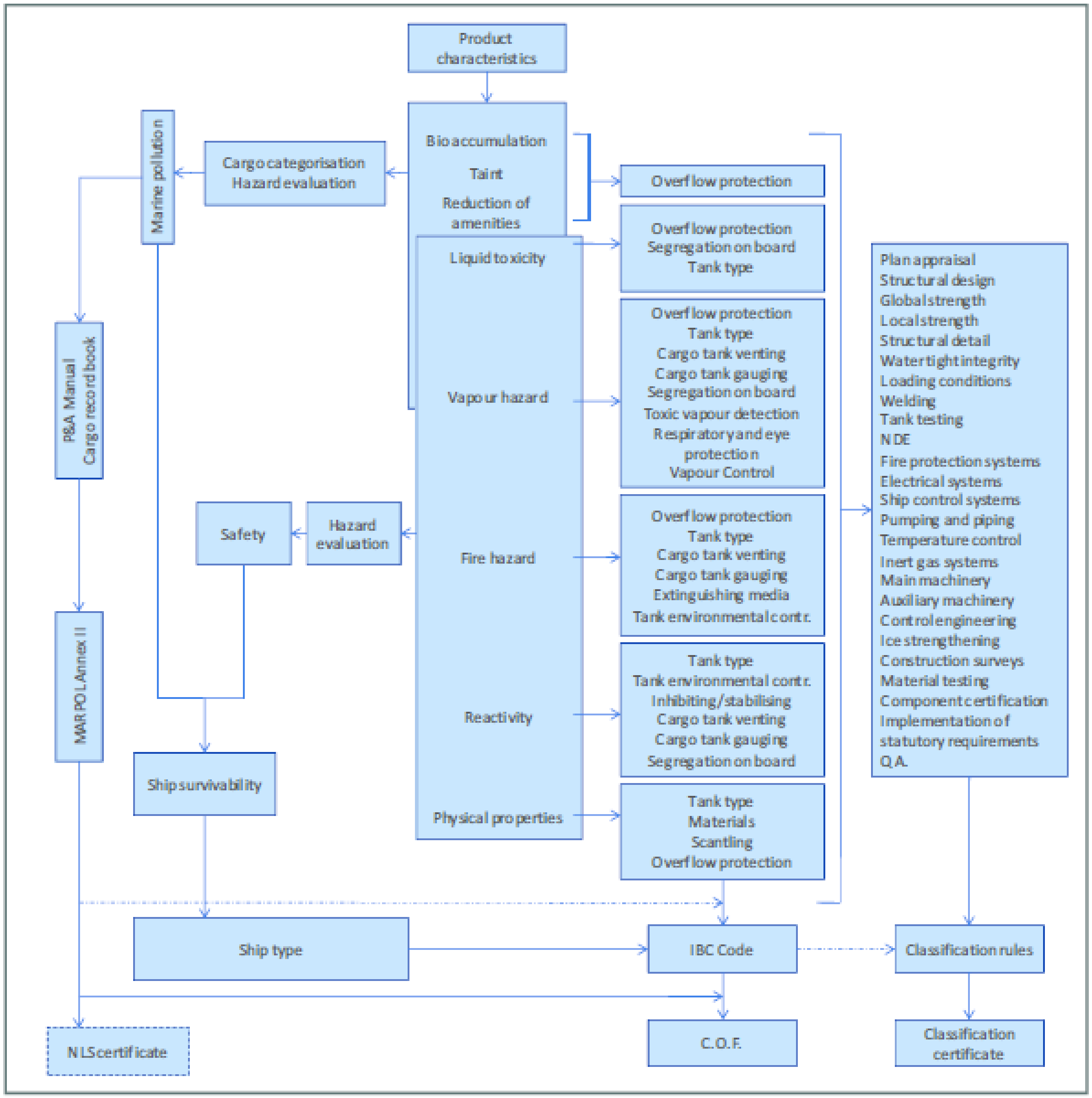

Figure 2.6 – Effect of chemical cargo characteristics on ship design[14]

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Chapter 3

Ship's Arrangements

3.1 Introduction

In this chapter, the general arrangement of typical chemical tankers is described and analyzed. Arrangement of spaces in chemical tankers should be designed in accordance with class regulations and rules, so as to eliminate problems and difficulties that a non-effective arrangement of spaces may occur, as well as to ensure that no hazards for the crew, the environment, or the vessel itself arise at any time.

At first point, the arrangement of cargo tanks will be analyzed. Cargo tank's arrangement and size are directly related to the type of vessel. A chemical tanker is categorized as of type I, II, or III, depending on the cargo she is intended to carry. The three types of chemical tanker vessels, as well as the effect the Ship Type has on the location of the cargo tanks, are presented in this chapter.

Due to their hazardous nature, chemical cargoes require special consideration regarding their segregation from other cargoes, from machinery and accommodation spaces, from heat, water and other. All the above affect the arrangement of the vessels which carry those cargoes, in ways that are described in this chapter.

Furthermore, location of cofferdams, fuel oil tanks, cargo pump rooms, bilge and ballast arrangements, accommodation, machinery and service spaces, openings to accommodation and cargo spaces are considered.

Finally, reference is been made to the hazardous locations and zones of a chemical tankers, and the effect they have on the vessel's arrangement.

3.2 The problem and the approach

As described in *Ship Design and Construction* [1], the first step in solving the general arrangement problems of a cargo ship is locating the main spaces and their boundaries within the ship hull and superstructure. These spaces are:

1. Cargo spaces
2. Machinery spaces
3. Crew, passenger and associated spaces
4. Tanks
5. Miscellaneous

At the same time, certain requirements must met, mainly:

1. Watertight subdivision and integrity
2. Adequate stability
3. Structural integrity
4. Adequate provision for access

The general arrangement is evolved by a gradual process of trial, check and improvement. As for any other problem, the first approach to a solution to the general arrangement must be based on a minimum amount of information including:

1. Required volume of cargo spaces, based on type and amount of cargo
2. Method of stowing cargo and cargo handling system
3. Required volume of machinery spaces, based on type of machinery and ship
4. Required volume of accommodation spaces, based on number of crew and passengers and standard of accommodations
5. Required volume of tankage, mainly fuel and clean ballast, based on type of machinery, type of fuel and cruising range
6. Required standard of subdivision and limitation of main transverse bulkhead spacing
7. Approximate principal dimensions (length, beam, depth and draft)
8. Preliminary lines plan

The first general arrangement layout to allocate the main spaces is based on the above information. Peak bulkheads and inner bottom are established in accordance with regulatory body requirements. Other main transverse bulkheads are located to satisfy subdivision requirements, based on preliminary floodable length curves. Decks are located to suit the requirements of the spaces, cargo, machinery, accommodations, etc., and to satisfy strength requirements. Allowance for space occupied by structure must be deducted in arriving at the resulting net usable volumes and the clear deck heights.

Usually, in the first approach, several preliminary general arrangements are laid out in the form of main space allocations, boundaries and subdivisions. These are checked for adequacy of volumes, weights and stability, and the changes to be made in the preliminary lines to make these features satisfactory. At this point, certain arrangements may be dropped, either because they are not feasible or are less efficient than other arrangements. The general arrangement process continues into more refined stages, simultaneously with the development of structure, machinery layout, and calculations of weights, volumes, floodable lengths, and stability, intact and damaged. The selection of one basic arrangement may come early in the process, or may have to be delayed and based on a detailed comparison of trade-offs. In any case, the selection is usually made in consultation with the owner so that consideration may be given to his more detailed knowledge of operating problems.

Chemical carriers may be designed for the carriage of a wide variety of chemicals in the in various lot sizes. Characteristics of various chemicals require such tank features as special tank materials such as stainless steel, special interior tank coatings, cofferdaming to separate from adjacent tanks, heating systems, and cleaning systems. The optimum arrangement of tanks for such a carrier can only be arrived at by comprehensive studies based on a clear definition of the service and product requirements.[1]

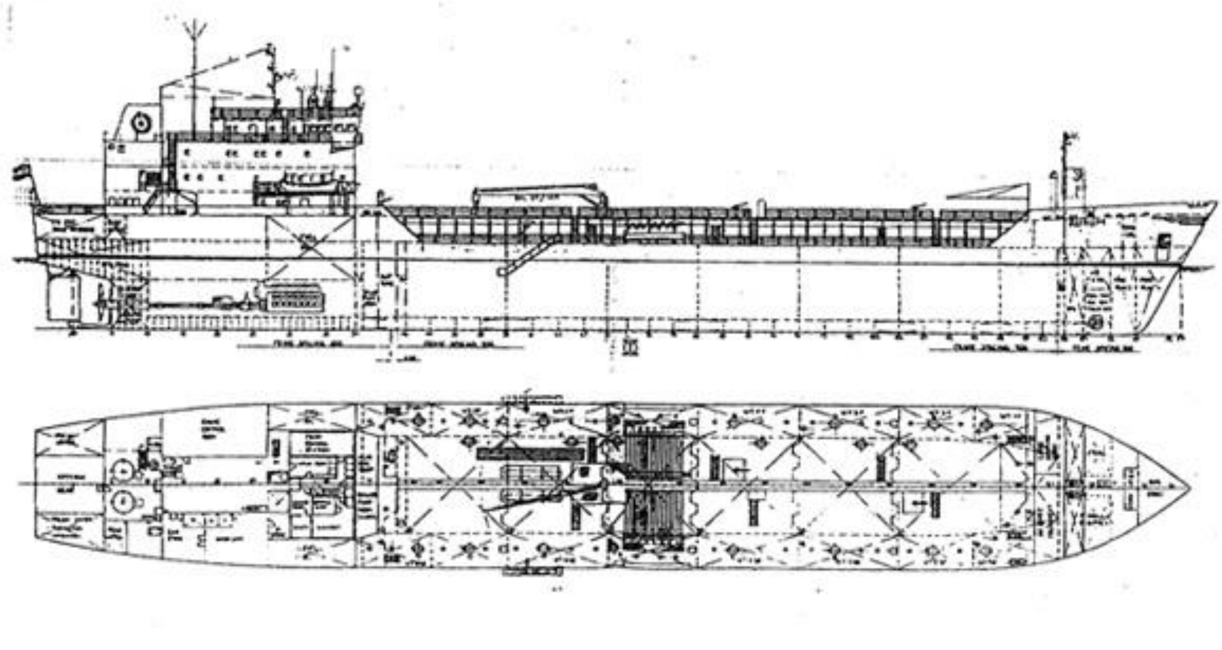


Figure 3.1 – Chemical tanker typical general arrangement

3.3 Cargo tanks arrangement

The types of cargoes a vessel is designed to carry influence to a major extent the arrangement of the cargo tanks. The IBC code provides requirements for the location of cargo tanks that are to carry ST1, 2, or 3 cargoes. The required locations are based on damage assumptions provided in the code.

Ships, subject to the Code, are to survive the normal effects of flooding following an assumed extent of hull damage caused by some external force. In addition, to safeguard the ship and the environment, the cargo tanks of certain types of ships are to be protected from penetration in the case of minor damage to the ship resulting, for example, from contact with a jetty or tug, and given a measure of protection from damage in the case of collision or stranding, by locating them at specified minimum distances inboard from the ship's shell plating. Both the assumed damage and the proximity of the cargo tanks to the ship's shell shall be dependent upon the degree of hazard presented by the products to be carried[2].

3.3.1 Groups of ship type

Ships subject to the Code shall be designed to one of the following standards[2]:

1. A type 1 ship is a chemical tanker intended to transport chapter 17 products with very severe environmental and safety hazards which require maximum preventive measures to preclude an escape of such cargo.

2. A type 2 ship is a chemical tanker intended to transport chapter 17 products with appreciably severe environmental and safety hazards which require significant preventive measures to preclude an escape of such cargo.

3. A type 3 ship is a chemical tanker intended to transport chapter 17 products with sufficiently severe environmental and safety hazards which require a moderate degree of containment to increase survival capability in a damaged condition.

Thus, a type 1 ship is a chemical tanker intended for the transportation of products considered to present the greatest overall hazard and type 2 and type 3 for products of progressively lesser hazards. Accordingly, a type 1 ship shall survive the most severe standard of damage and its cargo tanks shall be located at the maximum prescribed distance inboard from the shell plating.

3.3.2 *Location of cargo tanks*

Cargo tanks shall be located at the following distances inboard[3]:

1. **Type 1 ships:** Tanks intended for carriage of cargoes for which Ship type 1 is required shall be located at a minimum distance from the ship's side shell plating of B/5 or 11.5 m, whichever is less, measured inboard from the ship's side at right angle to the center line at the level of the summer load line, and at a vertical distance from the moulded line of the bottom shell plating at center line not less than B/15 or 6 m, whichever is less but not less than 760 mm from the shell plating.

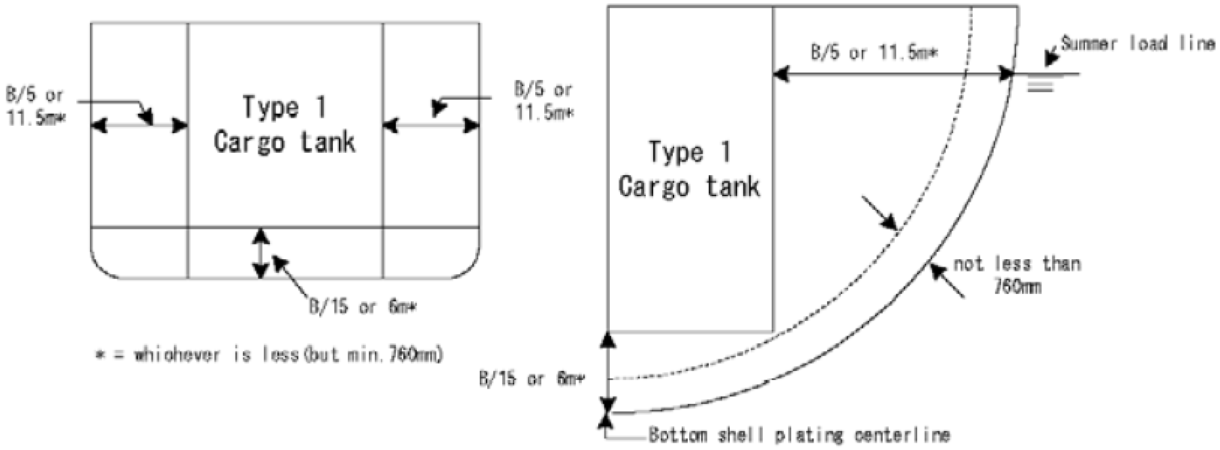


Figure 3.2 – Tank location of Type 1 ships

2. **Type 2 ships:** Tanks intended for carriage of cargoes for which **Ship type 2** is required shall be located at a vertical distance from the moulded line of the bottom shell plating at centerline of B/15 or 6 m, whichever is less, but not less than 760 mm from the shell plating.

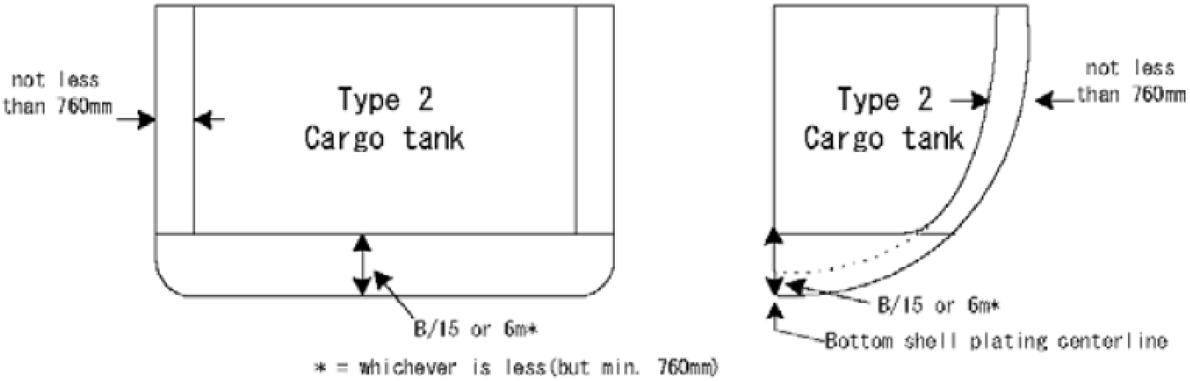


Figure 3.3 – Tank location of Type 2 ships

3. **Type 3 ships:** For Ship type 3, there are no restrictions in respect of cargo tank location. Therefore a ST 3 cargo can be carried in a cargo tank whose boundaries are common with the shell plating.

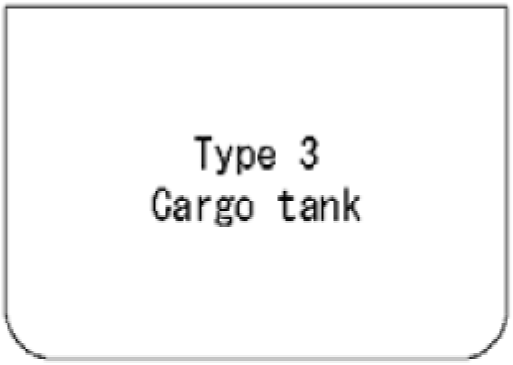


Figure 3.4 – Tank location of Type 3 ships

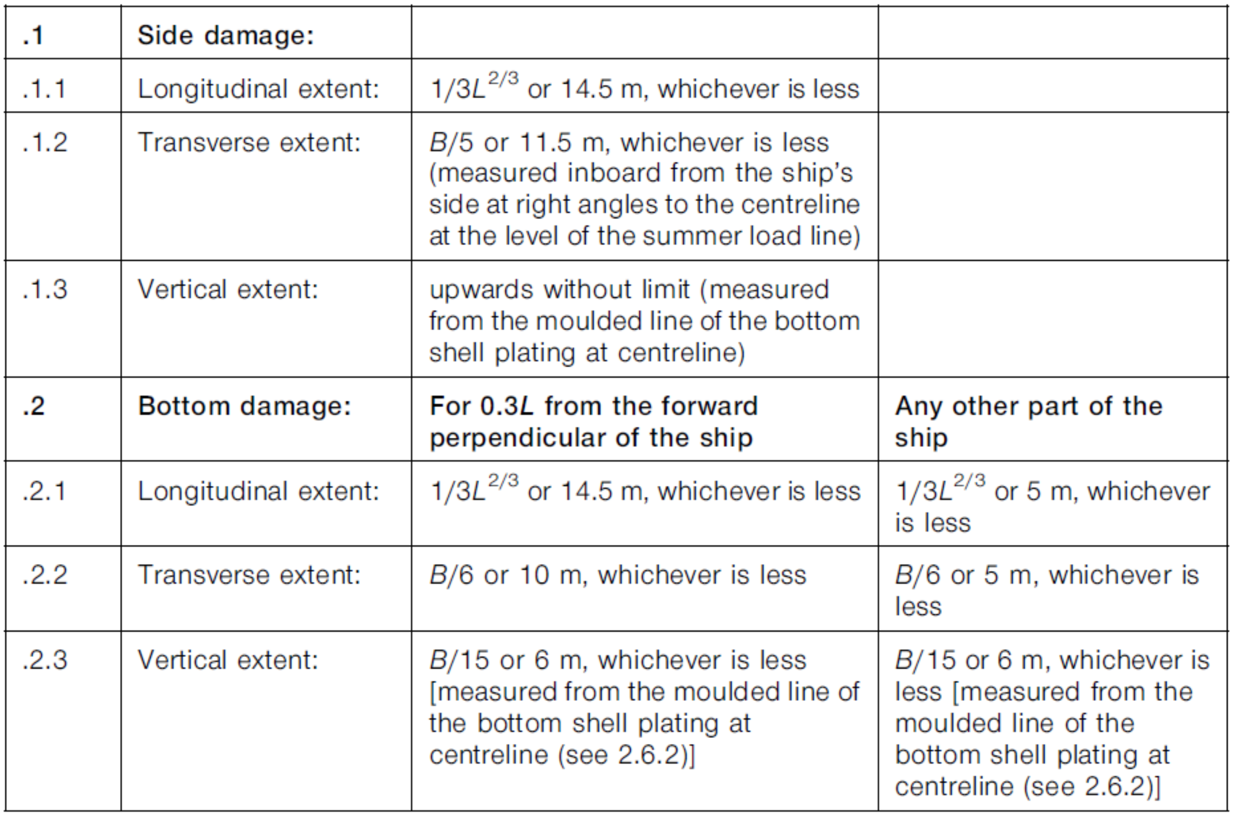
3.3.3 Deck tanks

The distances indicated in Images 3.1 – 3.3 also control the ship type cargo that may be carried in a deck tank. Clearly the double bottom height is not an issue but the distance between the tank boundary and side shell is relevant, as the vertical extend of side damage is assumed to be upwards without limit.[4]

3.3.4 *Damage stability*

Damage stability is a survival capability in the damaged condition of a ship which suffers damage in way of the side or bottom in specified damage assumption area. Damage stability varies depending on ship size, tank size, tank arrangement, loading condition and densities of cargoes to be loaded.[5]

The assumed maximum acceptable extent of damage is listed in the IBC code as follows[6]:



.1	**Side damage:**		
.1.1	Longitudinal extent:	$1/3L^{2/3}$ or 14.5 m, whichever is less	
.1.2	Transverse extent:	$B/5$ or 11.5 m, whichever is less (measured inboard from the ship's side at right angles to the centreline at the level of the summer load line)	
.1.3	Vertical extent:	upwards without limit (measured from the moulded line of the bottom shell plating at centreline)	
.2	**Bottom damage:**	**For 0.3*L* from the forward perpendicular of the ship**	**Any other part of the ship**
.2.1	Longitudinal extent:	$1/3L^{2/3}$ or 14.5 m, whichever is less	$1/3L^{2/3}$ or 5 m, whichever is less
.2.2	Transverse extent:	$B/6$ or 10 m, whichever is less	$B/6$ or 5 m, whichever is less
.2.3	Vertical extent:	$B/15$ or 6 m, whichever is less [measured from the moulded line of the bottom shell plating at centreline (see 2.6.2)]	$B/15$ or 6 m, whichever is less [measured from the moulded line of the bottom shell plating at centreline (see 2.6.2)]

Figure 3.5 - Maximum extend of damage

Ships shall be capable of surviving the damage indicated in the matrix above, to the extent determined by the ship's type according to the following standards[7]:

1. A type 1 ship shall be assumed to sustain damage anywhere in its length.
2. A type 2 ship of more than 150 m in length shall be assumed to sustain damage anywhere in its length.
3. A type 2 ship of 150 m in length or less shall be assumed to sustain damage anywhere in its length except involving either of the bulkheads bounding a machinery space located aft.
4. A type 3 ship of more than 225 m in length shall be assumed to sustain damage anywhere in its length.

5. A type 3 ship of 125 m in length or more but not exceeding 225 m in length shall be assumed to sustain damage anywhere in its length except involving either of the bulkheads bounding a machinery space located aft.
6. A type 3 ship below 125 m in length shall be assumed to sustain damage anywhere in its length except involving damage to the machinery space when located aft. However, the ability to survive the flooding of the machinery space shall be considered by the Administration.

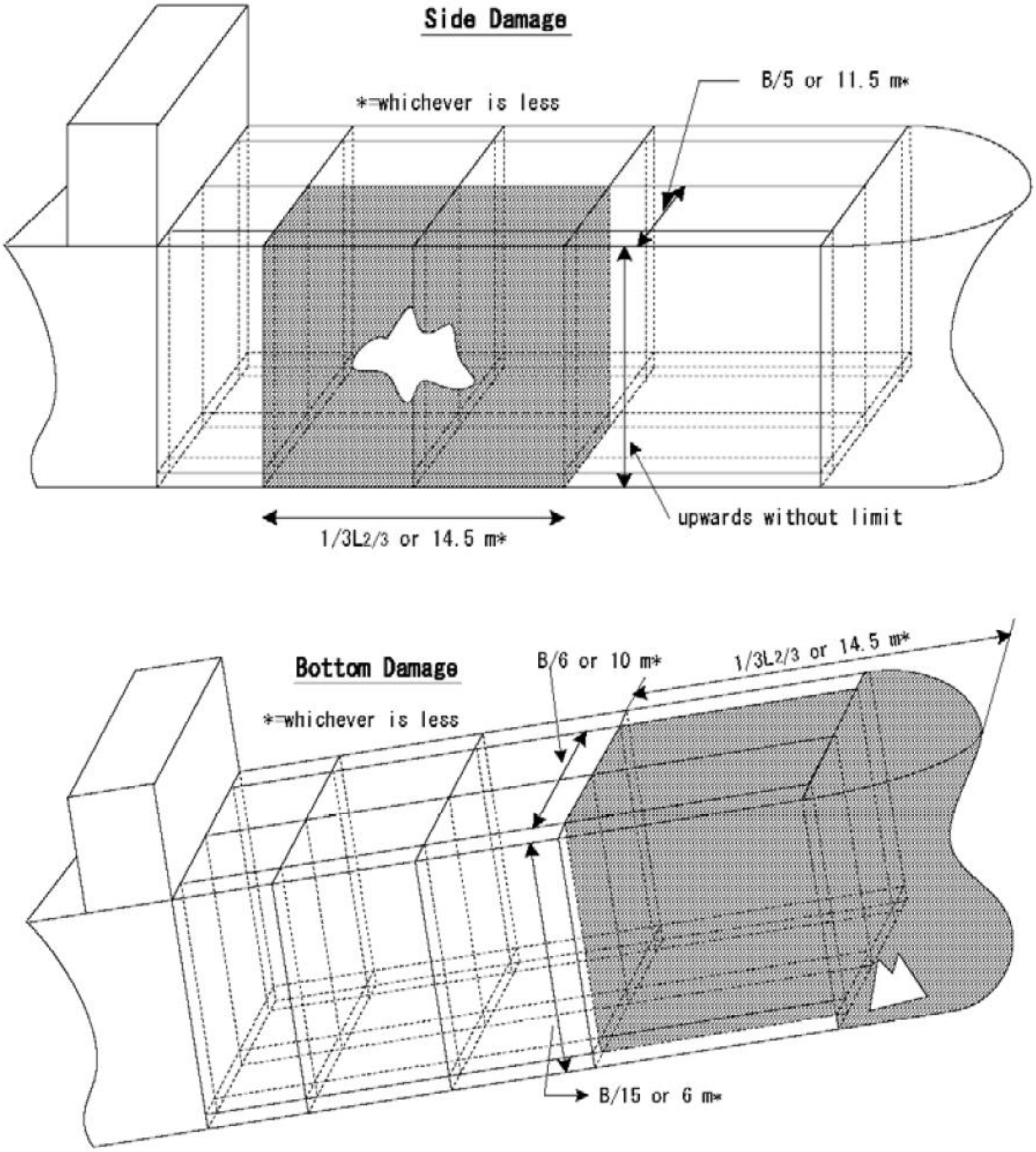


Figure 3.6 – Example of damage assumption

As far as practicable, tunnels, ducts or pipes which may cause progressive flooding in case of damage, shall be avoided in the damage penetration zone. If this is not possible, arrangements shall be made to prevent progressive flooding to volumes assumed intact. Alternatively, these volumes shall be assumed flooded in the stability calculations.[8]

3.3.5 Size of cargo tanks

The IBC code, in Chapter 16.1, limits the maximum quantity of cargo of a certain ship type that may be stored in a single tank. The maximum amount of ST 1 cargo that may be carried in a single tank is 1250 m^3. The maximum amount of ST 2 cargo that may be stored in a single tank is 3000 m^3. The code does not limit the maximum quantity of ST 3 cargo that may be stored in a single tank. These limits are on cargo quantity and not on tank size. However, if the volume of cargo tank that is designed to carry ST 1 cargoes is greater than 1250 m^3 it will have to be loaded in a slack condition when used to carry a ST 1 cargo. Loading tanks significantly below capacity reduces the total volume of cargo that a vessel can carry on a given voyage. Therefore, to maintain maximum operational flexibility the size of ST 1 tanks and ST 2 tanks are effectively limited to approximately 1250 m^3 and 3000 m^3, respectively.

Chemical tankers carrying flammable cargoes that are listed in Chapters 17 and 18 of the IBC code are exempt from the SOLAS regulations requiring tankers to be fitted with inert gas systems, provided that a) the individual cargo tank capacities do not exceed 3000 m^3, b) that the nozzle capacity of any single tank washing nozzle does not exceed 17.5 m^3/hour, and c) that the sum of all the washing machine nozzles in a single tank does not exceed 110 m^3/hour.

The trade in which the ship-owner plans to employ the vessel will also drive the size of the cargo tanks. To maximize operational flexibility and cargo carrying capacity on any given voyage the standard parcel sizes and typical specific gravities must be taken into account. An analysis of the cargoes shipped and the parcel sizes that are common in a given trade can provide the naval architect with guidelines for selecting the practical cargo tank sizes.

Figure 3.7 illustrates the breakdown of parcel of parcel sizes by percentage of total number of cargoes carried during a two-year period on a fixed trade route. The chart indicates that the most common parcel size was 500 tons, which accounted for nearly 30% of all parcels shipped. The number of parcels sized 1000 tons or less equaled 68% of the total parcels shipped over the two-year period.

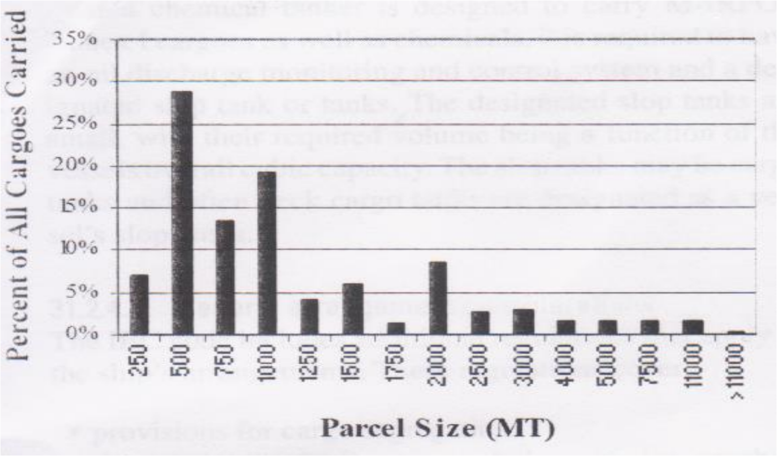


Figure 3.7 – Breakdown of parcel sizes

Based on this analysis the optimum tank sizes would be based on parcel sizes of 500, 750, 1000 tons. To determine the required tank volume to handle these parcel sizes a similar examination of the specific gravities of the cargoes carried must be performed. For example a 500 m^3 cargo tank is too small for a parcel of 500 tons of cargo with a specific gravity of 0.86. A 500 tons parcel at a specific gravity of 0.86 would require a minimum tank size of approximately 593 m^3 when filled at 98% capacity. In practice, cargo tanks are typically filled to a maximum of 98% of capacity to allow for thermal expansion of the cargo during carriage.

Figure 3.8 illustrates the breakdown of the specific gravities of cargoes carried by percentage of the total number of cargoes carried during the same two-year period on the same fixed trade route. This chart indicates that the most common cargo specific gravity was approximately 0.90 at 21% of the total cargo carried and that 62% of the total number of cargoes carried had specific gravities between 0.80 and 0.95.

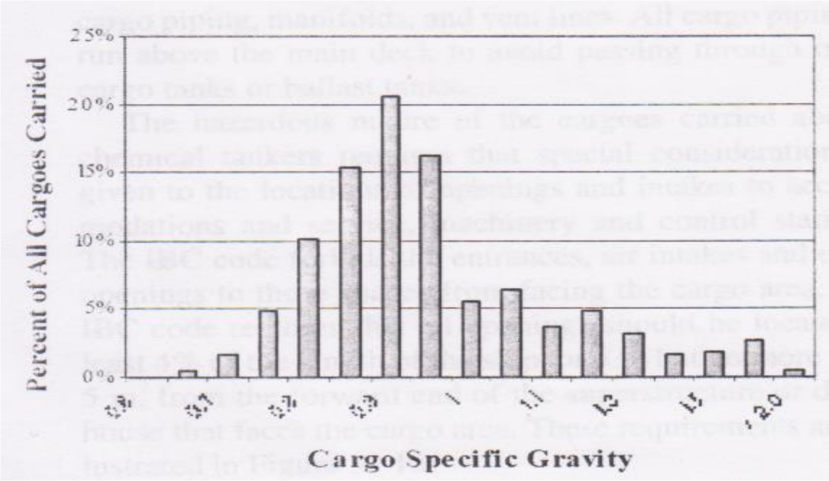


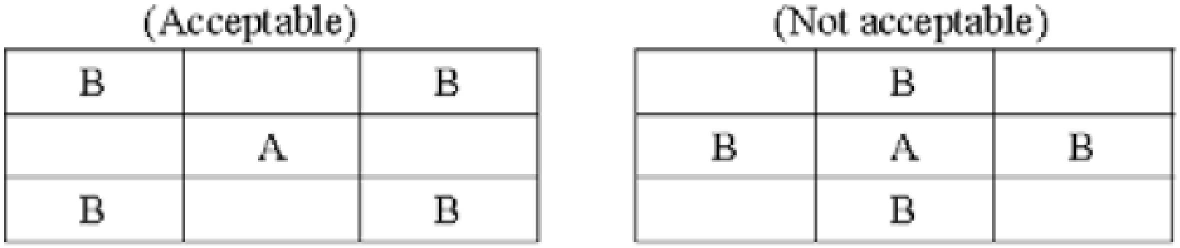
Figure 3.8 – Breakdown of cargo specific gravity

Utilizing the type of information provided in Figures 3.7 and 3.8 the naval architect could select various tank sizes that best fit the needs of the vessel’s intended trade. With the desired tank sizes in hand the tank arrangement can be developed. The arrangement of the cargo tanks should maximize the operational flexibility of the vessel and meet the need of the ship-owner.[9]

3.4 Cargo segregation[10]

3.4.1 Mutual compatibility of cargoes

The cargoes which react in a hazardous manner with other cargoes should be segregated from each other by means of a cofferdam, void space, cargo pump room, empty tank or tank containing a mutual compatible cargo, or should be loaded in the tanks touching adjacent other tanks at only one corner as shown below:



(Acceptable)

B		B
	A	
B		B

(Not acceptable)

	B	
B	A	B
	B	

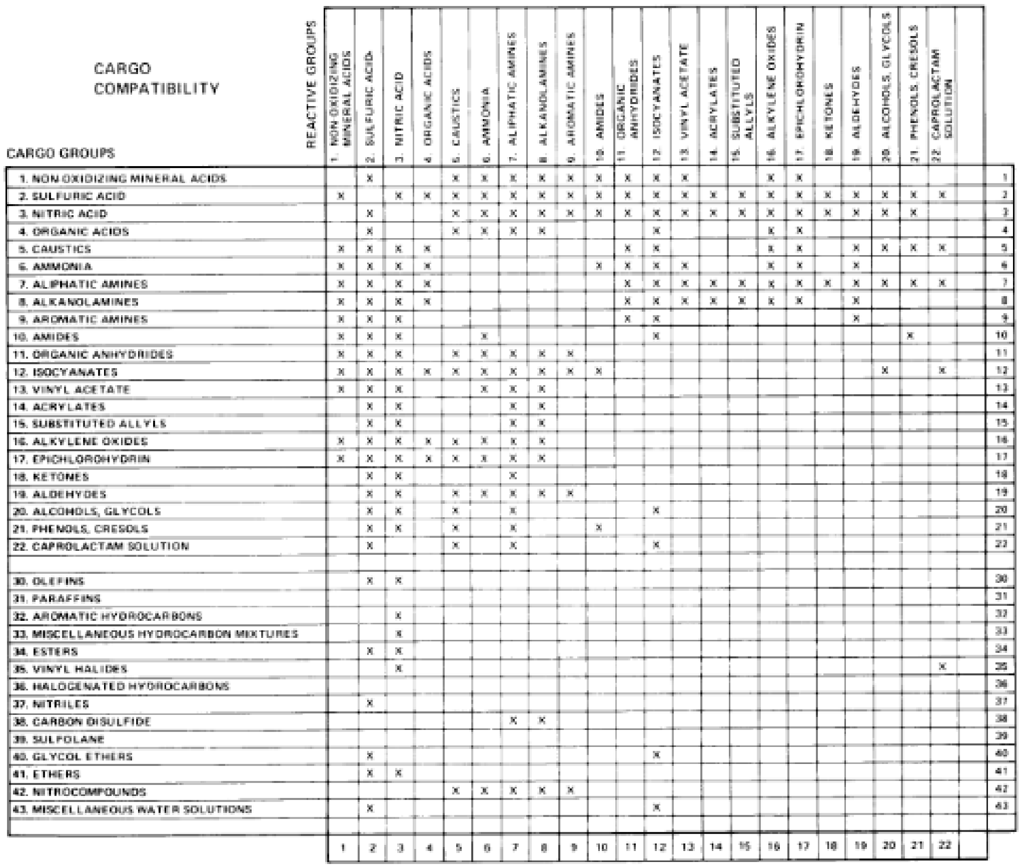
Figure 3.9 – Cargo segregation by loading

In addition, as per IBC code[11], these cargoes shall have separate pumping and piping systems which shall not pass through other cargo tanks containing such cargoes, unless encased in a tunnel, and shall have separate tank venting systems.

If cargo piping systems or cargo ventilation systems are to be separated, this separation may be achieved by the use of design or operational methods. Operational methods shall not be used within a cargo tank and shall consist of one of the following types:
1. Removing spool-pieces or valves and blanking the pipe ends;
2. Arrangement of two spectacle flanges in series, with provisions for detecting leakage into the pipe between the two spectacle flanges.

3.4.2 Compatibility chart

With regard to information of cargoes which react in a hazardous manner with other cargoes, the compatibility chart 46 CFR 150 of USCG[12] is most popularly used, which is reproduced in Figure 3.10.



CARGO COMPATIBILITY

CARGO GROUPS / REACTIVE GROUPS	1. NON OXIDIZING MINERAL ACIDS	2. SULFURIC ACID	3. NITRIC ACID	4. ORGANIC ACIDS	5. CAUSTICS	6. AMMONIA	7. ALIPHATIC AMINES	8. ALKANOLAMINES	9. AROMATIC AMINES	10. AMIDES	11. ORGANIC ANHYDRIDES	12. ISOCYANATES	13. VINYL ACETATE	14. ACRYLATES	15. SUBSTITUTED ALLYLS	16. ALKYLENE OXIDES	17. EPICHLOROHYDRIN	18. KETONES	19. ALDEHYDES	20. ALCOHOLS, GLYCOLS	21. PHENOLS, CRESOLS	22. CAPROLACTAM SOLUTION	
1. NON OXIDIZING MINERAL ACIDS		x			x	x	x	x	x	x	x	x	x			x	x						1
2. SULFURIC ACID	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	2
3. NITRIC ACID		x			x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		3
4. ORGANIC ACIDS		x			x	x	x	x				x				x	x						4
5. CAUSTICS	x	x	x	x							x	x				x	x		x	x	x	x	5
6. AMMONIA	x	x	x	x						x	x	x	x			x	x		x				6
7. ALIPHATIC AMINES	x	x	x	x							x	x	x	x	x	x	x	x	x	x	x	x	7
8. ALKANOLAMINES	x	x	x	x							x	x	x	x	x	x	x		x				8
9. AROMATIC AMINES	x	x	x								x	x							x				9
10. AMIDES	x	x	x			x						x									x		10
11. ORGANIC ANHYDRIDES	x	x	x		x	x	x	x	x														11
12. ISOCYANATES	x	x	x	x	x	x	x	x	x	x										x		x	12
13. VINYL ACETATE	x	x	x			x	x	x															13
14. ACRYLATES		x	x				x	x															14
15. SUBSTITUTED ALLYLS		x	x				x	x															15
16. ALKYLENE OXIDES	x	x	x	x	x	x	x	x															16
17. EPICHLOROHYDRIN	x	x	x	x	x	x	x	x															17
18. KETONES		x	x				x																18
19. ALDEHYDES		x	x		x	x	x	x	x														19
20. ALCOHOLS, GLYCOLS		x	x		x		x					x											20
21. PHENOLS, CRESOLS		x	x		x		x			x													21
22. CAPROLACTAM SOLUTION		x			x		x					x											22
30. OLEFINS		x	x																				30
31. PARAFFINS																							31
32. AROMATIC HYDROCARBONS			x																				32
33. MISCELLANEOUS HYDROCARBON MIXTURES			x																				33
34. ESTERS		x	x																				34
35. VINYL HALIDES			x																			x	35
36. HALOGENATED HYDROCARBONS																							36
37. NITRILES		x																					37
38. CARBON DISULFIDE							x	x															38
39. SULFOLANE																							39
40. GLYCOL ETHERS		x										x											40
41. ETHERS		x	x																				41
42. NITROCOMPOUNDS					x	x	x	x	x														42
43. MISCELLANEOUS WATER SOLUTIONS		x										x											43
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	

Note: 1) Blank: No reactivity

2) x: Reactivity in hazardous manner

Figure 3.10 – Compatibility chart

The cargo groups in the compatibility chart are divided into two categories: groups 1 through 22 are "reactive groups" and groups 30 through 43 are "cargo groups". Reactive groups contain products which are chemically the most reactive; dangerous combination may result between members of different reactive groups and between members of reactive groups and cargo groups. Products assigned to cargo groups, however, are much less reactive; dangerous combinations involving these products can be formed only with members of certain reactive groups. Products assigned to cargo groups do not react hazardously with one another.

The following explains the procedure for how to use compatibility chart to find compatibility information:

1. If both group numbers are between 30 and 43 inclusive, the products are compatible and the chart needs not be used.
2. If both group numbers do not fall between 30 and 43 inclusive, locate one of the numbers on the left of the chart (cargo groups) and the other across the top (reactive groups).

3. The box formed by the intersection of the column and row containing the two numbers will contain one of the following:
   (a) Blank – the two cargos are compatible
   (b) X- the two cargoes are not compatible

3.4.3 Segregation from heat

The cargoes which are easily affected by heat causing such hazards as polymerization, decomposition, production of dangerous gas should be loaded in tanks separated from other cargoes that are maintained at a high temperature. Associated piping should also be separated accordingly.

If there are such cargoes among the cargoes expected to be loaded, careful consideration should be paid in the preparation of the loading plan.

In order to ensure segregation from heat flow, the adjacency of two tanks is not permitted even though for the two tanks it is limited to a corner spot or to a corner line.

3.4.4 Segregation from F.O. tank

Toxic cargoes should not be loaded in tanks adjacent to F.O. tanks in order to avoid possible leakage of toxic cargoes into a F.O. tank. In this case, also, touching of the two tanks at a corner spot or along a corner line is not permitted.

3.4.5 Segregation of cargoes that react with water

The cargoes that react in a dangerous manner with water should be loaded separately from ballast water tanks or fresh water tanks except when the water tank is empty and dry. Touching of the two tanks, which is limited to corner spot or corner line, may be permitted.

3.4.6 Corner-to-corner situation

Where a corner-to-corner situation occurs between a non-hazardous space and a cargo tank, a cofferdam created by a diagonal plate across the corner on the non-hazardous side, may be accepted as separation.
Such cofferdams shall be:
— ventilated if accessible,
— filled with a suitable compound if not accessible.

3.5 Location of spaces

Additional regulations that apply to the ship's arrangement regarding the accommodation spaces, service and machinery spaces, control stations, paint lockers, fuel oil tanks and others, are presented below, as given by the IBC code[13], DNV[14] and Class NK rules[15].

3.5.1 Cargo segregation from accommodation spaces

Unless expressly provided otherwise, tanks containing cargo or residues of cargo subject to the IBC code shall be segregated from accommodation, service and machinery spaces and from drinking water and stores for human consumption by means of a cofferdam, void space, cargo pump-room, pumproom, empty tank, oil fuel tank or other similar space.

In addition, cargo piping shall not pass through any accommodation, service or machinery space other than cargo pump-rooms or pump-rooms.

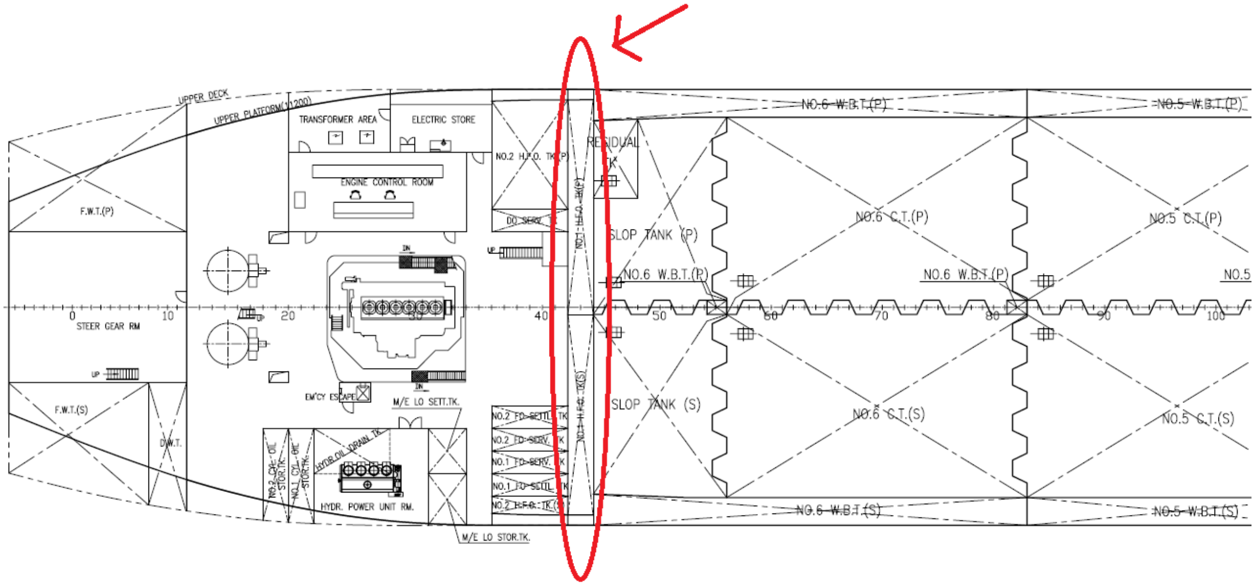


Figure 3.11 – Cargo segregation from accommodation by HFO tanks

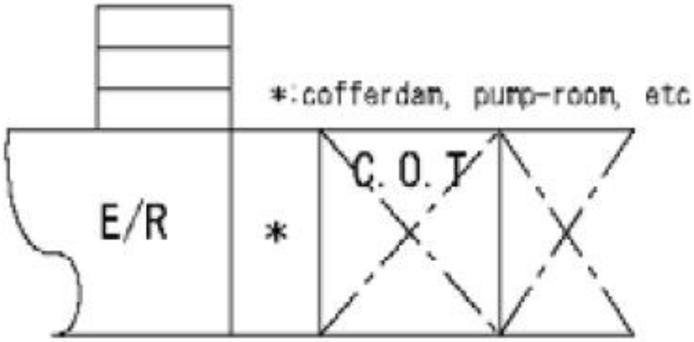


Figure 3.12 – Cargo segregation

3.5.2 Arrangement of Fuel Oil tanks

Fuel oil bunker tanks shall not be situated within the cargo area. Such tanks may, however, be situated at forward and aft end of cargo area instead of cofferdams, as shown in Figure 3.11. Also, the fuel oil tanks shall not extend beneath cargo tanks.

3.5.3 Accommodation, service and machinery spaces and control stations

No accommodation or service spaces or control stations should be located within the cargo area and no cargo or slop tank should be aft of the forward end of any accommodation.

Accommodation spaces and service spaces shall be positioned outside the cargo area, but not necessarily aft of fuel oil tanks, however accommodation spaces shall not be situated directly onto fuel oil bunker tanks adjacent to cargo tanks.

Exterior boundaries of superstructures and deckhouses shall be insulated to “A-60” standard for the whole of the portions which face the cargo area and on the outward sides for a distance of 3m from the end boundary facing the cargo area.

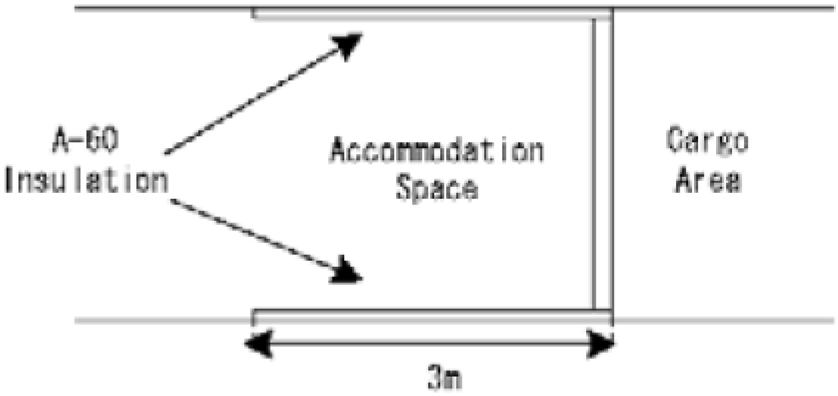


Figure 3.13 – Exterior boundaries of deck houses

Where the fitting of a navigation position above the cargo area is shown to be necessary, it shall be for navigation purposes only, and it shall be separated from the cargo tank deck by means of an open space with a height of at least 2 m.

Paint lockers shall not be located within the cargo area.

Machinery spaces of category A and boiler spaces shall be positioned aft of the cargo area, but not necessarily aft of fuel oil tanks.

Where deemed necessary, machinery spaces other than those of category A may be permitted forward of the cargo area.

Machinery spaces of category A[16] are those spaces and trunks to such spaces which contain either:
1. internal combustion machinery used for main propulsion;
2. internal combustion machinery used for purposes other than main propulsion where such machinery has in the aggregate a total power output of not less than 375 kW; or
3. any oil-fired boiler or oil fuel unit, or any oil-fired equipment other than boilers, such as inert gas generators, incinerators, etc.

3.5.4 Entrances and openings to accommodation

In order to safeguard against the danger of hazardous vapours, due consideration shall be given to the location of air intakes and openings into accommodation, service and machinery spaces and control stations in relation to cargo piping and cargo vent systems.

Entrances, air inlets and openings to accommodation, service and machinery spaces and control stations shall not face the cargo area. They shall be located on the end bulkhead not facing the cargo area and/or on the outboard side of the superstructure or deck-house at a distance of at least 4% of the length (L) of the ship but not less than 3 m from the end of the superstructure or deck-house facing the cargo area. This distance, however, need not exceed 5 m. No doors shall be permitted within the limits mentioned above, except that doors to those spaces not having access to accommodation and service spaces and control stations, such as cargo control stations and storerooms, may be fitted. Where such doors are fitted, the boundaries of the space shall be insulated to ‘‘A-60’’ standard. Bolted plates for removal of machinery may be fitted within the limits specified above. Wheelhouse doors and wheelhouse windows may be located within the limits specified above so long as they are so designed that a rapid and efficient gas- and vapour-tightening of the wheelhouse can be ensured. Windows and sidescuttles facing the cargo area and on the sides of the superstructures and deck-houses within the limits specified above shall be of the fixed (non-opening) type. Such sidescuttles in the first tier on the main deck shall be fitted with inside covers of steel or equivalent material.

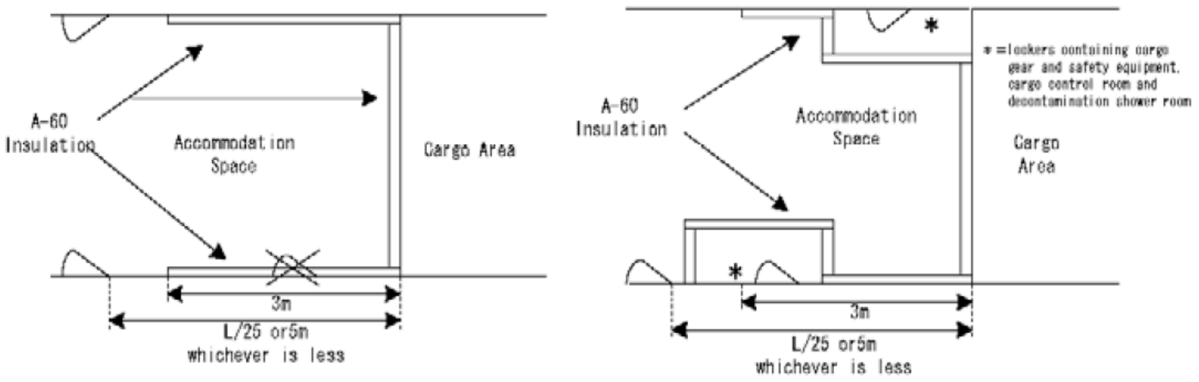


Figure 3.14 – Entrances to accommodation

Ventilation inlets for the spaces mentioned above shall be located as far as practicable from gas-dangerous zones, and in no case are the ventilation inlets nor outlets to be located closer to the cargo area than specified for other openings.

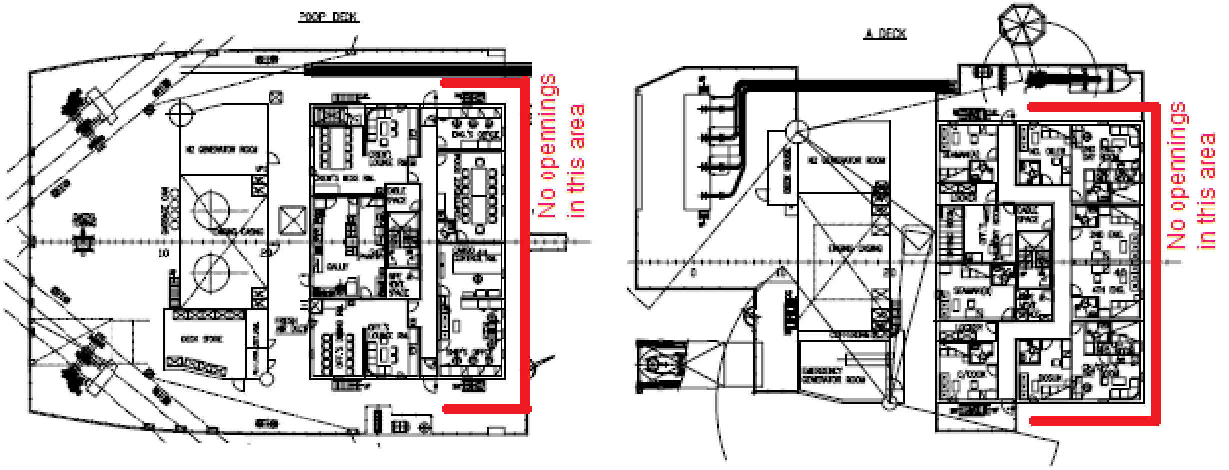


Figure 3.15 – Openings to accommodation

Entrance through air locks to non-hazardous spaces shall be arranged at a horizontal distance of at least 3 m from any opening to a hazardous space containing gas sources, such as valves, hose connection or pump used with the cargo.

Air locks shall comply with the following requirements:

- air locks shall be enclosed by gastight steel bulkheads with two substantially gas tight self-closing doors spaced at least 1.5 m and not more than 2.5 m apart.
- air locks shall have a simple geometrical form. They shall provide free and easy passage, and shall have a deck area not less than 1.5 m2. Air locks shall not be used for other purposes, for instance as store rooms.
- an alarm (acoustic and visual) shall be released on both sides of the air lock to indicate if more than one door have been moved from the closed position.
- air locks shall have effective ventilation.

Cargo control rooms, stores and other spaces other than accommodation and service spaces but located within accommodation, may be permitted to have doors facing the cargo area. Where such doors are fitted, the spaces shall not have access to the accommodation and service spaces and the boundaries of the spaces shall be insulated to A-60 class.

3.5.5 *Cargo pump rooms*

Cargo pump-rooms shall be so arranged as to ensure:

1. unrestricted passage at all times from any ladder platform and from the floor; and
2. unrestricted access to all valves necessary for cargo handling for a person wearing the required personnel protective equipment.

Guard railings shall be installed on all ladders and platforms, when normal access ladders shall not be fitted vertical and shall incorporate platforms at suitable intervals.

Means shall be provided to deal with drainage and any possible leakage from cargo pumps and valves in cargo pump-rooms. The bilge system serving the cargo pump-room shall be operable from outside the cargo pump-room. One or more slop tanks for storage of contaminated bilge water or tank washings shall be provided. A shore connection with a standard coupling or other facilities shall be provided for transferring contaminated liquids to onshore reception facilities.

Figure 3.16 – Cargo Pump Room

The lower portion of the cargo pump room may be recessed into machinery and boiler spaces to accommodate pumps, provided the deck head of the recess is in general not more than one-third of the moulded depth above the keel, except that in the case of ships of not more than 25 000 tons deadweight, where it can be demonstrated that for reasons of access and satisfactory piping arrangements this is impracticable, a recess in excess of such height may be permitted, though not exceeding one half of the moulded depth above the keel.

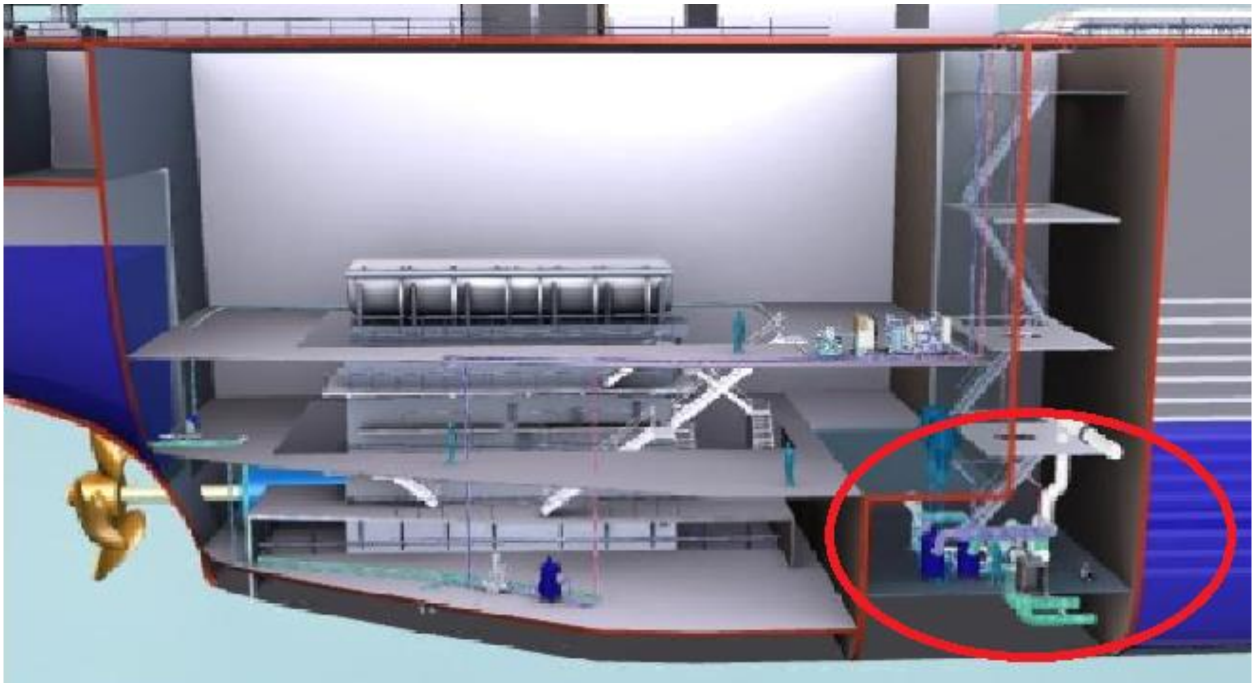


Figure 3.17 – Cargo Pump Room

3.6 Access to spaces in the cargo area

Access to cofferdams, ballast tanks, cargo tanks and other spaces in the cargo area shall be direct from the open deck and such as to ensure their complete inspection. Access to double-bottom spaces may be through a cargo pump-room, pump-room, deep cofferdam, pipe tunnel or similar compartments, subject to consideration of ventilation aspects.

For access through horizontal openings, hatches or manholes, the dimensions shall be sufficient to allow a person wearing a self-contained air-breathing apparatus and protective equipment to ascend or descend any ladder without obstruction and also to provide a clear opening to facilitate the hoisting of an injured person from the bottom of the space. The minimum clear opening shall be not less than 600 mm by 600 mm.

For access through vertical openings, or manholes providing passage through the length and breadth of the space, the minimum clear opening shall be not less than 600 mm by 800 mm at a height of not more than 600 mm from the bottom shell plating unless gratings or other footholds are provided.

Smaller dimensions may be approved by the Administration in special circumstances, if the ability to traverse such openings or to remove an injured person can be proved to the satisfaction of the Administration.

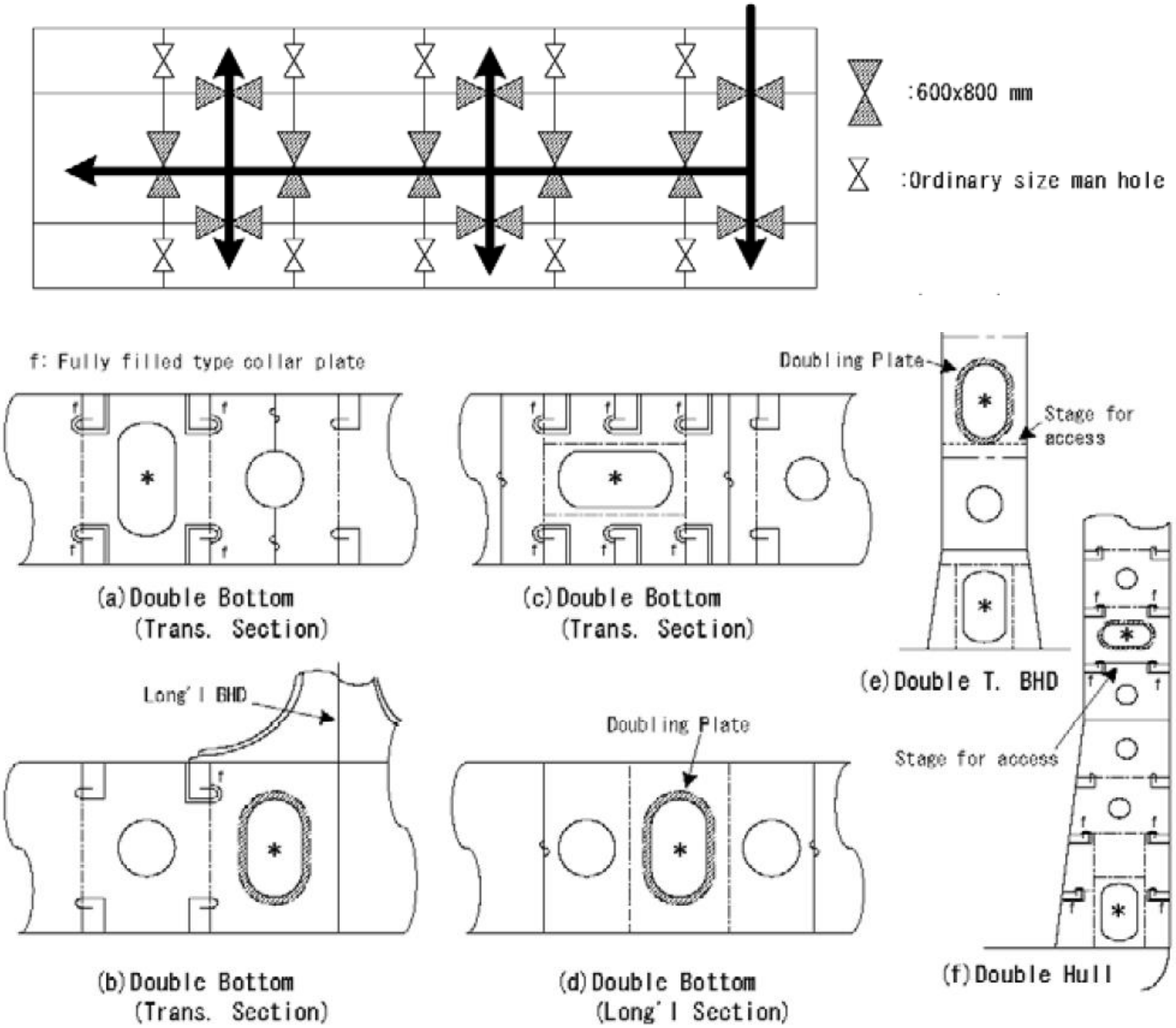


Figure 3.18 – Access and access openings

3.7 Bilge and ballast arrangements

Pumps, ballast lines, vent lines and other similar equipment serving permanent ballast tanks shall be independent of similar equipment serving cargo tanks and of cargo tanks themselves. Discharge arrangements for permanent ballast tanks sited immediately adjacent to cargo tanks shall be outside machinery spaces and accommodation spaces. Filling arrangements may be in the machinery spaces provided that such arrangements ensure filling from tank deck level and non-return valves are fitted.

Filling of ballast in cargo tanks may be arranged from deck level by pumps serving permanent ballast tanks, provided that the filling line has no permanent connection to cargo tanks or piping and that non-return valves are fitted.

Bilge pumping arrangements for cargo pump-rooms, pump-rooms, void spaces, slop tanks, double bottom tanks and similar spaces shall be situated entirely within the cargo area except for void spaces, double-bottom tanks and ballast tanks where such spaces are separated from tanks containing cargo or residues of cargo by a double bulkhead.

3.8 Bow or stern loading and unloading arrangements

Cargo piping may be fitted to permit bow or stern loading and unloading, however bow or stern loading and unloading lines shall not be used for the transfer of products required to be carried in type 1 ships or for the transfer of cargoes emitting toxic vapours, unless specifically approved by the Administration.

Bow or stern loading arrangements shall comply with the below:

1. The piping outside the cargo area shall be fitted at least 760 mm inboard on the open deck. Such piping shall be clearly identified and fitted with a shutoff valve at its connection to the cargo piping system within the cargo area. At this location, it shall also be capable of being separated by means of a removable spool-piece and blank flanges when not in use.
2. The shore connection shall be fitted with a shutoff valve and a blank flange.
3. The piping shall be full-penetration butt-welded, and fully radiographed. Flange connections in the piping shall only be permitted within the cargo area and at the shore connection.
4. Spray shields shall be provided at the connections as well as collecting trays of sufficient capacity, with means for the disposal of drainage.
5. The piping shall be self-draining to the cargo area and preferably into a cargo tank. Alternative arrangements for draining the piping may be accepted by the Administration.
6. Arrangements shall be made to allow such piping to be purged after use and maintained gas-safe when not in use. The vent pipes connected with the purge shall be located in the

cargo area. The relevant connections to the piping shall be provided with a shutoff valve and blank flange.

Entrances, air inlets and openings to accommodation, service and machinery spaces and control stations shall not face the cargo shore-connection location of bow or stern loading and unloading arrangements. They shall be located on the outboard side of the superstructure or deck-house at a distance of at least 4% of the length of the ship but not less than 3 m from the end of the house facing the cargo shore-connection location of the bow or stern loading and unloading arrangements. This distance, however, need not exceed 5 m. Sidescuttles facing the shore-connection location and on the sides of the superstructure or deck-house within the distance mentioned above shall be of the fixed (non-opening) type. In addition, during the use of the bow or stern loading and unloading arrangements, all doors, ports and other openings on the corresponding superstructure or deckhouse side shall be kept closed.

3.9 Hazardous Locations

The IBC code defines certain locations in the cargo areas as hazardous locations. The defined locations and the cargoes carried determine what types of electrical equipment can be used in certain areas of the ship. The areas defined as hazardous locations include the entire length of the cargo area from the bottom shell plating to a height above the main deck, holds containing independent cargo tanks, cargo pump rooms, pump rooms in the cargo area, and areas above cargo tank outlets, vapour outlets, ventilation openings, and cargo pipe fittings. Consideration must be given to the mechanical systems that are installed in the hazardous locations. Like the electrical components, the mechanical components employed in the hazardous areas must not present a source of ignition.

The carriage of toxic products result in additional hazardous areas that extend 15m in all directions from the exhaust openings of tank venting systems. No accommodation or service spaces may be located within the hazardous area.

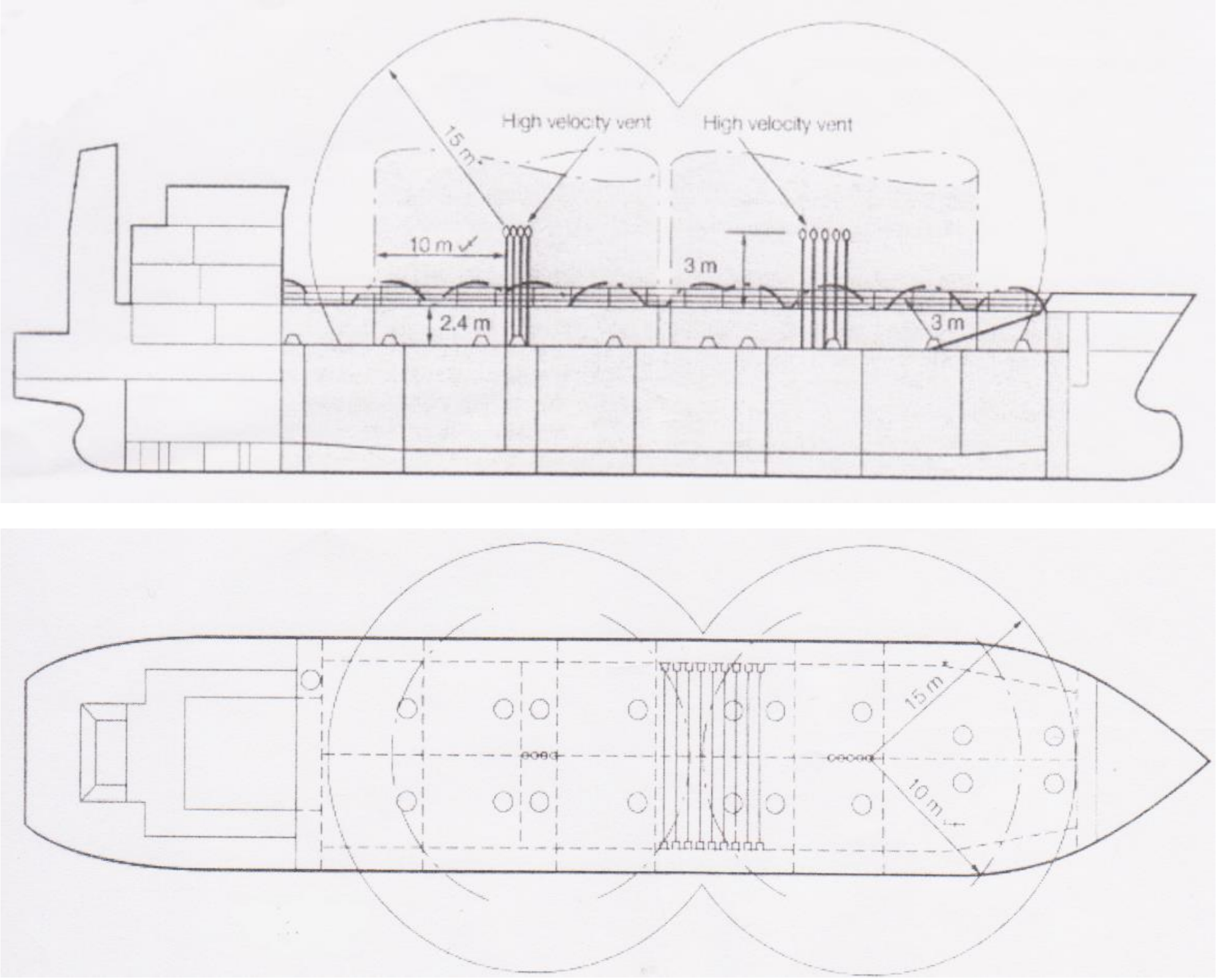


Figure 3.19 – Hazardous Zones

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Chapter 4

The Structural Design Process

4.1 Introduction

The scope of this chapter is to present the basic steps that are followed by the designer during the structural design process of a vessel, so that the importance and usefulness of each design stage is highlighted. The first section of this chapter summarizes the whole design procedure and aims to familiarize the reader with some basic concepts of it. Subsequently, two of the most important steps of the design process, the load analysis and the strength evaluation, are isolated and explained.

In the second section of this chapter, the loads that are predicted to be applied on the vessel, are analyzed and classified to static and dynamic loads based on their characteristics. Moreover, the ways in which these loads affect the transverse and longitudinal strength of the vessel are explained. Finally, the most commonly used methods of load calculations are presented. A brief description of impact dynamic loads, such as sloshing and slamming is also included.

The strength evaluation process is analyzed in the last section of the chapter, where reference is made to the main types of structural failure. The strength evaluation flow, conventional analytical methods as well as modern computational methods, such as the finite element method are also described here.

This chapter is not focused on chemical tankers exclusively, but it addresses to almost all types of commercial vessels, as they follow more or less the same design process. Special references in chemical tankers are made though, wherever appropriate.

4.2 The structural design process

The structural design process of a vessel begins by the time that the functional requirements have been set by the owner. Requirements such as the type and volume of cargoes, the routes of transportation, the ports of call and the speed of the vessel consist the basis on which the whole design procedure takes place. According to these requirements, a preliminary general arrangement is to be prepared and the major structural parameters are to be set.

Subsequently, an estimation of the loads and forces applied to the structure, such as the static loads of buoyancy, weight of ship and cargo weight, as well as the wave and other dynamic loads shall be made. For structural design and analysis, a structural engineer needs to have basic concepts of waves, motions and design loads. The wave load is a kind of natural phenomenon and therefore difficult to be estimated as it has many variations depending on the geographical area and the season. For that reason its estimation is based on accumulated observed data.

Once the functional requirements and loads are determined, an initial scantling may be sized based on formulae and charts in classification rules and design codes. The basic scantling of the structural components is initially determined based on stress analysis of beams, plates and shells under hydrostatic pressure, bending and concentrated loads. The rules provided by classification societies thought, are not always 100% perfect. For that reason the designer must do his utmost in the design.

The next steps of the design procedure, after the loads applied and the initial scantling have been calculated, are the estimation of the structural response of the hull structure when subjected to these loads, and the assessment of the obtained responses against the allowable values. Response calculations can now be done with sufficient accuracy by means of a framework or Finite Element Method thanks to the development of computers. The calculated results coincide well with the results of model tests and full-scale tests.

For the allowable values to be set, methods of limit state design have been implemented. A limit state is a condition of a structure beyond which it no longer fulfills the relevant design criteria. In a limit-state design, the design of structures is checked for all groups of limit-states to ensure that the safety margin between the maximum likely loads and the weakest possible resistance of the structure is large enough and that fatigue damage is tolerable. Limit state design criteria cover various failure modes such as serviceability limit state, ultimate limit state (including buckling/collapse and fracture), fatigue limit state, and accidental limit state. Each failure mode may be controlled by a set of design criteria. Limit-state design criteria are developed based on ultimate strength and fatigue analysis as well as use of the risk/reliability methods.

Theoretical reliable design, such as the limit state design, aims to keep reliability by gathering data on statistical parameters and calculating failure probabilities theoretically for many kinds of failure modes.

The failure probability can be obtained by considering the distribution patterns of the forces applied and the strength of the structure. As shown in Figure 4.1, if probability density functions of forces applied and strength of structure are given with the horizontal axis indicating stress *X*, the failure probability is given by the following equation:

$$P_f = \int_0^\infty Q_d\{X\}P_c\{X\}dX = \int_0^\infty (1 - Q_c\{X\})Pd\{X\}dX$$

where

$P_d\{X\}$: probability density function of demand (load)

$P_c\{X\}$: probability density function of capacity (strength)

$Q_d\{X\}$: probability of demand (load) exceeding certain value

$Q_c\{X\}$: probability of capacity (strength) exceeding certain value

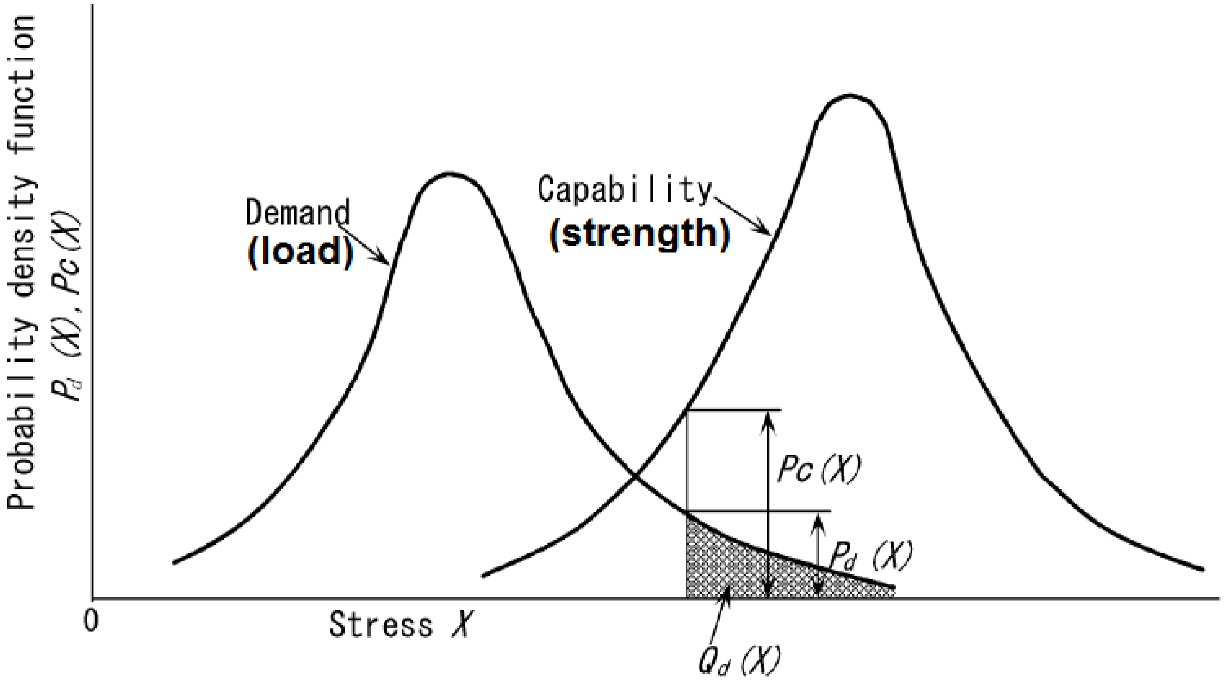


Figure 4.1 – Probability of fracture

However, in case of ordinary ships, for which past experience has been accumulated, the allowable limits can be alternatively decided by comparing results of response calculations for estimated applied forces with damage data of the ship in service. This is an empirical reliable design [1,2].

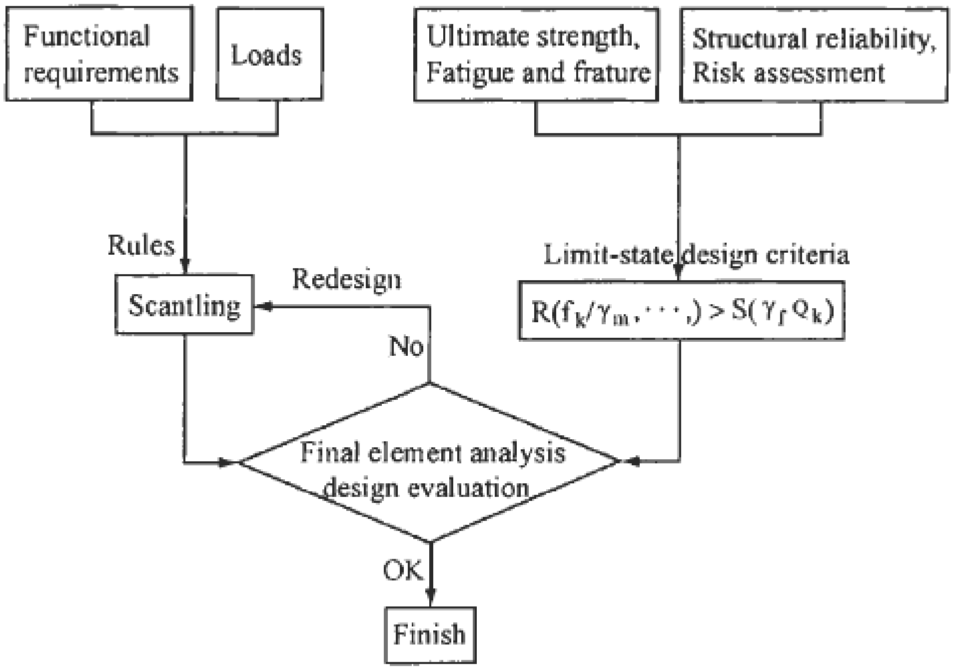


Figure 4.2 – Modern theory for marine structural design

When it comes to chemical tankers, the functional requirements are mostly set by the types of cargoes that are to be transported by the vessel. The implementation of double bottom and double hull, the materials that are going to be used for tank construction, the types of tanks and many other design parameters are determined depending on the cargo. For the estimation of loading and forces, the conventional analysis is followed as the hull form of chemical tankers is in general no different than these of other cargo vessels.

Regarding the scantling of the structural components and the loads calculations, the rules of the classification society that each vessel is registered shall be followed, as there are no Common Structural Rules issued by IACS for chemical tankers. In some cases, the Common Structural Rules for Double Hull Oil Tankers can be used, however these rules are applicable only to chemical tankers having MARPOL Certificate for carriage of oil or oil products and length more than 150m .[3]

4.3 Load analysis

One of the first steps in the structural design process of a vessel, is the estimation of the loads that she is expected to face during her life cycle. Based on this estimation, the scantling calculations – and later the strength evaluation - will take place. On an ocean going vessel, the loads applied on the construction may derive from the sea water, the vessel-water interaction, the transported cargo, or the vessel herself. Even though, due to the unpredictability of the sea water environment and its behavior, it is hard to accurately analyze and predict each and every load that the vessel will face, several methods and patterns have been developed that give the designer all the necessary information that he or she needs.

The loads that the ship structure must be strong enough to withstand have many sources. There are static components which consist principally of the weight and buoyancy of the ship in calm water. There are dynamic components caused by wave induced motions of the ship, and by slamming in waves, as well as vibratory loads by the propeller and machinery, all of which are of different frequency ranges.

4.3.1 Static loads

The static loads acting on a ship afloat in still water consist of two parts: buoyancy forces and gravity forces, or weights. The buoyancy force is the resultant of the hydrostatic pressure distribution over the immersed external area of the ship. This pressure is a surface force per unit area whose direction is everywhere normal to the hull. However, the buoyant force is the resultant perpendicular to the water surface and directed upward. The weights are body forces distributed throughout the ship and its contents, and the direction of the weight forces is always vertically downward. These component force systems are illustrated schematically in Figure 4.3.[4]

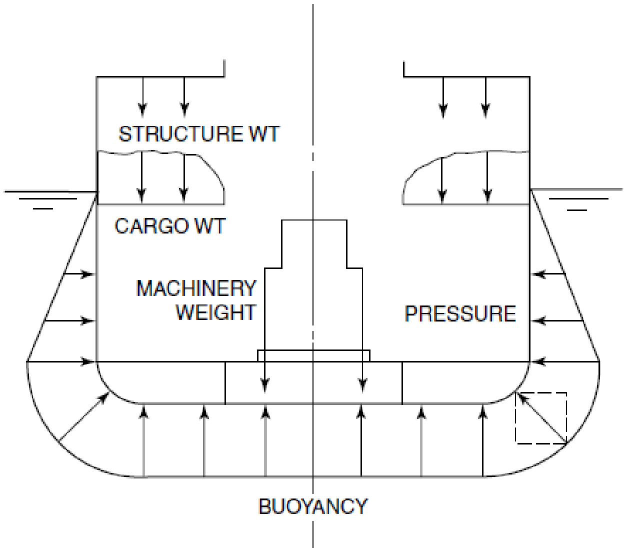


Figure 4.3 – Static load components on hull

Static loads have major impact both on transverse and longitudinal strength of the vessel. When it comes to transverse strength, the transverse strength loads represent the loads which act on transverse members and cause structural distortion of a cross section. This loads may include the hydrostatic pressure applied on the outer shell, the internal pressure caused by the liquid chemical cargo, the weight of the cargo, the weight of machineries, cranes and other cargo equipment, the pressure and weight applied by the ballast water filled in ballast tanks etc. The combination of some of these loads in each transverse section results in a local deformation of the section, which could be of minor or significant extent.

For instance, let's imagine a transverse section of a ship floating in still water as illustrated in Figure 4.4. This section is subjected to: (a) hydrostatic pressure due to surrounding water, (b) internal loading due to self-weight and cargo weight. These loads are not always equal to each other at every point, consequently loads working on transverse members will produce transverse distortion as shown by the broken line.

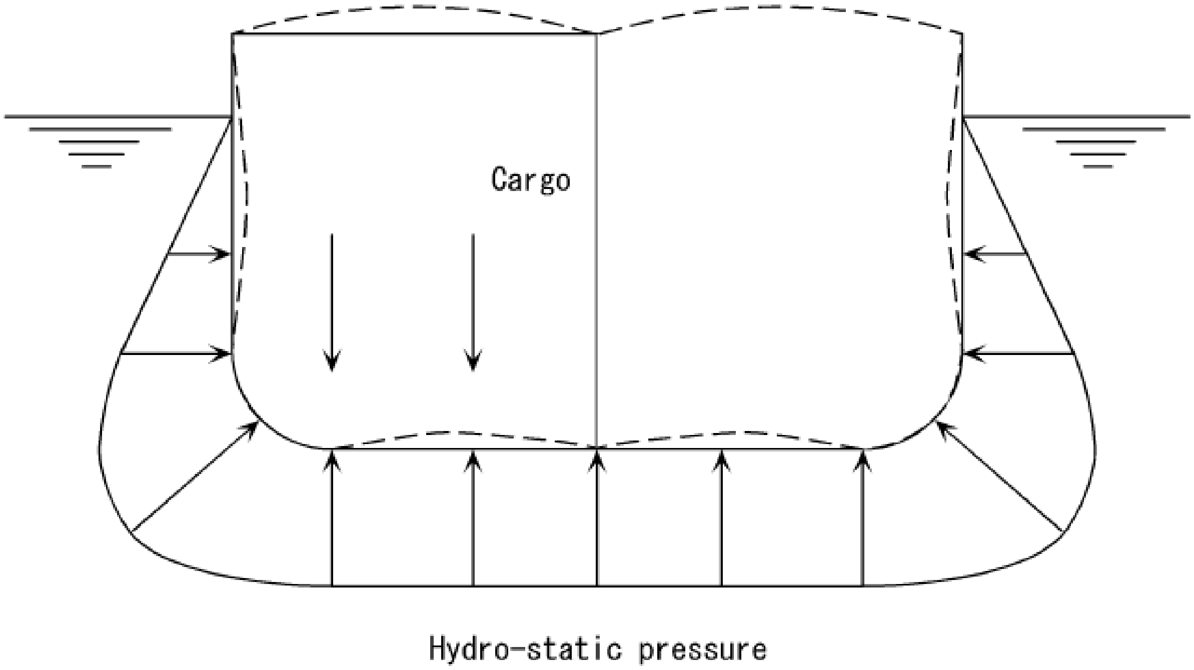


Figure 4.4 – Example of deformation due to transverse strength loads

The static sea pressure is given equal to:

Phys = $\rho_{sw} g (T_{LC} - z)$ kN/m^2

Where:

z: vertical coordinate of load point, in m, and is not to be greater than T_{LC}:

T_{LC}: draught in the loading condition being considered, in m

ρ_{sw}: density of sea water equal to 1.025 t/m^3

g: acceleration due to gravity, 9.81 m/s^2

The static tank pressure is to be taken as:

$P_{in-tk} = \rho g z_{tk}$ kN/m2

Where:

z_{tk}: vertical distance from highest point of tank, excluding small hatchways, to the load point, see Image 4.5

ρ: density of liquid in the tank

g: acceleration due to gravity, 9.81 m/s^2

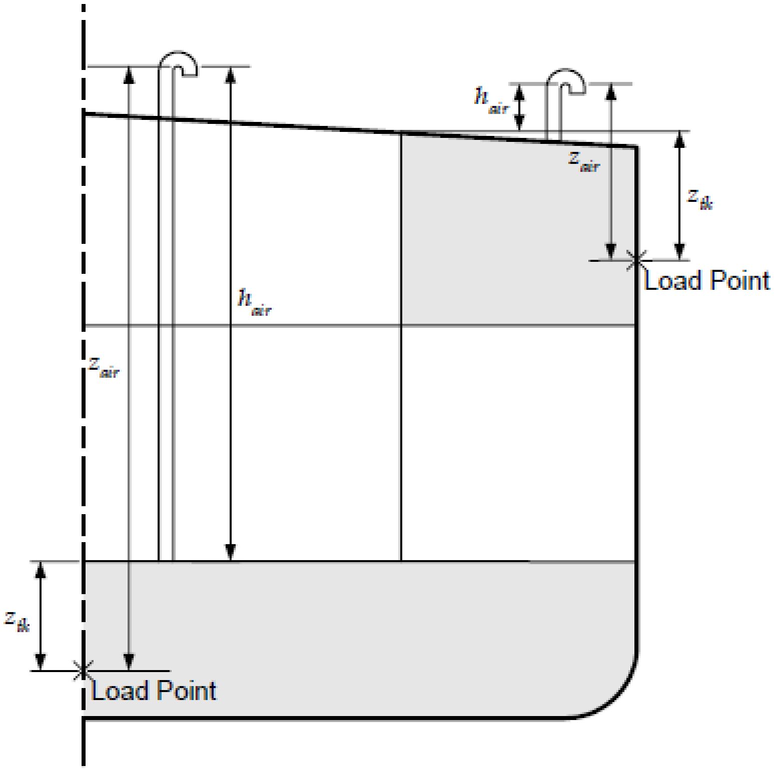


Figure 4.5 – Distances used in calculations for inner tank pressure

In the case of overfilling or filling during flow through ballast water exchange h_{air} should be added to z_{tk}.[5]

Each transverse section of any vessel should be designed in such way that it sustains the forces and stresses developed on it due to the transverse loads. In order of this to happen, the thickness of the plates should be the appropriate and sufficient stiffening should be provided. The transverse loads however are not limited to the static loads, as dynamic loads shall be added to them. Especially in chemical tankers dynamic loads have a major effect, due to potential tank sloshing.

Static loads however, do not have effect only in the transverse strength of the vessel, but also in the longitudinal. To examine these effects, we shall consider the vessel's hull bending and twisting as a beam, under the external longitudinal distribution of vertical, lateral, and twisting loads.

Figure 4.6 illustrates a typical longitudinal distribution of weight and buoyancy for a ship afloat in calm water. A curve of buoyancy force per unit length is plotted in the lower part of this figure, which as noted previously is equal to the weight density, ρg, of water multiplied by the sectional area. The upper curve (2) in the figure shows the longitudinal distribution of the weight force plotted according to a commonly employed convention. In this procedure, the length of the ship is subdivided into a number of equal station spaces, for example, the 20 or so station subdivisions that were used to prepare the line drawing. The hull weights, equipment, and contents lying in the interval between station i and station i + 1 are added together and treated as a single uniformly distributed load over this station interval. This is essentially an accounting process in which every item in the ship—hull structure (plating, frames, weld material), outfit (piping, deck covering, cargo gear), propulsion machinery, cargo, and so on—is recorded and assigned to a station interval. The procedure must be performed with meticulous care and in great detail to ensure accuracy.[4]

When we consider transverse loads and longitudinal loads, the following characteristic is significant from the strength analysis point of view: The distortion due to longitudinal loads does not affect the deformation of the transverse section. For example, the longitudinal bending moment or shear force can never have an influence on the distortion of the cross section. It is therefore necessary to recognize the transverse deformation of the ship structure due to the transverse load, independently from the deformation induced by a longitudinal load. Transverse strength loads are commonly used in cases where we investigate the strength of primary members, such as transverse rings, transverse web frames, etc. On the other hand, longitudinal strength loads affect the overall strength of a ship's hull girder.[6]

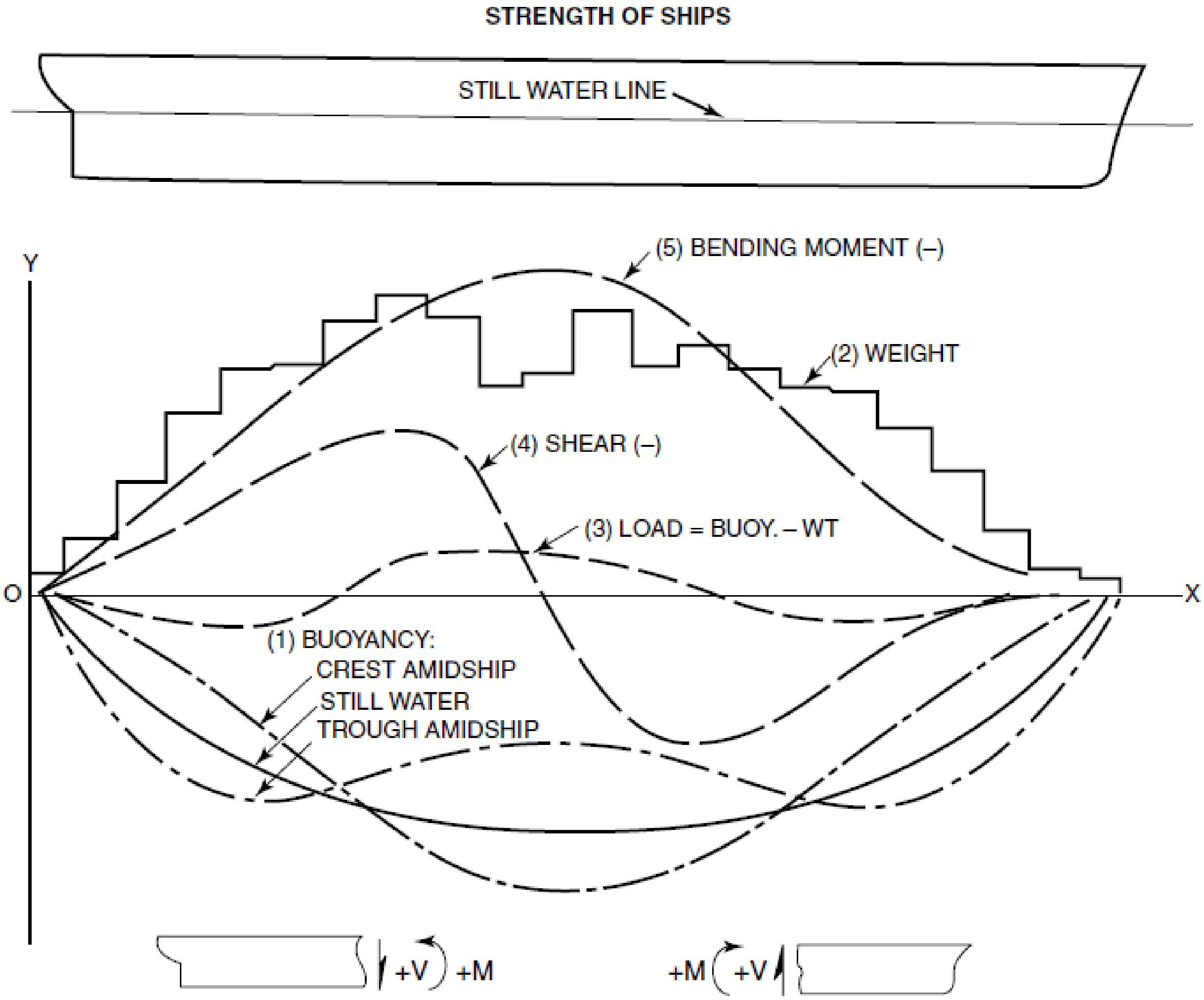


Figure 4.6 – Static loads, shear and bending moment

The design still water bending moments within 0.4 L amidships for vessels with length less than 100m is given as per DNV[7] equal to:

$M_{SO} = 0.0052\ L^3\ B\ (C_B + 0.7)$ (kNm)

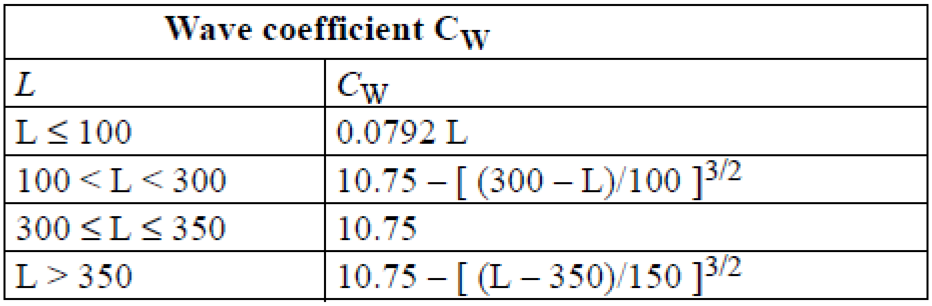
Outside 0.4 L amidships M_{SO} may be gradually decreased to zero at the F.P. and A.P.

For vessels with lengths that exceed 100m, the bending moments are given for sagging and hogging as per DNV[8] as equal to:

$M_{SO} = -\,0.065\ C_{WU}\ L^2\ B\ (C_B + 0.7)$ (kNm) in sagging

$= C_{WU}\ L^2\ B\ (0.1225 - 0.015\ C_B)$ (kNm) in hogging

$C_{WU} = C_W$ for unrestricted service.



Wave coefficient C_W	
L	C_W
$L \leq 100$	$0.0792\ L$
$100 < L < 300$	$10.75 - [\ (300 - L)/100\ ]^{3/2}$
$300 \leq L \leq 350$	10.75
$L > 350$	$10.75 - [\ (L - 350)/150\ ]^{3/2}$

Figure 4.7 – Wave coefficient

For calculation of shear forces, again as per DNV:

$$Q_S = k_{sq}\ Q_{SO} \quad (\text{kN})$$

$$Q_{SO} = 5\frac{M_{SO}}{L} \quad (\text{kN})$$

M_{SO} = design still water bending moments (sagging or hogging)

k_{sq} = 0 at A.P. and F.P.
= 1.0 between 0.15 L and 0.3 L from A.P.
= 0.8 between 0.4 L and 0.6 L from A.P.
= 1.0 between 0.7 L and 0.85 L from A.P.

4.3.2 Dynamic loads

In addition to the static loads caused by the still water buoyancy and the weight of the vessel's construction, machineries and equipment, a sea going vessel is also subjected to a sum of dynamic loads that may derive from the ship's motion in the sea, the action of the ship and the waves, the effects of operating machinery, or other factors. These dynamic loads, vary in time with periods ranging from a few seconds to several minutes. A brief categorization of the dynamic load applied on a vessel can be found below[4]:

- Low frequency dynamic loads.

Low frequency dynamic loads are loads that vary in time with periods ranging from a few seconds to several minutes, and therefore occur at frequencies that are sufficiently low, compared to the frequencies of vibratory response of the hull and its parts, that there is no appreciable resonant amplification of the stresses induced in the structure. The loads are called dynamic because they originate mainly in the action of the waves through which the ship moves, and therefore are always changing with time. Such kind of loads are usually the wave induced loads that are applied to the vessel's hull and cause pressure variations on the hull, bending moments and shearing forces, or even inertial reactions resulting from the acceleration of the mass of the ship and its contents.

- High frequency dynamic loads

High frequency dynamic loads are time-varying loads of sufficiently high frequency that they may induce a vibratory response in the ship structure. Some of the exciting loads may be quite small in magnitude but, as a result of resonant amplification, can give rise to large stresses and deflections. Such load are most commonly cause by unbalanced and not properly edged rotary machineries, hydrodynamic effects of the propeller rotation, or even by short waves whose frequency of encounter overlaps the lower natural frequencies of hull vibration.

- Impact loads

Impact loads are dynamic loads resulting from slamming or wave impact on the forefoot, bow flare, and other parts of the hull structure, including the effects of green water on deck (In heavy storms, the waves and ship motions can become so large that water flows onto the deck of a ship. The term ‘green water’ is used to distinguish between the spray (small amounts of water and foam) flying around and the real solid seawater on the deck). Another impact load that is very common in vessels carrying liquid cargo, such as chemical tankers, is the sloshing load caused by the movement of liquid cargo in half empty tanks.

From all the dynamic loads that may be applied to a vessel, the most important are the low frequency dynamic loads which lead to creation of bending moment and shearing forces, and the impact loads. As both are wave-induced loads, one could say that when it comes to dynamic loads, the wave-induced loads’ effect is much more significant than that of mechanically induced ones (vibrations etc.). High frequency dynamic loads have of course their own importance, especially when it comes to local strength and local design issues. For example, during the design of the areas where rotary machineries are attached to, or of this of the stern tube area where the effect of propeller’s function is significant, special attention should be paid to and a detailed analysis of the high frequency loads should be carried out.

Due to the major significance of wave-induced loads in a ship’s structure, their calculation is one of the important aspects of ship design. However as the behavior of the sea is highly irregular, this is not an easy task. Hence a number of probabilistic and statistical techniques have been developed to tackle this problem. These techniques enable the sea waves be defined in a mathematical form and this may then be used to calculate the wave loads on the ship and ultimately the response of the ship to these loads. When designing a ship though, formulae provided by classification societies are used in order to calculate the wave loads and ship response.[6]

These formulas are the results of approximate methods and may include semi-empirical formulations and quasi-static computations. For these methods, the ship is regarded in a state of static equilibrium on either the crest or trough of a wave whose length is equal to the ship’s length between perpendiculars, L, and whose height is L/20 [9]. The standard height of the wave may change depending on the classification society. In that state the buoyancy can be calculated on the wave's profile, and with the longitudinal distribution of weights known, the bending moments and shear forces can be estimated.

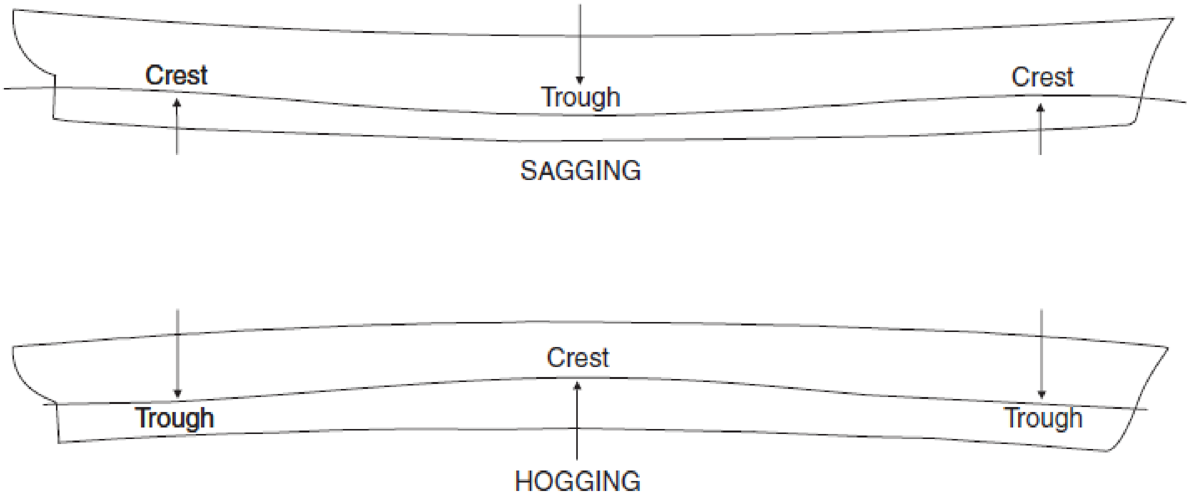


Figure 4.8 – Sagging and Hogging conditions

The DNV proposes the following expressions for the calculation of wave bending moments:

For ships with a length less than 100 m:

$M_{WO} = 0.11\ C_W\ L^2\ B\ (C_B + 0.7)$ (kNm) in sagging
$= 0.19\ C_W\ L^2\ B\ C_B$ (kNm) in hogging.

For ships with a length exceeding 100 m:

$M_{WO} = -\ 0.11\ \alpha\ C_W\ L^2\ B\ (C_B + 0.7)$ (kNm) in sagging
$= 0.19\ \alpha\ C_W\ L^2\ B\ C_B$ (kNm) in hogging
$\alpha = 1.0$ for seagoing conditions
$= 0.5$ for harbor and sheltered water conditions (enclosed fjords, lakes, rivers).

M_W is to be taken equal to M_{WO} between 0.4 L and 0.65 L from A.P. Outside this region M_W may be reduced linearly to zero at F.P. and A.P.

The vertical wave shear forces according to DNV are given as:

Positive shear force, to be used when positive still water shear force:
$Q_{WP} = 0.3\ \beta\ k_{wqp}\ C_W\ L\ B\ (C_B + 0.7)$ (kN)

Negative shear force, to be used when negative still water shear force:
$Q_{WN} = -0.3\ \beta\ k_{wqn}\ C_W\ L\ B\ (C_B + 0.7)$ (kN)

Positive shear force is considered when there is a surplus of buoyancy forward of section and negative shear force when there is a surplus of weight forward of section.

β = 1.0 for seagoing conditions
= 0.5 for harbor and sheltered water conditions (enclosed fjords, lakes, rivers)
k_{wqp} = 0 at A.P. and F.P.
= 1.59 $C_B/(C_B + 0.7)$ between 0.2 L and 0.3 L from A.P.
= 0.7 between 0.4 L and 0.6 L from A.P.
= 1.0 between 0.7 L and 0.85 L from A.P.
k_{wqn} = 0 at A.P. and F.P.
= 0.92 between 0.2 L and 0.3 L from A.P.
= 0.7 between 0.4 L and 0.6 L from A.P.
= 1.73 $C_B/(C_B + 0.7)$ between 0.7 L and 0.85 L from A.P.

The sum of still water loads and wave induced loads in each condition give an estimation for the loads a vessel's hull needs to resist. Based on these estimations the designer shall proceed to the scantling calculation in accordance with the classification society guidelines. However, in most cases these approximate methods overestimate the actual wave induced bending moment for any given wave height, resulting in higher estimations of the applied loads.

In the approximate methods described above, the vessel's length has great effect in the calculation of the bending moment, as for longer vessels the bending moment is increased exponentially. Chemical tankers have significantly smaller length compared to other commercial vessels, and for that reason the design against bending is not a complicated design issue.

Apart from the approximate methods, according to *Strength of ships and ocean structures*[9], other methods can also be used for the estimation of the loads a vessel will need to resist. The ideal scenario would be that full scale measurements and tests would take place in actual size models. This could lead to very accurate results regarding the loads on a ship, however this scenario is not feasible due to the expenses it would entail. Full scale measurements have been conducted in actual vessels by the classification societies and other research institutions in the past, and the results from these measurements constitute a statistical data pool from which useful information can be extracted and used during the design of a vessel.

Another method is the laboratory measurements of loads in scaled models. These models are constructed according to the lines plan of the actual vessel and are equipped with instruments that measure vertical or horizontal shear and bending moment, or torsional moment, amidships and at other sections. The results are then edited accordingly and lead to estimation for the loads in the full scale construction. Finally, another method is the direct computation of the wave-induced fluid load, where the appropriate hydrodynamic theories used to calculate ship motions in waves are applied to compute the pressure forces caused by the waves and ship motion in response to these waves. Due to the huge volume of calculations needed, the use of computer and computational methods is necessary. However, this theoretical way of load estimation, is not always accurate and in line with the actual loads the vessel will face.

4.3.3 Slamming

During a voyage in rough seas, the vessel's bow and stern may occasionally emerge from a wave and re-enter the wave with a heavy impact or slam as the hull structure comes in contact with the water. A vessel with such excessive motions is subject to very rapidly developed hydrodynamic loads. The vessel experiences impulse loads with high-pressure peaks during the impact between the vessel's hull and water. The most affected parts of the hull are the bow flare, the forward part of the bottom and the stern.

As discussed by Church[10], the damage induced by slamming can be subdivided into two areas of concern: the damage brought about by high-intensity local forces, and the damage due to gross hull structural response. In the first case, the damage can result to local structural defects such as buckling of plates due to plastic deformation. In the second case the slamming effect contributes to the overall response analysis of the ship as a beam and should be taken into account in relative calculations.

The slamming effect is very important and may be proved disastrous for the hull structure if not sufficient measures are taken during the design procedure. The design against slamming may include increased plate thickness or advanced web framing to the areas that will be affected. The extend of the hull structure to be evaluated is given by the ABS[11], as a minimum of at least 8 frame stations for bottom slamming and at least 10 frame stations for bow flare and stern slamming, and also as shown in Figure 4.9.

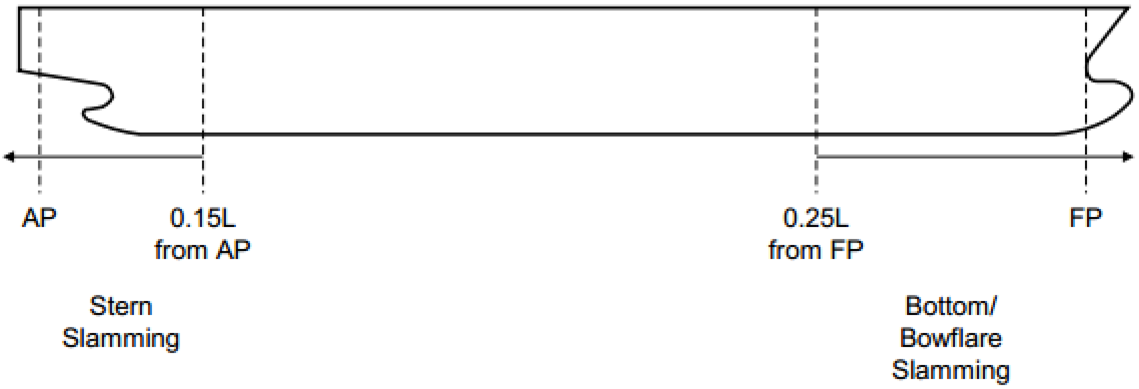


Figure 4.9 – Extent of hull structure for slamming load prediction

4.3.4 Sloshing

Sloshing is a phenomenon where the fluid movement in the tank gets into resonance with the ship motion and creates an impact force between the moving free surface of the fluid and the tank structure. Sloshing is caused by the movement of the fluid's free surface, therefore, if the tank is fully filled with fluid, sloshing will never happen since the free movement of the liquid's surface is restricted. When the level of the liquid reaches to a certain portion of the tank, the liquid resonates with the movement of the tank and then sloshing occurs.[12]

Chemical tankers carry liquid cargoes, and as a matter of fact sloshing is a phenomenon that needs to be taken into account during their structural design. The effects of sloshing in a chemical tanker can be various and disastrous. First of all, the slamming effect of the liquid inside the tank may lead to structural damage to the tank structure and fittings. Inside a chemical tanker's cargo tank there are numerous cargo equipment such as cargo pumps, cargo piping and washing appliances, which are sensitive and could easily be damaged. In addition, even a slight movement of the surface of the liquid cargo could create an electrostatic charge, which could potentially lead to ignition. This could also happen in tanks which are partially filled with a mixture of oil and water, such as dirty ballast, tank washings or slops. Finally, the effect of free surface reduces the ship's GM and may even lead to a loss of stability.[13]

Even small angles of rolling or pitching could generate sloshing. The sloshing phenomenon is difficult to predict as it depends on the geometry of the tank and the level of the liquid. For that reason slack tanks must be avoided wherever possible and it is imperative that no cargo tank, unless so designed and permitted by Classification, is allowed to remain in a slack condition whilst the vessel is at sea.

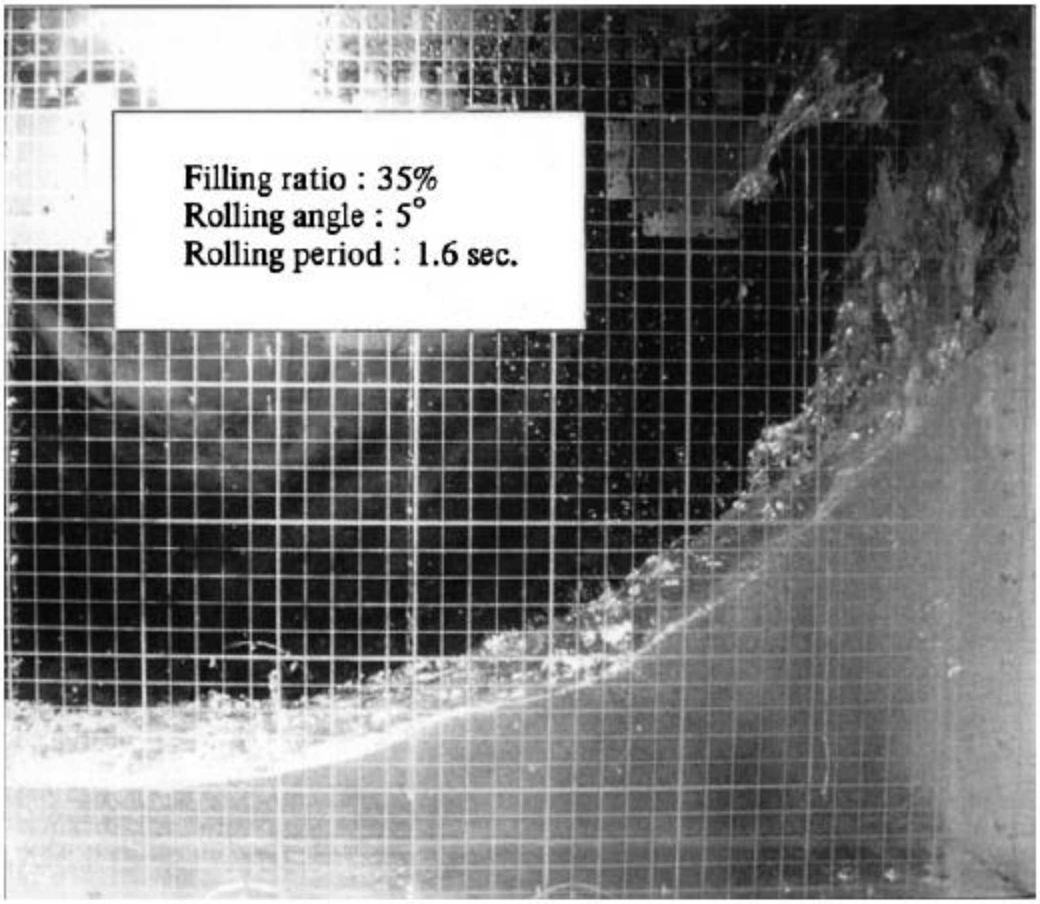


Figure 4.10 – Sloshing in a rectangular tank

4.4 Strength evaluation

The strength evaluation is one of the most important parts in the design procedure of a vessel, as it determines whether the construction is capable of sustaining the loads that it is expected to face, or whether it will collapse under these loads, with the devastating consequences that such an incident will have. In order to perform a valid and accurate strength assessment of the construction, the designer must be able to analyze the behavior of the structural components under loads, the actual stresses and tensions that the loads will occur, the way that a component may collapse and many other relevant parameters. The basic steps of the evaluation of structural strength procedure of a vessel are presented in *Design of ship hull structures*[14], and are analyzed in this section:

1. Determine an initial system of structural members
2. Presume a magnitude, direction, and probability of load
3. Assume a failure mode of structure due to the load
4. Select an appropriate analysis method
5. Choice of an acceptable strength criteria for a particular failure mode
6. Analysis of structural response
7. Evaluation of the response for given criteria

4.4.1 Determination of structural members

An initial determination of the structural members of the vessel is necessary in order to proceed with the structural analysis. Most of the conventional commercial vessels nowadays, consist, more or less, of the same groups of structural members and components, which are in line with the classification societies' rules and the modern structural design principles. Differences may exist of course, between different cargo type vessels, or even between the same cargo type vessels due to special requirements.

The strength deck, bottom and side shell of a ship act as a box girder in resisting bending and other loads imposed on the structure. The weather deck, bottom and side shell also form a tight envelope to withstand the sea locally, and to provide the buoyancy which keeps the ship afloat. The remaining structure contributes either directly to these functions, or indirectly by maintaining the main members in position so that they can act efficiently. Additional structural members suck as the inner bottom, the inner hull, the transverse and longitudinal bulkheads, etc. contribute also significantly in the overall strength of the construction.

All these structural elements of a ship are basically large sheets of plate whose thickness are very small compared with their other dimensions, and which, in general, carry loads both in and normal to their plane. These sheets of plate may be flat or curved, but in either case they must be stiffened in order to perform their required function efficiently. Corrugated bulkheads, stiffened by the corrugations, may also be used.

The various stiffening members have several functions: the beams stiffen the deck plating, the girders support the beams, transferring the load to the pillars or bulkheads. For transverse framing, the transverse beams stiffen the side shell and support the ends of transverse deck beams and are, in turn, supported by the decks and stringers. For longitudinal framing, the frames supporting the plating run fore and aft and are in turn supported by transverse members. Stiffening members are not independent from the plates they are attached to, and they contribute both in enhancing their strength, and transferring and distributing the load to other structural members[15].

In the final analysis, the whole construction of a vessel is a combination of plates, flat or curved, and beams of different dimensions, shape, and characteristics. So, after all, the strength evaluation of a vessel concludes to whether these plates and beams, and the combined arrangement of them, are able sustain the loads that will be applied on them.

4.4.2 *Effect of loads*

The loads that will be applied on a vessel, and the methods to calculate them have been analyzed in previous section of this chapter. Of same importance with estimating the loads, is for the designer to be able to analyze, how these loads will affect the structural components. The bending moments and shearing forces contribute to the formation of stresses in the components of the hull. Eyres[16] explains the relation between bending moments and bending stresses:

From classic bending theory the bending stress (σ) at any point in a beam is given by:

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

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

When the beam bends it is seen that the extreme fibers are, say in the case of hogging, in tension at the top and in compression at the bottom. Somewhere between the two there is a position where the fibers are neither in tension nor compression. This position is called the neutral axis, and at the farthest fibers from the neutral axis the greatest stress occurs for plane bending. In the theory considering the hull of a ship as a beam, the neutral axis will be generally nearer to the bottom, since the bottom shell will be heavier than the deck, having to resist water pressure as well as the bending stresses.

Occasionally reference is made to the sectional modulus (Z) of a beam. This is simply the ratio between the second moment of area and the distance of the point considered from the neutral axis, i.e. $I/y = Z$, so that the bending stress (σ) is then given by $\sigma = M/Z$.

When calculating the second moment of an area of the cross-section all longitudinal material is of greatest importance and the further the material from the neutral axis the greater will be its second moment of area about the neutral axis. Bending stresses are greater over the middle portion of the length and for that reason the design and the scantling of the midship section is one of the most important steps of the structural design. It is common, however, that the maximum bending moment is considered not only at amidships but also over forty percent of the vessels length around amidships, giving maximum scantlings to all that section.

According to Taggart[17], unlike bending stresses, the maximum value of shearing force occurs at about one quarter of the vessel's length from either end. The shearing forces are received only from vertical, or nearly vertical members, therefore the side shell and longitudinal bulkheads receive all the shear.

For vessel without longitudinal bulkheads the shear stress τ is calculated as per below:

$$\tau = Q\alpha c / tI$$

Where
Q = total shearing force
αc = moment of area above shear plane under consideration taken about neutral axis
t = thickness of material at the shear plane
I = moment of inertia of the entire section

4.4.3 Types of failure

Due to the various kinds of loads acting on a hull structure during a voyage, a damage of the structure may be caused if the load reaches a certain critical level. There may be several failure modes, however yielding, buckling, and fatigue are the most significant for the designer to take into account.

4.4.3.1. Buckling

As explained by Caridis[18], in case an axial load is applied to a structural component of a construction, like a beam or a plate, in order of deformation to take place one of the following conditions should be met:

1. The point that the force is applied to, not to coincide with the center of gravity axis of the section.
2. The component to have initial imperfections.

In real life constructions both of the above condition are usually met. As a matter of fact, when axial forces are applied to a structural member of a construction, some bending will occur to it. When the force will be removed, the structural member will return to its initial form. In case though the axial force is increased above a critical level, there will be permanent deflection to it. This phenomenon is named buckling, and the load at which it will be initiated depends on the material, the geometry and other characteristics of the construction.

Gaspar et al[19] point out that the buckling strength requirements considered are used in the initial stage of the hull girder scantlings' design to control the buckling capacity of longitudinal stiffened panels subjected to the compressive loads induced by the hull girder vertical bending. The following buckling collapse failure modes are explicitly considered in the design formulation: uniaxial buckling of the plating between stiffeners, column buckling of stiffeners with attached plating and lateral-torsional buckling or tripping of stiffeners.

For the initial stage of the hull girder scantlings calculation, the design rules formulation for buckling strength assessment of stiffened panels under uniaxial compression in the longitudinal direction is based on the compressive stress induced by the hull girder vertical bending, with all the other in-plane load components, lateral pressure and shear lag effects not explicitly accounted for. This compressive stress component is given by the following equation:

$$\sigma_x = \left| \frac{(z - z_{na})(M_{sw} + M_{wv})}{I_v} \right| 10^{-3}$$

Where z is the vertical distance to the baseline, z_{na} is the vertical position of the horizontal neutral axis of the cross section considered and Iv is the second moment of area of the cross section relative to the horizontal neutral axis. The hull girder vertical bending moments are Msw for the still water component and Mwv for the wave component.

The structural design shall be performed in such a way so that the compressive stress will not be greater than the critical buckling stress for plate panels and columns or stiffeners. This will happen by increasing the Iv factor of the above equation either by advanced plate thickness or advanced stiffening. The critical buckling stress for plate panels under uniaxial compression, columns and stiffeners are determined by the classification societies.

4.4.3.2. Yielding

In case a tensile load is gradually applied to a structure, like a beam or a plate, then some elongation might be induced. This elongation will be proportional to the load increment as long as the load is relatively small. When the load ceases to exist, the structure returns to its initial form. However, as the load increases beyond a certain point, that elongation will increase rapidly, and will cause plastic deformation to the structure. That failure mode is called yielding, and is highly undesirable in metal constructions as it may affect significantly its strength and lead to collapse.

The tensile load at which the yielding will take place is called yielding point and it depends primary on the material and secondary on parameters such as the temperature, the increase rate of the load and others. The designer needs to take care so that the strength of the structure will not exceed the yield point.

For edge stress or stresses in the extreme fiber of plate elements and axial stresses in rod elements, the yielding criteria of the structural members are to compare the normal stresses to the yielding stress of the material. For the case of bi-axial stresses in plate elements, a specific combination of stresses, rather than the maximum normal stresses, constitutes the limiting condition. In this regard, the yielding criteria is that the Hencky-von Mises stress, σ, is not to exceed 95 percent of the yield stress of the material. That is[20]:

$$\sigma = \sqrt{\sigma_x^2 + \sigma_y^2 - \sigma_x \sigma_y + 3\tau_{xy}^2} \leq 0.95 f_y$$

Where σ_X and σ_Y are respectively the normal stresses in x- and y-directions, τ_{XY} is the shear stress, and f_y is the specified minimum yield point.

4.4.3.3. Fatigue

Fatigue is the cumulative material damage caused by cyclic loading. The structural components of a vessel must withstand numerous stresses reversals during their lifetime, occurred by the repetitive wave induced loads, the wind and other environmental effects and the vibrations of the machinery. These stresses are not large enough to cause structural failure in one cycle, but failure could occur when the accumulated damage experienced by the structure reaches a critical level.

The fatigue mechanism can be analyzed in three stages, as given by Yong Bai[21]. The first stage is the crack initiation, which is tied to the microscopic material behavior. Fatigue failure in a marine structure is most possible to be initiated at welding points. This is because initial weld defects always exist either internally or on the weld surface. The cyclic loading may trigger these cracks, especially the ones on the surface, to grow.

The second stage is the crack propagation, when the crack has now been created and started to grow. This stage, which covers almost 90% of the fatigue life of a structural member, is easier to be understood compared to the crack initiation stage, as it is no longer tied to microscopic material behavior, but can actually be modelled via several theories such as fracture mechanics. The crack propagation is governed by several parameters, such as the welding geometry and the initial crack size. The major parameter governing crack propagation though, is the stress range to which the structural detail is subject to.

The final stage is the fracture failure of the structural details, which will occur eventually when the crack size propagates a critical size. The parameters that affect the final fracture are the stress level, the crack size and the material toughness.

Fatigue failure can be classified into two types: low-cycle fatigue failure, and high-cycle fatigue failure. Fatigue failure that takes place for less than 10^4 cycles is called low-cycle, when for more than 10^4 cycles is called high-cycle.

Among all methods applicable for fatigue design, the S-N approach is the most commonly used. S-N curves indicate the relationship between the stress range and the number of cycles to failure.

For fatigue analysis based on the nominal stress approach, welded joints are divided into several classes. Each class has a designated S-N curve. The classification of S-N curves depends on the geometry of the detail, the direction of the fluctuating stress relative to the detail, and the method of fabrication and inspection of the detail, as given by IACS[22]. Each construction detail, at which fatigue cracks may potentially develop, should be placed in its relevant joint class in accordance with criteria given in the codes. Fatigue cracks may develop in several locations, e.g. at the weld toe in each of the parts joined, at the weld ends, and in the weld itself. Each location should be classified separately.

The basic design S-N curve is given as:

$$\log N = \log K - m \log S$$

Where:

S = Stress range

N= Predicted number of cycles to failure for stress range S

m= Negative inverse slope of S-N curve (typically m=3)

log K = Intercept of log N-axis by S-N curve = log a - 2std

where, a and std are constant relating to mean S-N curve and standard deviation of log N, respectively.

Other methods of S-N curves creation are also applicable, however this is the most commonly used.

The assessment of the fatigue strength of a ship structure is also presented by IACS. Assessment of the fatigue adequacy of the structure is based on the application of the Palmgren-Miner cumulative damage rule given by:

$$D = \sum_{i=1}^{i=n_k} \frac{n_i}{N_i}$$

Where :

ni = number of cycles of stress range Si,

Ni = number of cycles to failure at stress range Si.

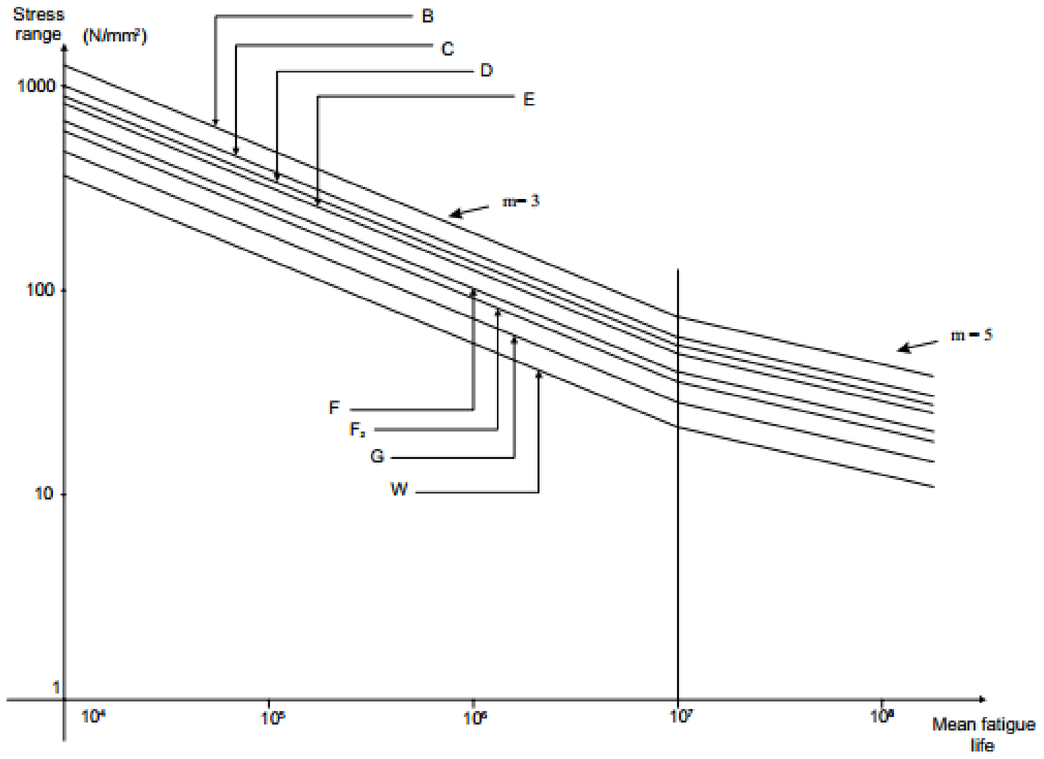


Figure 4.11 – S-N curve (logarithmic scales)

From this definition, the structure is generally considered as failed when the cumulative damage ratio D is equal to unity or greater. In order for the cumulative damage ratio to be calculated, the stress ranges need to be calculated, and the appropriate S-N curve to be selected.

For the calculation of stress ranges, three types of stresses should be taken into account. First of all, the nominal stress, which is the stress calculated by beam theory based on the applied loads and the sectional properties of the component. In addition to the nominal stress, the hot spot stress and the notch stress should also be taken into account. The hot spot stress is the local stress at a critical point where cracks may be initiated. The notch stress is a peak stress at the root of a weld or notch taking into account stress concentrations due to the effects of structural geometry as well as the presence of welds.

After the fatigue damage ratio is calculated, the expected fatigue life of the structure can be calculated as:

$$Fatigue\ life = \frac{Design\ life}{D}$$

4.4.4 Selection of analysis method and strength criteria

During the strength evaluation, the selection of the appropriate analysis method in each case is very important, as if a non-appropriate analysis method is used, this could lead to mistaken results and conclusions regarding the strength of the construction.

Since a hull structure is mainly composed of several types of stiffened plates, the load on the hull is at first transmitted from panels to stiffeners, then from stiffeners to primary member such as transverse rings or longitudinal girders, and finally from primary members to shell plating. The strength analysis can be held in several ways. Structural analysis of the individual structural members can take place, investigating the strength of a panel by thin shell theory and this of the stiffeners and primary members by simple beam theory. However in case strength concentrations or fatigue strength need to be studied, most sophisticated analysis such as finite element analysis must be adopted, as the conventional strength analysis will not highlight the crucial points.

It is up to the designer, to evaluate each structural issue and decide what kind of analysis needs to be performed. The same needs to be done when it comes to strength criteria. Some strength criteria are proposed by the classification societies and should be followed during the strength evaluation procedure. However these criteria are not always unchangeable. The strength criteria are usually related to the prediction method of load. For that reason different criteria from these proposed in structural rules may be used.[14]

4.4.5 Finite Element Method

The conventional, analytical method of solving stress and deformation problems by using theories of beams, columns and plates is limited to simple structures and loads. When it comes to more complex constructions and distribution of loads, this conventional method becomes very complicated and cannot lead to safe results. For that reason, Finite Element Methods (FEM) are used for such cases.

The basic concept and characteristics of FEM are analyzed by Okumoto et al[23]. Finite element method divides the structure into small elements, then assumes each element to be a mathematical model, and finally assembles the elements and solves the overall. It can solve actual structural problems by using some models, although their shapes and loads are complex and it is used for a wide variety of steel, nonferrous materials and complex materials. Also it can perform very complex and long calculations as it is relies on computer technology. However, it is not as accurate as the analytical methods, because even the most complex structures are assumed as combinations of simple elements and loads.

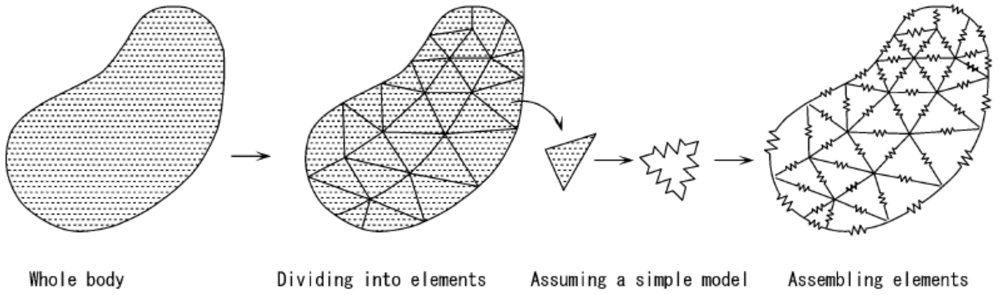


Figure 4.12 – Basic concept of FEM

To carry out the finite element analysis, the geometric model which is generated from computer-aided design (CAD) software, must be properly converted to the geometric model for the analysis. The resulting shape is often different due to simplifications of the detailed configuration. After the generation of this geometric model, the finite element model needs to be properly generated. It is not good enough just to divide the design domain into smaller parts. The mechanical behavior should also be considered in generating the finite element mesh. For example, the elements around the area of stress concentration need to be smaller in order to give good accuracy[24].

The finite element method might be a very useful tool, however it does not perform the structural analysis by itself. The designer is the one who will input all the required data, like loads and materials, and who will perform the modelization of the structure as required, giving emphasis to the areas that are more probable to fail. For that reason good engineering background is required to use the method effectively.

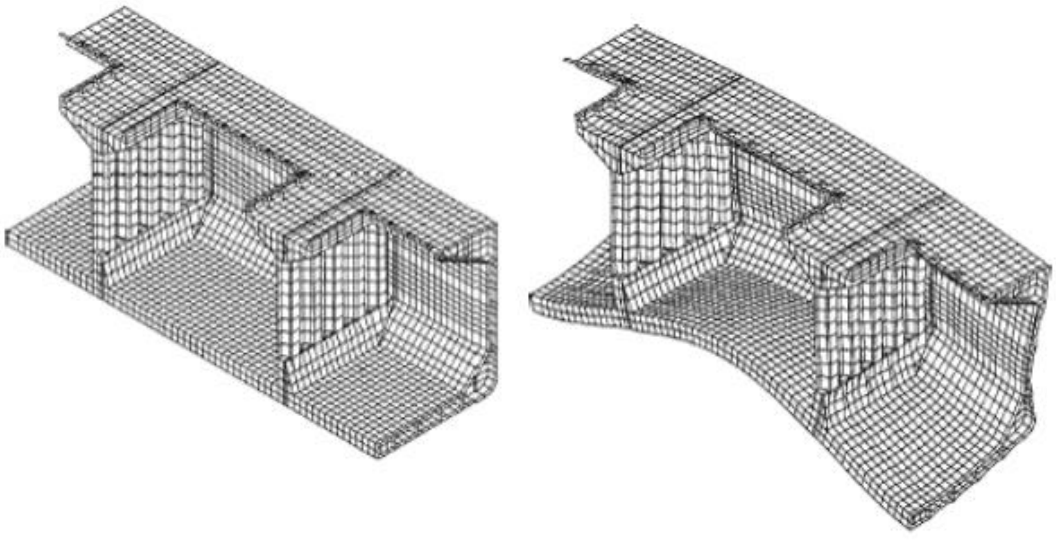


Figure 4.13 – Deformation of ship bottom

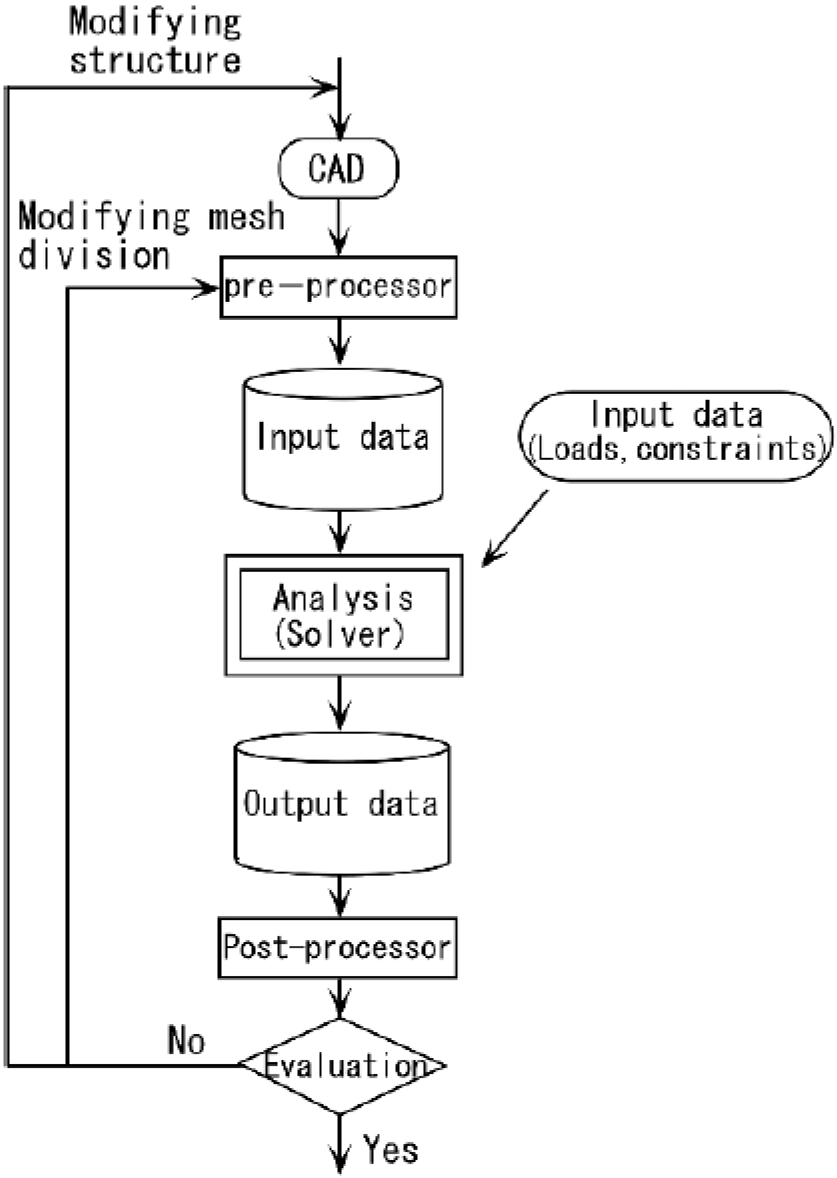


Figure 4.14 – Procedure of FEM

According to IACS[25], the finite element analysis for double hull tanker consists of two parts:

a) Cargo tank analysis to assess the strength of longitudinal hull girder structural members, primary supporting structural members and transverse bulkheads.
b) Fine mesh analysis to assess detailed stress levels in local structural details.

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Chapter 5

Cargo Tank Materials

5.1 Introduction

The scope of this chapter is to explain which are the most common materials used for the construction of cargo tanks in chemical tankers, why they are used, and which are the selection criteria.

The most important parameter when it comes to the selection of cargo tank materials, is these materials to be able to withstand the corrosive effect of the chemical cargoes. For that reason, the mechanism and the most common types of corrosion that take place in chemical tankers are explained.

The most commonly used materials for the construction of cargo tanks nowadays, are the stainless steel and the mild steel. Mild steel, when it is used, should be sufficiently coated in order to withstand the corrosive effect of the cargo. Firstly, the two main types of stainless steel are presented: austenitic stainless steel and duplex stainless steel. Their microstructure and their basic characteristics are analyzed and compared. Additionally, the enhanced resistance of stainless steels against corrosion is explained.

When it comes to mild steel, the selection of the proper coating is of vital importance. Each type of coating has its own characteristics, advantages and disadvantages. The most commonly used coatings are presented, and several information are given regarding their properties.

Finally, a reference is been made to the selection procedure and analysis of the correct material for cargo tank construction.

5.2 Materials of tank construction

Due to the reactive behavior of chemical cargoes, the selection of the appropriate material for the construction of cargo tanks is of great importance, not only regarding the strength of the vessel, but also regarding reactivity and corrosion issues. The selection needs to be made, not only for structural material used for tank construction, but also for cargo piping, pumps, valves, vents and their jointing.

Class NK[1] proposes that the following shall be taken into account during the selection of the materials:

1. Corrosive effect of cargo.
2. Possibility of hazardous reactions between the cargo and material of construction.
3. Suitability of linings.

In addition, as per IBC code[2], structural materials shall be suitable at the temperature and pressure for the cargo to be carried in accordance with recognized standards. Each cargo requires to be carried under some specific temperature and pressure values. In case the tank material is not able to withstand the combination of temperature, pressure, and cargo corrosiveness effects, then this chemical cargo cannot be transferred into the specific tank.

It is clear that not all construction materials are suitable to sustain all chemical cargoes. As a matter of fact, prior to the selection of cargo tank material, the chemical cargo – or at least the type of chemical - that is intended to be carried should be specified.

Steel is the most common material for cargo tank construction. Farrell[3] states that cargoes which are highly corrosive to mild steel will generally require the use of special materials for tank construction and cargo systems, although increased mild steel scantlings may be acceptable in association with means of controlling tank temperature and environment for substances or concentrations having marginal effects. Due to its non-effectiveness in corrosion resistance, mild steel is usually used for no reactive cargoes, and after a specialized coating has been applied on its surface to increase its resistance.

However, as stated by Werner[4], the most commonly used cargo tank material in modern chemical tankers is the stainless steel. The corrosion-resistance properties of stainless steel allow chemical tankers to safely transport hundreds of highly corrosive cargoes that are unsuitable for mild steel and for many specialized tanks coatings. Stainless steel's properties also allow for easy tank cleaning and protect the quality of the cargo being transported while maintaining the vessel's structural integrity. For these reasons stainless steel has become the material of choice for chemical tanker cargo tanks and cargo systems.

Stainless steel is preferred, even though its cost is significantly higher than the cost of mild still. In addition, stainless steel requires a higher level of skill in its fabrication, fact that further increases its overall price. However, when compared to the cost of applying and maintaining a high quality cargo tank-coating system, the initial cost of stainless steel cannot be considered excessive in light of the benefits it provides.

5.3 Corrosion

5.3.1 Mechanism of corrosion

Common structural metals are obtained from their ores or naturally-occurring compounds by the expenditure of large amounts of energy. These metals can therefore be regarded as being in a metastable state and will tend to lose their energy by reverting to compounds more or less similar to their original states. Since most metallic compounds, and especially corrosion products, have little mechanical strength a severely corroded piece of metal is quite useless for its original purpose.

Virtually all corrosion reactions are electrochemical in nature, at anodic sites on the surface the iron goes into solution as ferrous ions, this constituting the anodic reaction. As iron atoms undergo oxidation to ions they release electrons whose negative charge would quickly build up in the metal and prevent further anodic reaction, or corrosion. Thus this dissolution will only continue if the electrons released can pass to a site on the metal surface where a cathodic reaction is possible. At a cathodic site the electrons react with some reducible component of the electrolyte and are themselves removed from the metal. The rates of the anodic and cathodic reactions must be equivalent according to Faraday's Laws, being determined by the total flow of electrons from anodes to cathodes which is called the "corrosion current", I_{cor}. Since the corrosion current must also flow through the electrolyte by ionic conduction the conductivity of the electrolyte will influence the way in which corrosion cells operate. The corroding piece of metal is described as a "mixed electrode" since simultaneous anodic and cathodic reactions are proceeding on its surface. The mixed electrode is a complete electrochemical cell on one metal surface.[5]

The most common and important electrochemical reactions in the corrosion of iron are thus

Anodic reaction (corrosion)

$$Fe \rightarrow Fe^{2+} + 2e$$

Cathodic reactions (simplified)

$$2H^{+} + 2e \rightarrow H_2$$

or

$$H_2O + \frac{1}{2}O_2 + 2e \rightarrow 2OH^-$$

In simple terms, the corrosion procedure can be expressed by the following chemical reaction[6]:

$$Aa+bB=cC+dD$$

where A is the metal and B the non –metal reactant (reactants) and C, D are the products of the reaction. In other words it is an electrochemical reaction of a metal with its environment.

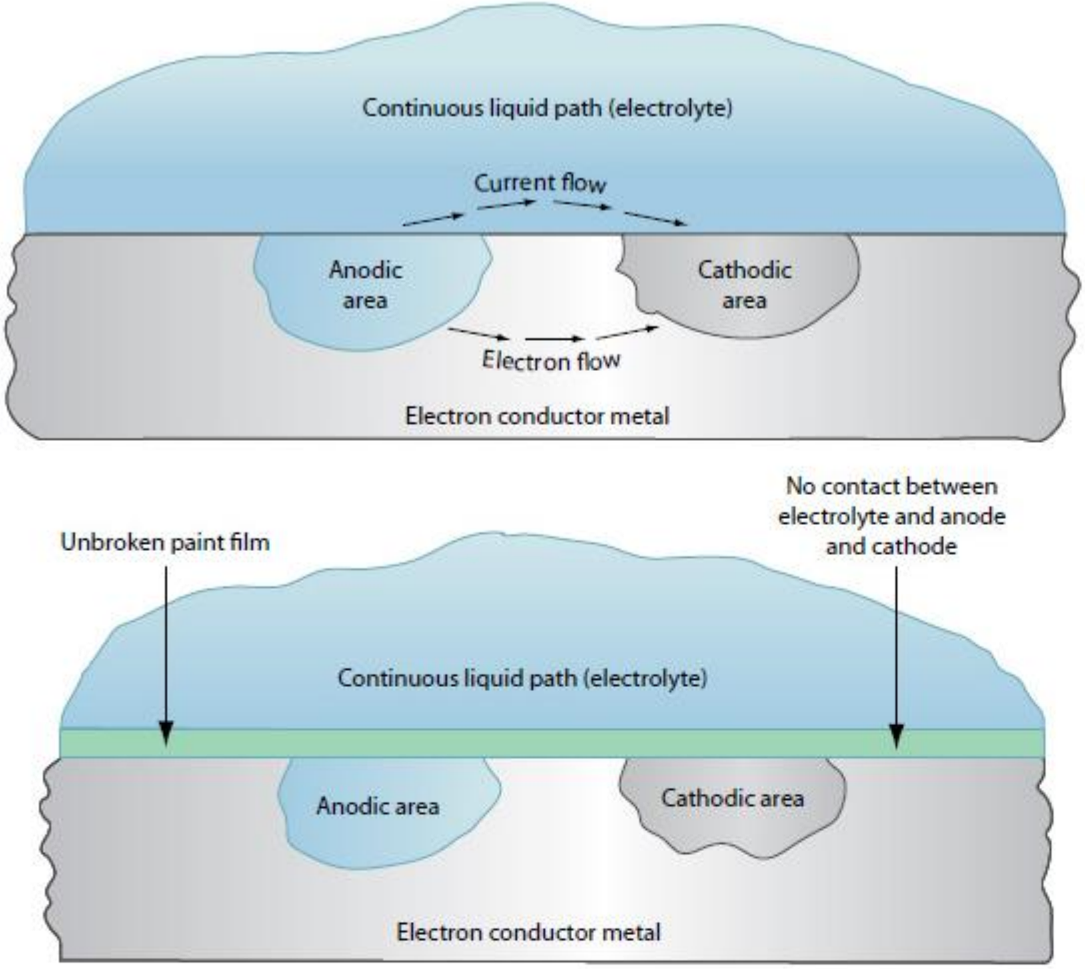


Figure 5.1 – Corrosion mechanisms

5.3.2 Types of corrosion

Corrosion in metals may take place in several types and forms, depending on the conditions, the material etc. The six types of corrosion that are most commonly developed in cargo tanks of chemical tankers are explained by Kelly[7] and Taggart[8] as per below:

- **General corrosion:** This is the most common type of corrosion in metals, which can lead to great loss of the material. It is characterized by relatively uniform attack of the entire area exposed to the corrosive environment, and it is most common for stainless steel when exposed to mineral acid, non-oxidizing acidic solutions, and hot caustic solutions. In general corrosion, the passive film slowly dissolves but continually re-forms. Since the attack is linear with time, the life of equipment subject to general corrosion is reasonably predictable. Uniform corrosion rates may be stated as an average metal thickness loss with time, in mils per year or millimeters per year.

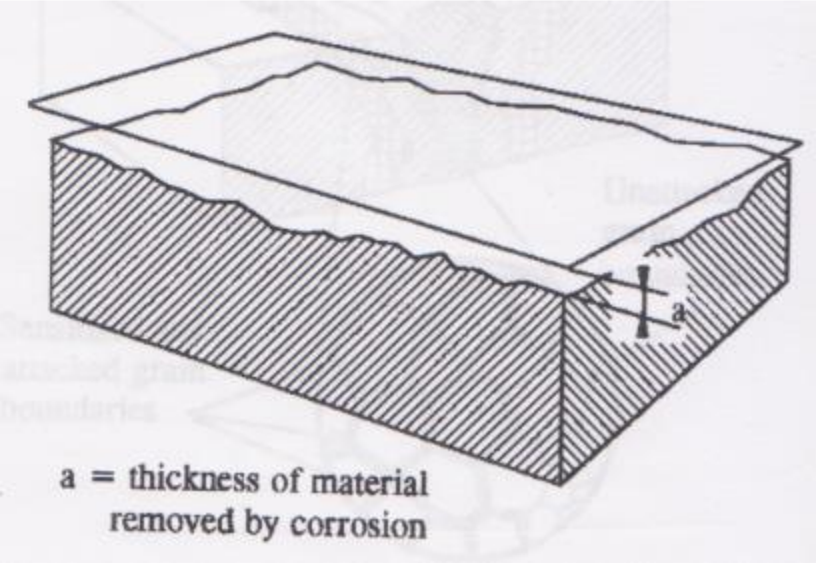


Figure 5.2 – General corrosion

- **Pitting corrosion:** Pitting corrosion results from a local breakdown of the passive film and the inability of the passive layer to reform. It is an extremely localized form of corrosion that results in holes in the metal. Although total metal loss may be small, the equipment may be rendered useless because of perforation. Pitting usually requires a long initiation period before attack is visible, however once a pit has begun, the attack continues at an accelerating rate. Pits tend to grow in a manner that undermines or undercuts the surface. Typically a very small hole is seen on the surface. Poking at this hole with a sharp instrument may reveal a rather cavernous hole under what had looked like solid metal. In effect, a pit may be considered a self-formed crevice. Pitting attack increases with temperature.

Chloride solutions are the most common cause of pitting attack on stainless steels and nickel alloys. The pitted areas, when noticed, shall be repaired in time, as they can lead to preformation of the steel, or the weak spots may become focal points for corrosion fatigue, or stress corrosion failure.

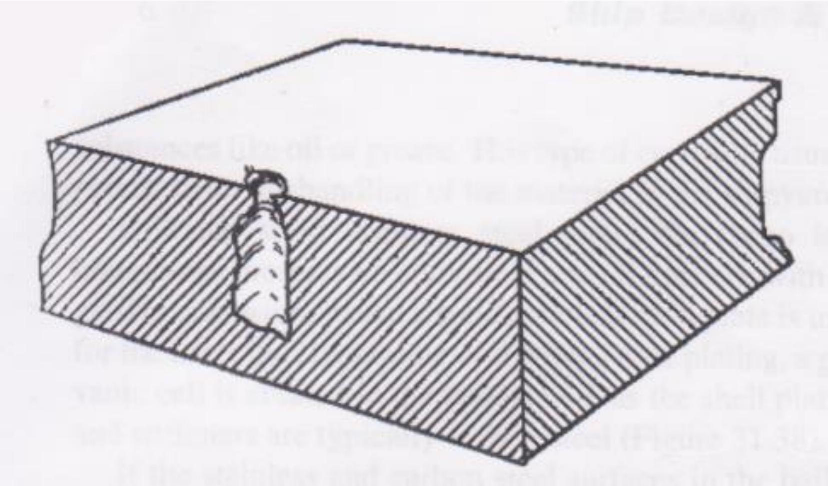


Figure 5.3 – Pitting corrosion

- **Stress corrosion:** For just about every alloy, there is some chemical environment that, combined with stress and high temperature will cause cracking. The source of stress is usually residual forming and welding stresses, which may reach the yield point of the material. Operating stress is rarely the issue. Chlorides are the major cause of stress-corrosion cracking in stainless steels, combined with temperatures exceeding 60°C.

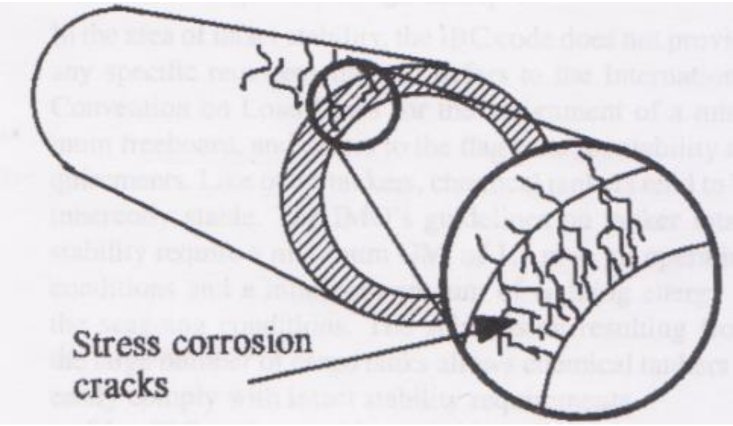


Figure 5.4 – Stress corrosion

- **Crevice corrosion:** This type of corrosion usually occurs in small volumes of stagnant solution under gasket surfaces, lap joints, marine fouling, and solid deposits and in the crevices under bolt heads and the mating surfaces of male and female threads. A breakdown in the passive layer within the crevices leaves the surfaces within the crevice susceptible to rapid corrosion that is often undetectable outside of the crevice. Crevice corrosion typically occurs in the presence of solutions containing halogen ions such as chlorides. Susceptibility to crevice corrosion increases rapidly with temperature.

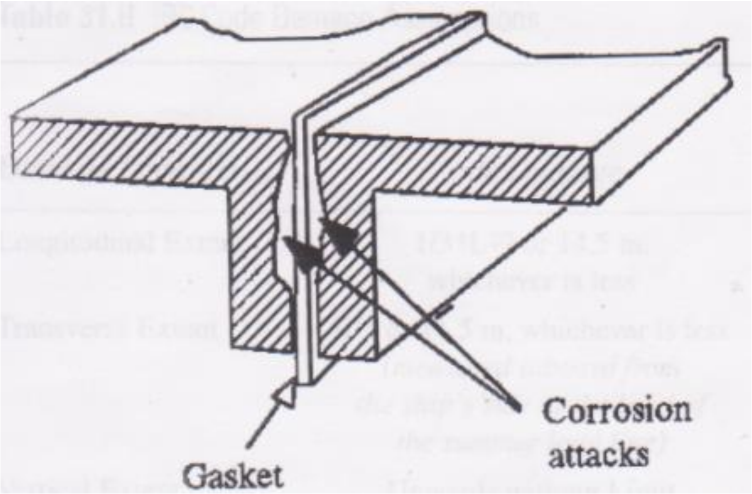


Figure 5.5 – Crevice corrosion

- **Intergranular corrosion:** This type of corrosion consist of localize attack along the grain boundaries of the metal and is a result of weakened corrosion resistant areas resulting from heating and contamination by substance like oil and grease. The initiation is usually occurred by mishandling of the material in the shipyard, like a slow cool down after annealing, or prolonged exposure to intermediate temperatures.

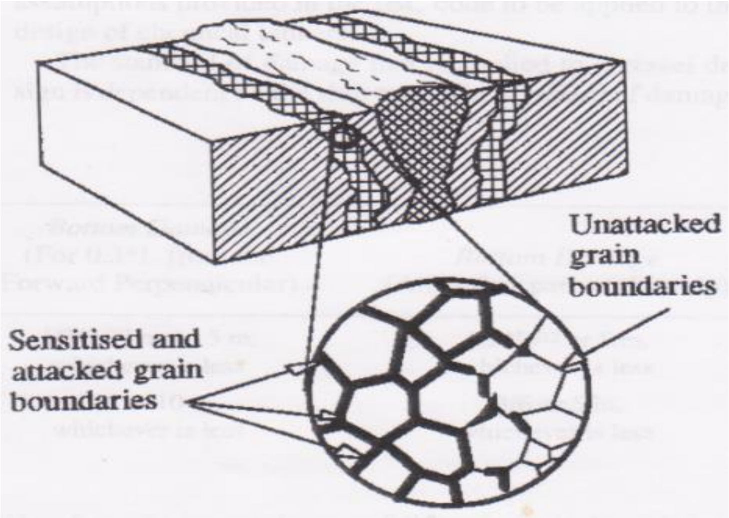


Figure 5.6 – Intergranular corrosion

- **Galvanic corrosion:** Galvanic corrosion occurs when two metals of different potentials are in metallic contact in an electrolyte. The electrical potential, or voltage, that exists between the two metals causes current to flow and the less noble, or more anodic, metal suffers increased corrosion rate. The severity of attack depends upon the relative voltage difference between the metals, the relative exposed areas of each, and the particular corrosive environment.

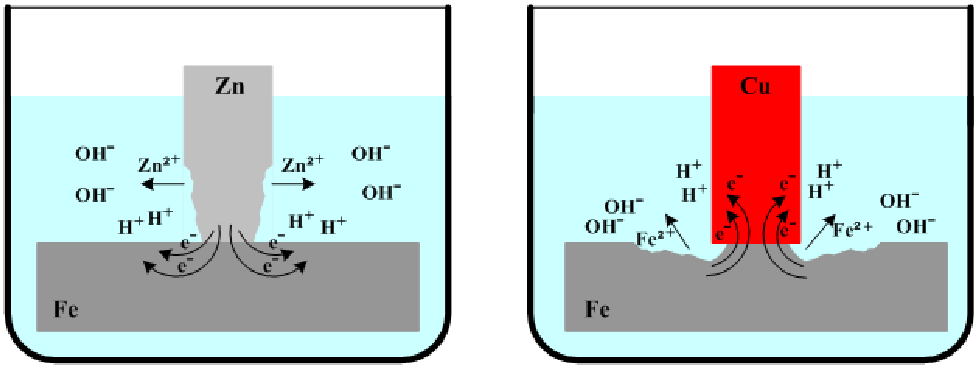


Figure 5.7 – Galvanic corrosion

5.3.3 *Corrosion in chemical tankers*

The corrosion behavior in metals is greatly affected by the environment, and most of all by the type and chemical characteristics of the electrolyte. For example, the pH of the electrolyte affects the corrosion rate of steel in way that is shown in Figure 5.8.[9]

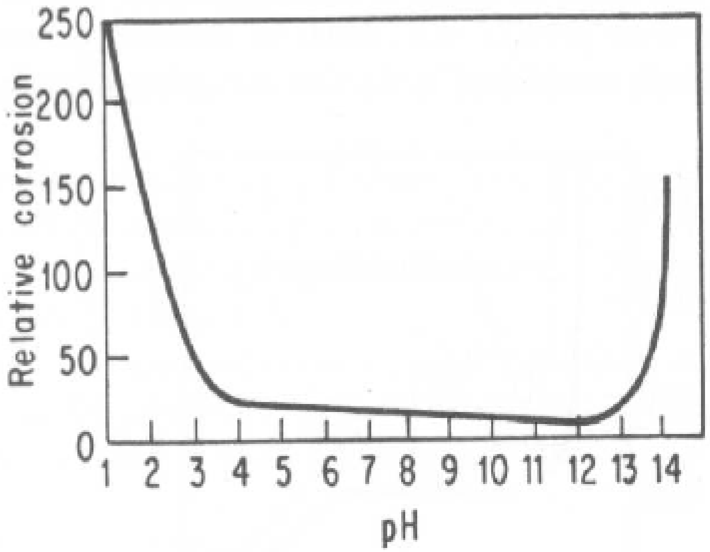


Figure 5.8 – Influence of pH in steel corrosion rate

The cargoes carried by chemical tankers, like acids, anhydrides and alkalis, because of their chemical characteristics, increase the possibility of corrosion to take place in the cargo tank metal structure, compared to other commercial vessels.

In cargo tanks made by stainless steel, general corrosion is possible to occur in areas where the stainless steel corrosion resistance characteristics have been reduced, such as where welding and grinding burns remain in the surface. Because of the large amount of cargo equipment inside a cargo tank, that require welding, like cargo pipes, heating coils, washing appliances etc., such areas can easily be created. Therefore, special attention shall be given during the welding procedure.

Pitting corrosion on the other hand, is more likely to occur in areas that include connections with sharp gouges or dents in the surface, or where the surface of the stainless steel has been contaminated by iron particles or rust. Pitting corrosion is also likely to occur in areas where solids and sludge from chemical cargoes accumulate. For that reason good cargo tank and piping system designs are required, to eliminate the areas where solids from cargoes may collect.

Other types of corrosion may also take place in cargo tanks of chemical tankers. Crevice corrosion may occur in threaded and flanged joints, and fasteners in the cargo tanks and piping. Stress corrosion may be created on heating coils, and intergranular corrosion in defected parts of the steel plates.

Finally, galvanic corrosion is possible to take place when solid stainless steel plates are used for the inner bottom plating or the inner side platting. In this case, a galvanic cell is created in the ballast tank as the shell plating and stiffeners are typically made by carbon steel. If the stainless and carbon steel surfaces in the ballast tank are left uncoated, the less noble carbon steel will undergo rapid galvanic corrosion. In order to prevent this, all surfaces of the ballast tanks shall be covered with a paint coating that will act as insulation and stop the current flow. The stainless steel surfaces shall also be coated in that case, as if left uncoated and small areas of the carbon steel become uncoated, these exposed areas will undergo rapid corrosion. The corrosion will increase in scope as larger areas of the coating on the wasting carbon steel will fail.[10]

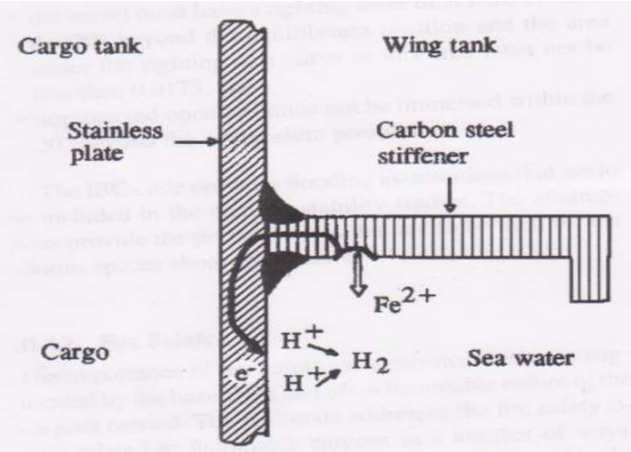


Figure 5.9 – Galvanic corrosion in ballast tank

5.4 Stainless steel

5.4.1 Austenitic stainless steel

Stainless steel is the most common material used for cargo tank construction in chemical tankers, as it offers several advantages compared to mild steel, such as anti-corrosion behavior, better ultimate strength characteristics, less requirements for maintenance, etc. In addition to use in association with aggressive cargoes such as nitric acid, it is utilized where high standards of cargo purity and avoidance of rust contamination are of major importance. There are several grades of stainless steel that are currently being utilized aboard modern chemical tankers. These grades must resist the cargoes that the ship is to carry as well as the seawater that is used to clean the cargo tanks and lines. Traditionally, austenitic stainless steel grades such as 316L, 317L, 316LN, and 317LN were used.

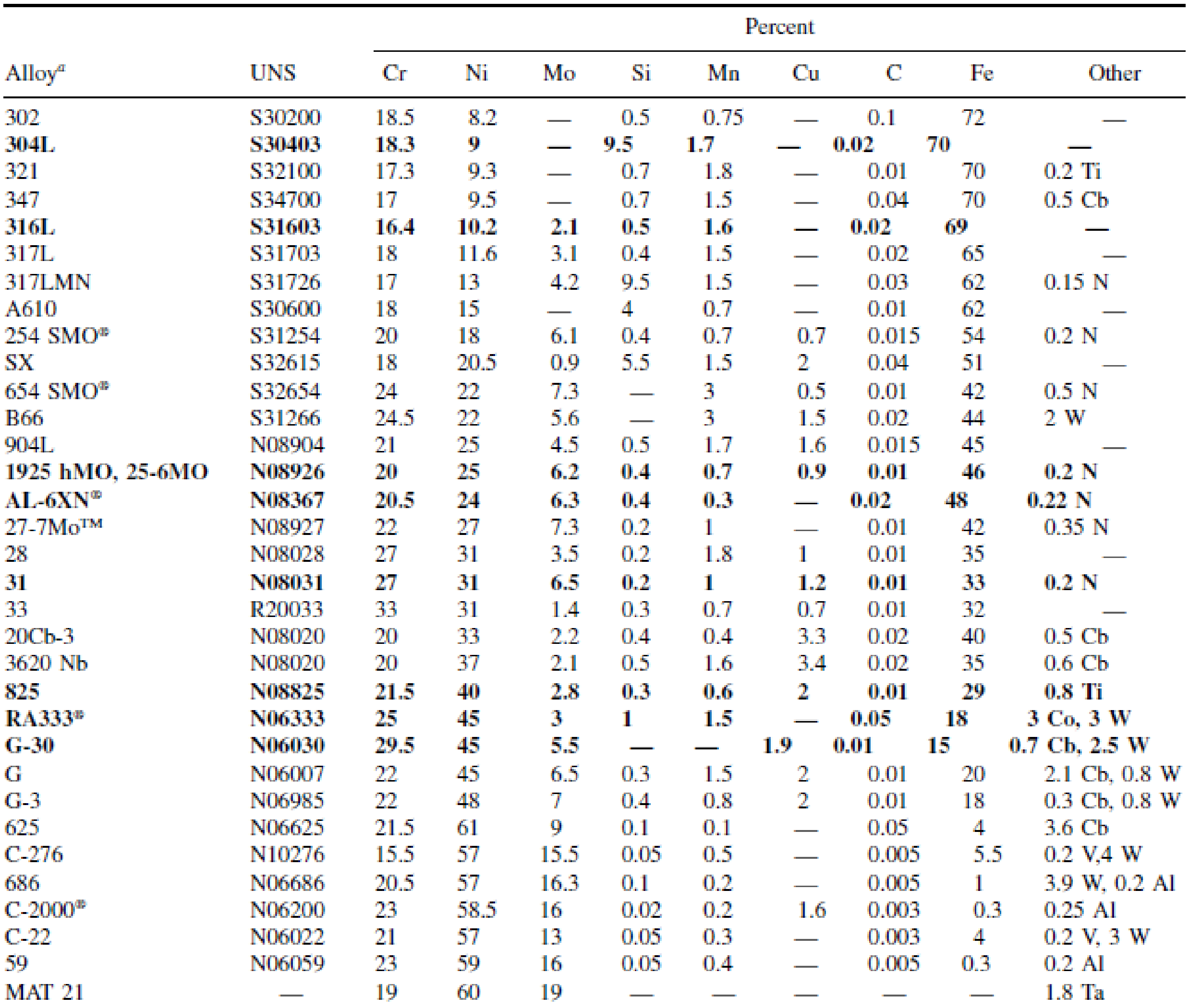
Austenitic stainless steels are the most common and familiar types of stainless steel. They are most easily recognized as nonmagnetic. Their properties, such as good corrosion resistance, workability, weldability, and good ductility, make them suitable for use in chemical tankers. Austenitic stainless steels contain between about 16% and 25% chromium, and they can also contain nitrogen in solution, both of which contribute to their high corrosion resistance.

Austenitic stainless steels have also many advantages from a metallurgical point of view. They can be made soft enough to be easily formed by the same tools that work with carbon steel, but they can also be made incredibly strong by cold work. Their austenitic (fcc, face-centered cubic) structure is very tough and ductile down to absolute zero. They also do not lose their strength at elevated temperatures as rapidly as ferritic (bcc, body-centered cubic) iron base alloys. The least corrosion-resistant versions can withstand the normal corrosive attack of the everyday environment that people experience, while the most corrosion-resistant grades can even withstand boiling seawater.[11]

The most common austenitic steel alloy used for chemical tankers construction, is 316L. Formerly, when 316L was inadequate, the designer switched to the high end of the spectrum, alloy C-276, which is still considered the most broadly useful of the high-nickel alloys. Type 317L is a more highly alloyed material than type 316L and its increased molybdenum content imparts greater resistance to pitting, an advantage in phosphoric acid service.[12] Today there are numerous other choices, ranging from those of intermediate cost to alloys superior to C-276 in specific environments. Materials in the 5–7% molybdenum range are used for seawater service and chemical process vessels in general. Alloys N08367, S31254, and N08926 constitute the ‘‘6 moly’’ alloys. These have both corrosion resistance and cost intermediate between 316L and alloy C-276. [13]

The selection of the most appropriate alloy for cargo tank construction is not an easy task. The designer needs to take into account the type of chemical cargo and its corrosion behavior. Previous experience, extensive testing in the exact corrosive environment of interest, and detailed knowledge of the various alloys to be considered are also required.

Austenitic steel grade 316L is also used for the construction of cargo tank fittings such as tank hatches and hatch coamings and cargo tank ladders. The submerged cargo pumps and the components of the tank cleaning system that are exposed to the cargo are also available in corrosion resistance stainless steel.[4]



		Percent								
Alloy[a]	UNS	Cr	Ni	Mo	Si	Mn	Cu	C	Fe	Other
302	S30200	18.5	8.2	—	0.5	0.75	—	0.1	72	—
304L	**S30403**	**18.3**	**9**	**—**	**9.5**	**1.7**	**—**	**0.02**	**70**	**—**
321	S32100	17.3	9.3	—	0.7	1.8	—	0.01	70	0.2 Ti
347	S34700	17	9.5	—	0.7	1.5	—	0.04	70	0.5 Cb
316L	**S31603**	**16.4**	**10.2**	**2.1**	**0.5**	**1.6**	**—**	**0.02**	**69**	**—**
317L	S31703	18	11.6	3.1	0.4	1.5	—	0.02	65	—
317LMN	S31726	17	13	4.2	9.5	1.5	—	0.03	62	0.15 N
A610	S30600	18	15	—	4	0.7	—	0.01	62	—
254 SMO®	S31254	20	18	6.1	0.4	0.7	0.7	0.015	54	0.2 N
SX	S32615	18	20.5	0.9	5.5	1.5	2	0.04	51	—
654 SMO®	S32654	24	22	7.3	—	3	0.5	0.01	42	0.5 N
B66	S31266	24.5	22	5.6	—	3	1.5	0.02	44	2 W
904L	N08904	21	25	4.5	0.5	1.7	1.6	0.015	45	—
1925 hMO, 25-6MO	**N08926**	**20**	**25**	**6.2**	**0.4**	**0.7**	**0.9**	**0.01**	**46**	**0.2 N**
AL-6XN®	**N08367**	**20.5**	**24**	**6.3**	**0.4**	**0.3**	**—**	**0.02**	**48**	**0.22 N**
27-7Mo™	N08927	22	27	7.3	0.2	1	—	0.01	42	0.35 N
28	N08028	27	31	3.5	0.2	1.8	1	0.01	35	—
31	**N08031**	**27**	**31**	**6.5**	**0.2**	**1**	**1.2**	**0.01**	**33**	**0.2 N**
33	R20033	33	31	1.4	0.3	0.7	0.7	0.01	32	—
20Cb-3	N08020	20	33	2.2	0.4	0.4	3.3	0.02	40	0.5 Cb
3620 Nb	N08020	20	37	2.1	0.5	1.6	3.4	0.02	35	0.6 Cb
825	**N08825**	**21.5**	**40**	**2.8**	**0.3**	**0.6**	**2**	**0.01**	**29**	**0.8 Ti**
RA333®	**N06333**	**25**	**45**	**3**	**1**	**1.5**	**—**	**0.05**	**18**	**3 Co, 3 W**
G-30	**N06030**	**29.5**	**45**	**5.5**	**—**	**—**	**1.9**	**0.01**	**15**	**0.7 Cb, 2.5 W**
G	N06007	22	45	6.5	0.3	1.5	2	0.01	20	2.1 Cb, 0.8 W
G-3	N06985	22	48	7	0.4	0.8	2	0.01	18	0.3 Cb, 0.8 W
625	N06625	21.5	61	9	0.1	0.1	—	0.05	4	3.6 Cb
C-276	N10276	15.5	57	15.5	0.05	0.5	—	0.005	5.5	0.2 V,4 W
686	N06686	20.5	57	16.3	0.1	0.2	—	0.005	1	3.9 W, 0.2 Al
C-2000®	N06200	23	58.5	16	0.02	0.2	1.6	0.003	0.3	0.25 Al
C-22	N06022	21	57	13	0.05	0.3	—	0.003	4	0.2 V, 3 W
59	N06059	23	59	16	0.05	0.4	—	0.005	0.3	0.2 Al
MAT 21	—	19	60	19	—	—	—	—	—	1.8 Ta

Figure 5.10 – Austenitic stainless steel alloys

5.4.2 *Duplex stainless steel*

As stated by Werner[4], duplex stainless steel grades have recently become the material of choice for cargo tank plating. Duplex stainless steel, which is an austenitic-ferritic stainless steel, has greater overall corrosion resistance and higher strength than the austenitic grades while maintaining good forming and welding characteristics, and is becoming widely available at a moderate cost.

Duplex stainless steel was for the first time introduced as a material for the construction of chemical tankers in 1970, where three chemical tankers (Zambeze, Zeebrugge and Zeeland) were built with UR50 grade. The production of stainless steel at that time was limited, however, and due to the successful operation of the above vessels, since that time steel industries have made continuous developments of their process up to the present time. This has led to a significant improvement in the control of the residual elements such as oxygen and sulphur, when at the same time guaranteeing narrow composition range including that for nitrogen.

From metallurgic point of view, the accuracy and reproducibility of the chemical composition enable the amounts of the two phases α and γ to be closely adjusted. In addition, improvement of the corrosion resistance characteristics and the high temperature stability of the duplex structure – particularly in the heat affected zones of welds – are possible through the increased control of nitrogen levels of the alloy. Finally, the reduction in the levels of residuals has resulted in a marked beneficial effect on the hot workability, made possible the production of wide plates.[14]

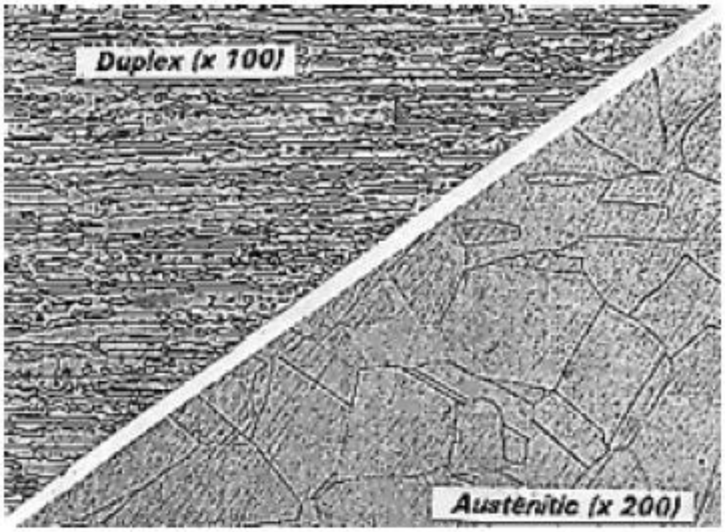
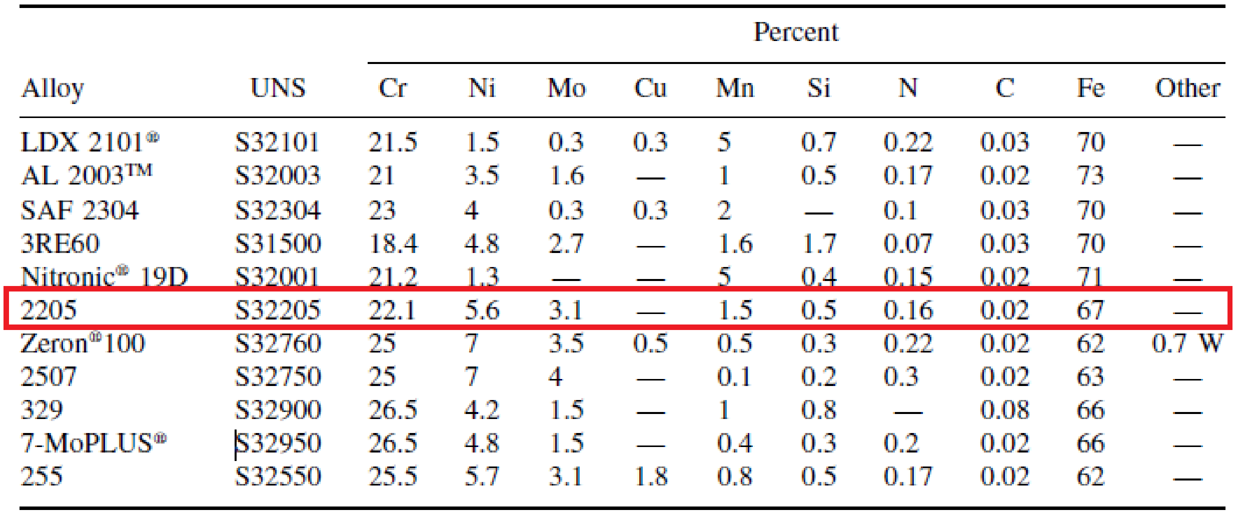


Figure 5.11 – Micrographic view of duplex and austenitic stainless steel

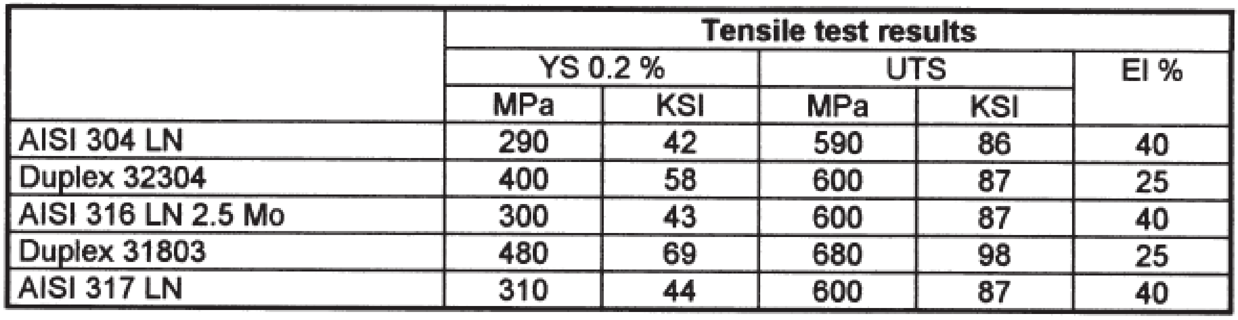
The most common duplex grade that is currently used for cargo tank plating is the 2205 (also found as UR 45N or 31803). Many of the mechanical properties of this grade are closer to those of carbon steel than are the mechanical properties of either the 316L or 316LN grades of austenitic stainless steel. The chemical composition of the 2205 grade is indicated in the below Figure.



		Percent									
Alloy	UNS	Cr	Ni	Mo	Cu	Mn	Si	N	C	Fe	Other
LDX 2101®	S32101	21.5	1.5	0.3	0.3	5	0.7	0.22	0.03	70	—
AL 2003™	S32003	21	3.5	1.6	—	1	0.5	0.17	0.02	73	—
SAF 2304	S32304	23	4	0.3	0.3	2	—	0.1	0.03	70	—
3RE60	S31500	18.4	4.8	2.7	—	1.6	1.7	0.07	0.03	70	—
Nitronic® 19D	S32001	21.2	1.3	—	—	5	0.4	0.15	0.02	71	—
2205	S32205	22.1	5.6	3.1	—	1.5	0.5	0.16	0.02	67	—
Zeron®100	S32760	25	7	3.5	0.5	0.5	0.3	0.22	0.02	62	0.7 W
2507	S32750	25	7	4	—	0.1	0.2	0.3	0.02	63	—
329	S32900	26.5	4.2	1.5	—	1	0.8	—	0.08	66	—
7-MoPLUS®	S32950	26.5	4.8	1.5	—	0.4	0.3	0.2	0.02	66	—
255	S32550	25.5	5.7	3.1	1.8	0.8	0.5	0.17	0.02	62	—

Figure 5.12 – Duplex grades chemical composition

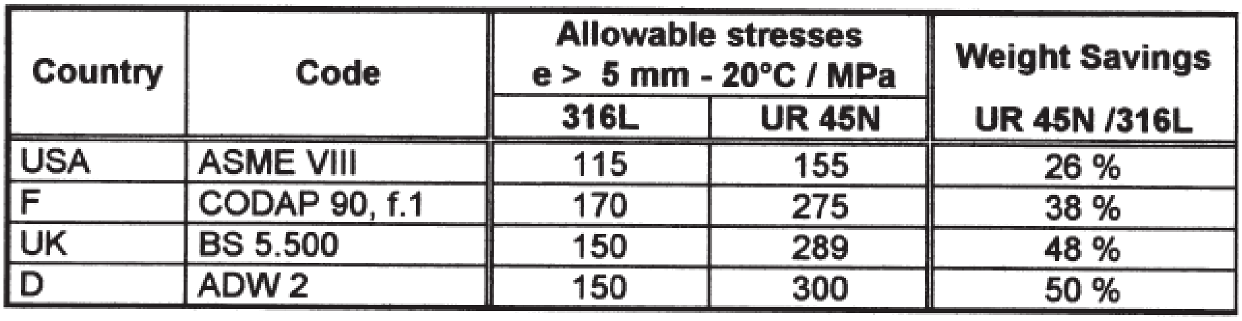
As stated by Jacques[14], one of the greatest advantages of duplex stainless steel compared to austenitic stainless steel is the enhanced mechanical properties of the first. In Figure 5.13 it is indicated that the yield strength of the duplex stainless steel is almost twice that of the austenitic grades.



	Tensile test results				
	YS 0.2 %		UTS		El %
	MPa	KSI	MPa	KSI	
AISI 304 LN	290	42	590	86	40
Duplex 32304	400	58	600	87	25
AISI 316 LN 2.5 Mo	300	43	600	87	40
Duplex 31803	480	69	680	98	25
AISI 317 LN	310	44	600	87	40

Figure 5.13 – Mechanical properties of duplex and austenitic stainless steels

The greater strength of duplex stainless steel as compared to austenitic stainless steel permits a reduction in the scantling of the stainless steel plates used for the cargo tank boundaries. This reduction translates into reduced steel weight and increased cargo capacity. This benefit must be included in the analysis when comparing the costs and benefits of using duplex stainless in place of the austenitic grades. In Figure 5.14, some allowable design stress values for the erection of pressure vessels, following several codes, are given. Those results indicate the thickness reductions that can take place when duplex stainless steel is considered as cargo tank material.



Country	Code	Allowable stresses e > 5 mm - 20°C / MPa		Weight Savings
		316L	UR 45N	UR 45N /316L
USA	ASME VIII	115	155	26 %
F	CODAP 90, f.1	170	275	38 %
UK	BS 5.500	150	289	48 %
D	ADW 2	150	300	50 %

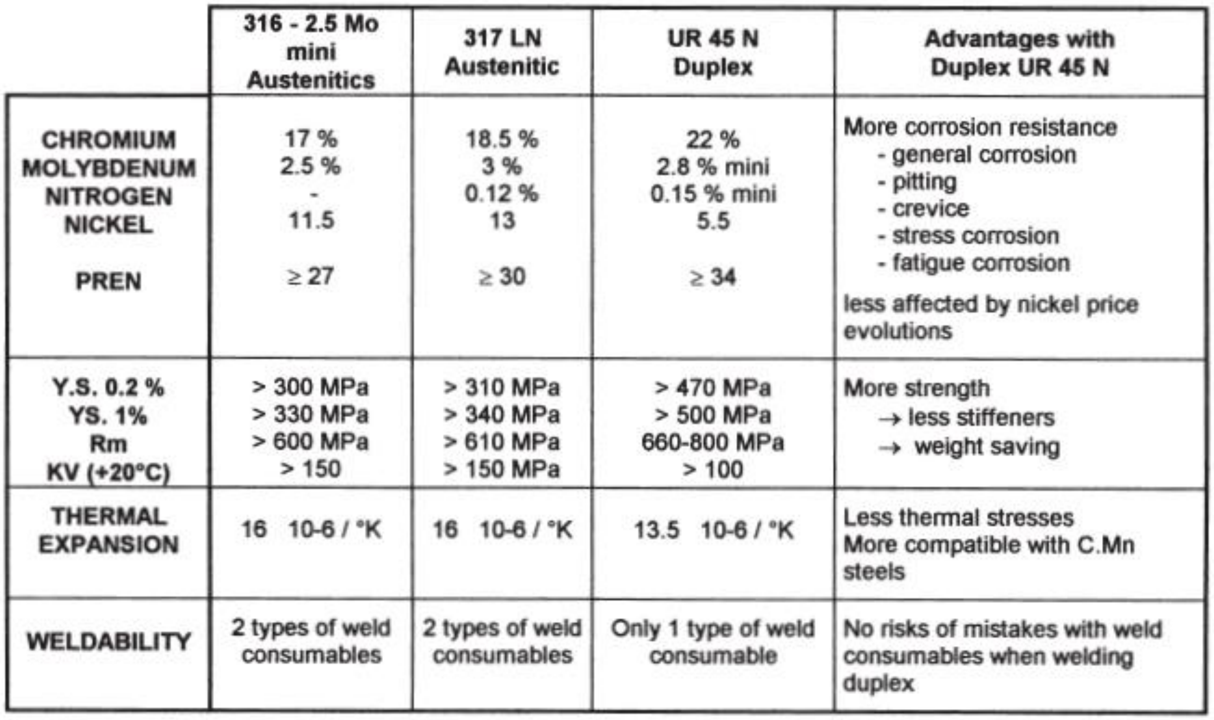
Figure 5.14 – Allowable design stress values for several pressure vessel codes

Apart from the ultimate strength benefits, duplex steels have several other advantages compared to austenitic stainless steels. Their stronger magnetic behavior enabling the use of magnetic clamps during machining, when their lower thermal expansion coefficient makes it possible to reduce thermal stresses when the cargoes carried are heated, resulting to a reduction in the number of expansion joints.

Another very important advantage of duplex stainless steel is its corrosion resistance properties. Duplex stainless steel 2205 performs better than austenitic grades 316L or 317L against different corrosion mechanisms such as general corrosion, pitting corrosion, or stress corrosion cracking. More specifically, general resistance of duplex steel is greatly increased compared to austenitic steel when it comes to cargoes containing phosphoric acid – due to its high contents of chromium and molybdenum - , sulphuric acid, and organic and caustic solutions.

A summary of the advantages of duplex stainless steel grade 2205 compared to austenitic stainless steel grades 316LN 2.5Mo mini. and 317LN is indicated in Figure 5.15.

There is no concern that duplex stainless steels are a way better choice for multipurpose applications for the new generation of chemical tankers, as they offer better characteristics at lower cost when a proper design of tanks takes place. For all the reasons explained above, duplex stainless steels are the most commonly used material for the cargo tanks construction of modern chemical tankers.



	316 - 2.5 Mo mini Austenitics	317 LN Austenitic	UR 45 N Duplex	Advantages with Duplex UR 45 N
CHROMIUM	17 %	18.5 %	22 %	More corrosion resistance - general corrosion - pitting - crevice - stress corrosion - fatigue corrosion less affected by nickel price evolutions
MOLYBDENUM	2.5 %	3 %	2.8 % mini	
NITROGEN	-	0.12 %	0.15 % mini	
NICKEL	11.5	13	5.5	
PREN	≥ 27	≥ 30	≥ 34	
Y.S. 0.2 %	> 300 MPa	> 310 MPa	> 470 MPa	More strength → less stiffeners → weight saving
YS. 1%	> 330 MPa	> 340 MPa	> 500 MPa	
Rm	> 600 MPa	> 610 MPa	660-800 MPa	
KV (+20°C)	> 150	> 150 MPa	> 100	
THERMAL EXPANSION	16 10-6 / °K	16 10-6 / °K	13.5 10-6 / °K	Less thermal stresses More compatible with C.Mn steels
WELDABILITY	2 types of weld consumables	2 types of weld consumables	Only 1 type of weld consumable	No risks of mistakes with weld consumables when welding duplex

Figure 5.15 – Duplex steel – Austenitic steel grades comparison

5.4.3 Stainless steel and corrosion

Stainless steel is corrosion resistant but not corrosion proof. There are cargoes that are transported by sea in bulk that are not compatible with the stainless steel grades used in chemical tankers. Other cargoes that can be carried in stainless steel tanks can lead to corrosion when the right conditions exist. An examination of the types or corrosion to which stainless steels are susceptible reveals design features, fabrication mistakes and operational errors which should be avoided.[15]

Improper handling and construction techniques may result in localized areas where the stainless steel loses its corrosion resistance properties. For that reason, it is preferred that prior and during the construction procedure, the stainless steel plates are stored in protected indoor areas or under a roof, and separate from carbon steel, to prevent contamination that may occur when carbon steel comes in contact with stainless steel, or contamination from oil, grease etc.

In addition, stainless steel components should be handled with care in order to avoid mechanical damage. Bends, dents and scratches on the surface of stainless steel plates are always areas that are more vulnerable to corrosion.

Clean equipment and tools are another important factor in order to avoid contamination of the stainless steel plates. The equipment used for the fabrication of the stainless steel should be free from dirt, grease, oil, and carbon steel dust. Furthermore, all clamps, fixtures, lifting gear, and tools used in the fabrication of stainless steel components should be made of stainless steel to avoid contamination of the material, and should be dedicated to stainless steel fabrication.

The reason why stainless steel may become, under specific circumstances, vulnerable to corrosion can be understood by analyzing its metallurgic structure. Stainless steel is an alloy of iron and carbon, just like all other steels. What makes it so corrosion resistant is the presence of a minimum of 10.5% chromium. On contact with oxygen, a chromium oxide layer is formed on the surface of the material. This passive layer protects the material and has the particular ability to self-repair. However, if there is insufficient oxidizing power available at the steel's surface, or the protective layer is damaged, the passive layer cannot be maintained or repaired and the start of corrosion can appear.[16]

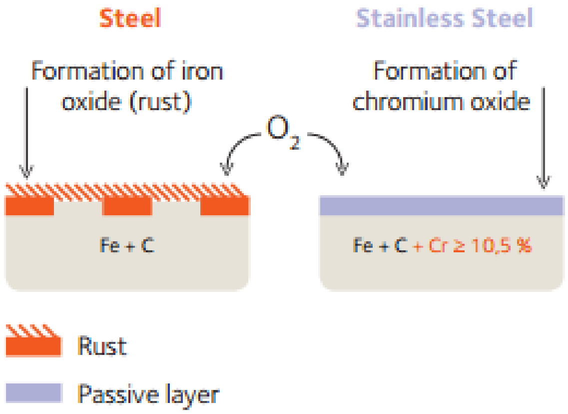


Figure 5.16 – Corrosion in stainless steels

5.5 Cargo tank coatings

5.5.1 The role of coatings

Cargoes which are generally compatible with mild steel may be transported in tanks to which paint coating of normal thickness have been applied. However, conventional coatings of this type are effective in reducing corrosion only if they are wholly compatible with the cargoes being carried[17]. For that reason, the selection of the proper cargo tank coating is a matter of high importance.

The choice of the correct coating alone though, does not mean that no other actions should be taken in order to maintain the coating in good state and avoid its wear. Restrictions such as limited terms of exposure, required recovery periods (eg. as a result of softening the coating) and the need to ensure that no water is present in the tank or in the cargo, should be followed. Additionally, as failure of the coating system may not be due to the chemical most recently carried, but may be influenced by the preceding sequence of cargoes, specially attention should be given in that aspect.[17]

The role of the coating in cargo tanks of chemical tankers is double. Firstly, it is used in order to generate a protective barrier between the chemical cargo and the – vulnerable to corrosion – mild steel. Secondly, it provides a very smooth surface within the cargo tank, which enhances and accelerates the tank cleaning procedures[18]. For that reason, the coatings used in a cargo tank should be corrosion inhibiting, free from pores, and easy to clean. Additionally, as the quality of the cargo transferred should be maintained in high standards, they must not contaminate or affect the color or taste of the cargo, particularly for cargoes intended for human consumption and pure chemical cargoes.[19]

5.5.2 Coating application procedure

The application of the coating in a proper way is of equal importance with the selection of the correct coating. For that reason, a common procedure is usually followed, including preparation of the surface with blasting and repair of structural anomalies, application of several coating and touch-up layers, washing, and testing of the coated surface.

Depending on the kind of coating that is going to be used, the number of layers that will be applied is defined. In Figure 5.17, a three layer coating system is presented. The purpose of the first layer (primer) is to ensure adhesion of the coating to the surface. Proper preparation of the surface will make this adhesion easier. The second layer’s purpose is either to improve chemical resistance, serve as an adhesion coat between the primer and topcoat when the primer and topcoat are not compatible, or just to increase the thickness of the coating. Finally, the third layer is the one that will come in contact with the cargo, therefore has all the relevant characteristics required.[20]

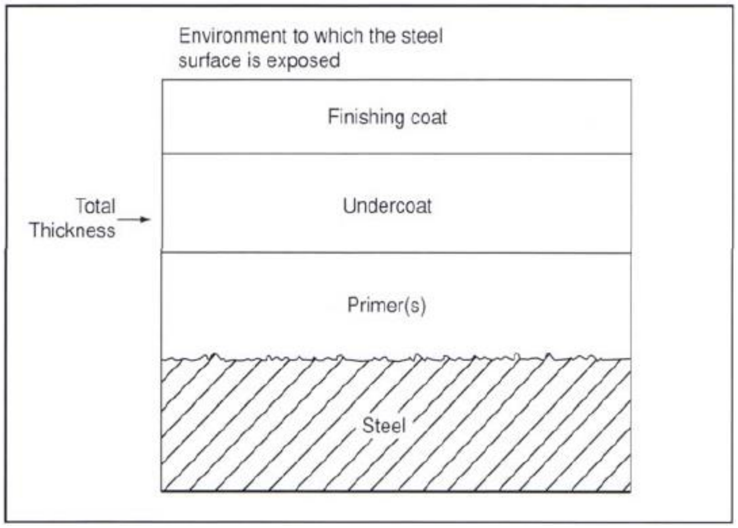


Figure 5.17 – Three layer coating system

The steps required for the cargo tanks coating procedure of a 16500 DWT chemical tanker constructed in China, as defined by the shipyard, are presented as flow chart in Figure 5.18.

Figure 5.18 – Coating procedure

5.5.3 Types of coatings

The selection of the proper cargo tank coating has been already highlighted in this chapter. The most commonly used coating in chemical tankers nowadays are presented below, as given by Ackermann.[21]

5.5.3.1 Alkaline zinc silicates

Alkaline zinc silicates may be composed of zinc powder which has particles size of 5~9 microns, water-dissolved sodium silicate, potassium silicate, or lithium silicate. The chemistry of these inorganic silicates is very different from organic compounds such as epoxies, since curing occurs by a reaction between the pigment (zinc powder) and the binder (silica gel), and their curing mechanism is too complex.

The corrosion resistance of alkaline zinc silicates is related to the percentage by weight of zinc in the dried film. The greater the zinc percentage, the better the corrosion resistance of the coating. Top grade zinc silicates contain more than 90% zinc.

Small amounts of additional pigments such as iron oxide or chromium oxide may be used to change the color from the light grey of zinc. This helps a lot when spraying and inspecting the coating, since the abrasive-blasted surface is also grey. For application in cargo tanks, colored zinc silicates make avoiding holidays and stripe coat defects much easier.

The application of alkaline zinc coatings is more complex and require more attention compared to this of the organic coatings like epoxies, as because of their high content in metallic zinc powder, they cannot be applied by airless spraying but only with low pressure air spray equipment. Proper ventilation and dehumidification is also vital during the application of the coating. Additionally, alkaline zinc silicates are sensitive to overthickness and are applied at a single, one-striped coat. This means that possible coating defects cannot be rectified by subsequent coats.

Regardless the difficulties in application, when alkaline zinc coating are properly applied they offer a tank lining with outstanding corrosion protection, superior solvent resistance, and excellent mechanical resistance, when at the same time the duration may equal the service life of the tanker, compared to a duration of 10–15 years for organic coatings. Alkaline zinc coatings however, are not suitable for all chemical cargoes, as their properties are significantly reduced for cargos with pH range out of 6-9.

5.5.3.2 Ethyl zinc silicates

Ethyl zinc silicates are organic, solvent-borne paints consisting of ethyl silicate and zinc powder. To be self-curing, the silicate binder must be partially hydrolyzed. Their curing reaction is similar to the reaction that occurs in water-borne, self-curing products.

Unlike alkaline zinc silicates, their application can be carried out by airless spraying, since they have a lower content of zinc powder. Ventilation and dehumidification conditions are less critical, however the relative humidity of the tank should not fall below 60%. A serious problem though with ethyl zinc silicate coatings is the difficulty of respraying low DFT areas, since intercoat adhesion problems may occur.

Their application nowadays is very limited, as they pose the risk of cargo contamination from the zinc, for cargoes like vegetable oil, aviation fuel etc.

5.5.3.3 Pure epoxies

Pure epoxy coatings are based on bisphenol and epichlorhydrin resins reacting, through their terminal epoxide (oxirane) groups, with hardeners having polyfunctional –NH2 groups (polyamines or polyamides). Their chemical resistance and mechanical properties may vary to a great extent, depending on their formulation, such as the molecular weight of resins, the type of hardener, and, to a lesser degree, pigmentation and solvent mixture.

Low molecular weight epoxy resins, offer better chemical and water resistance than the medium ones, which however offer better mechanical characteristics. Polyamine hardenings are preferred for cargo tank coatings rather than amine hardenings, as they also offer better mechanical properties.

Epoxy coatings are widely used linings for cargo tanks because of their versatility, resistance range, and application properties. However their application is not suitable for transportation of methanol, ethanol, methyl ethyl ketone, or some unleaded gasolines, as their chemical resistance to strong solvents is limited. Additionally, maximum overcoating intervals are relatively short (three to five days), requiring a tight application schedule.

5.5.3.4 Epoxy phenolics

Epoxy phenolics are multifunctional epoxy resins, such as epoxy phenol novolacs, prepared by the epoxidation of phenolic resins with epichlorhydrin. Aliphatic amine-cured resins of this type result in polymers with very high crosslink density and, therefore, outstanding chemical resistance.

In order, though, to reach these high chemical resistance standards, the epoxy phenolics need to be heated up to a temperature of 50-60°C and be kept at that temperature for about a week. As this is very difficult to happen, requiring several heating equipment and coils all around the cargo tanks, their maximum chemical resistance is not reachable. Generally, the chemical resistance of epoxy phenolics when properly heated, against strong solvents and fatty acids is better than pure epoxies. When not heat treated, their chemical resistance improves after a period of almost three months, without though reaching the initial standards.

As a matter of fact, they are limited to applications similar to those of the pure epoxies, as they are not recommended for the carriage of strong chemical cargoes. Their overcoating period though is significantly lower, making recoating less critical.

5.5.3.5 Epoxy Isocyanates

Higher molecular weight epoxy resins can be crosslinked with polyisocyanate compounds. This reaction occurs at room temperature, and the isocyanate reacts with the hydroxyl groups of the epoxy resin. A densely crosslinked (epoxy urethane linkage) structure with excellent chemical resistance is obtained.

Cured epoxy isocyanates offer a resistance range similar to heat cured epoxy phenolics, without though the need to be heated first in order to obtain their chemical resistant properties. Most cargoes can be carried after a curing time of 10 days, when more aggressive cargoes such as methanol can be carried after a period of three months. The only exception are the alkaline cargoes, for which epoxy isocyanates are not recommended.

Overcoating intervals of epoxy isocyanates are almost the same with those of epoxy phenolics. Their application to the surface though requires more attention as a small overspray may cause problems. In addition, formation of cracks is easier to take place. The cracks however can be easily detected with naked eye during inspection, in order to be repaired.

Areas usually affected by cracking are angular welding seams and corroded spots (pitting). Stripe-coated areas, if over-coated before completely dry, can also cause cracking or blistering. These application problems, besides the well-known health problems of isocyanates, are the main reasons for the reduced usage of epoxy isocyanates. However, if they are used anyway, epoxy isocyanates offer an excellent tank coating system for aggressive cargoes, especially in the case of newbuildings. When considering repainting of in-service ships, epoxy isocyanates might not be recommended if the tank plates are already heavily corroded, since it may be difficult to avoid overthickness on pitted areas.

5.5.3.6 Cyclosilicon epoxies

These coatings are based on a completely new resin, which is essentially a cyclic silicon structure with five phenol glycidyl ether groups (epoxidised phenol groups) that are cured by means of a catalyst to give a highly cross-linked homopolymer. Polymerization occurs through etherification of the epoxy groups, resulting—after curing—in strong ether (oxygen to carbon) linkages without hydroxyl or ester groups, which are subject to acid attack or hydrolysis.

Cyclosilicon epoxies are characterized by enhanced properties compared to zinc silicates and phenolic epoxies. This is due to their more densely crossed – linked molecular structure, which delivers higher chemical and temperature resistance, higher reactivity at lower temperature and resistance to absorption, and greater toughness. The greater the distance between the cross-links, the greater the permeation that leads to chemical attack and coating absorption. In Figure 5.19, the number of cross-links for the same size coating cutaway is illustrated for phenol epoxy and cyclosilicon epoxy.[22]

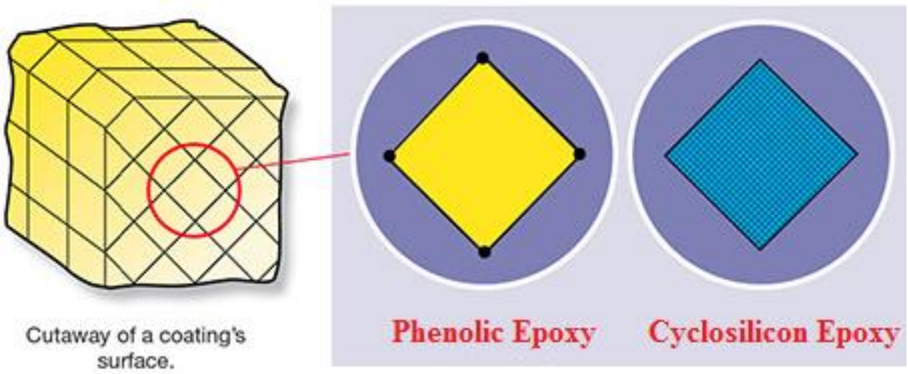


Figure 5.19 – Cross-links in cyclosilicon epoxy

Both phenolic epoxy and zinc silicate coatings absorb cargo particles in a high rate and they release them very slowly. This may lead to subsequent cargo contamination or reduced resistance to acids, caustics, and acid-concentrating oils, as shown in Figure 5.20. Cyclosilicon epoxies are capable of eliminating such incidents, for the reasons described above. Additionally, they provide smooth and glossy surfaces that can cut cleaning time by 70% compared to other epoxies.

Due to the above characteristics, it is estimated[23] that such coatings could handle all but 10 of the 1,000 cargoes on the IMO list. Their enhanced properties have led to their increased application in new-built chemical tankers.

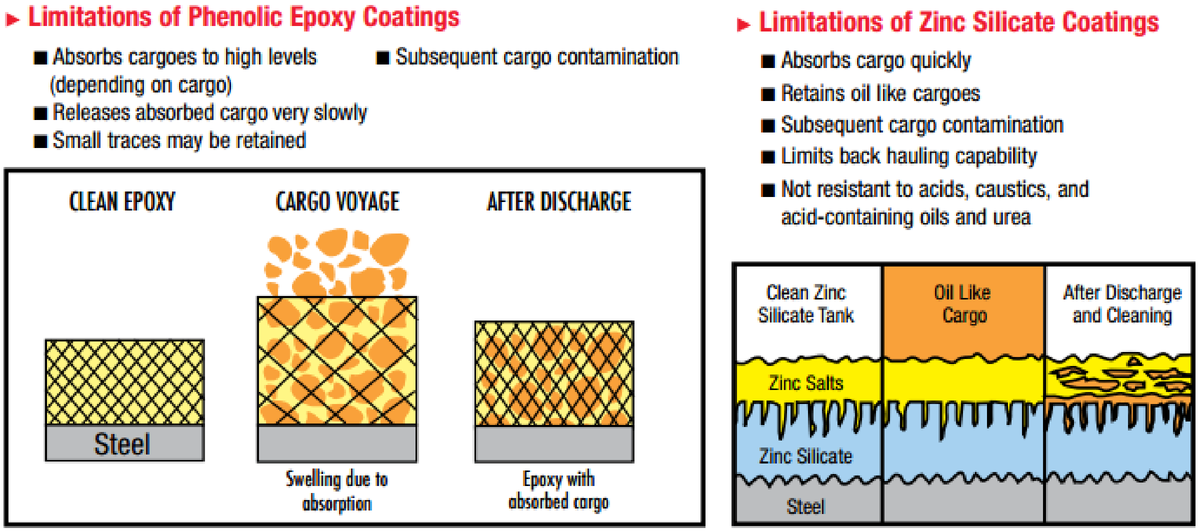


Figure 5.20 – Cargo absorption by coatings

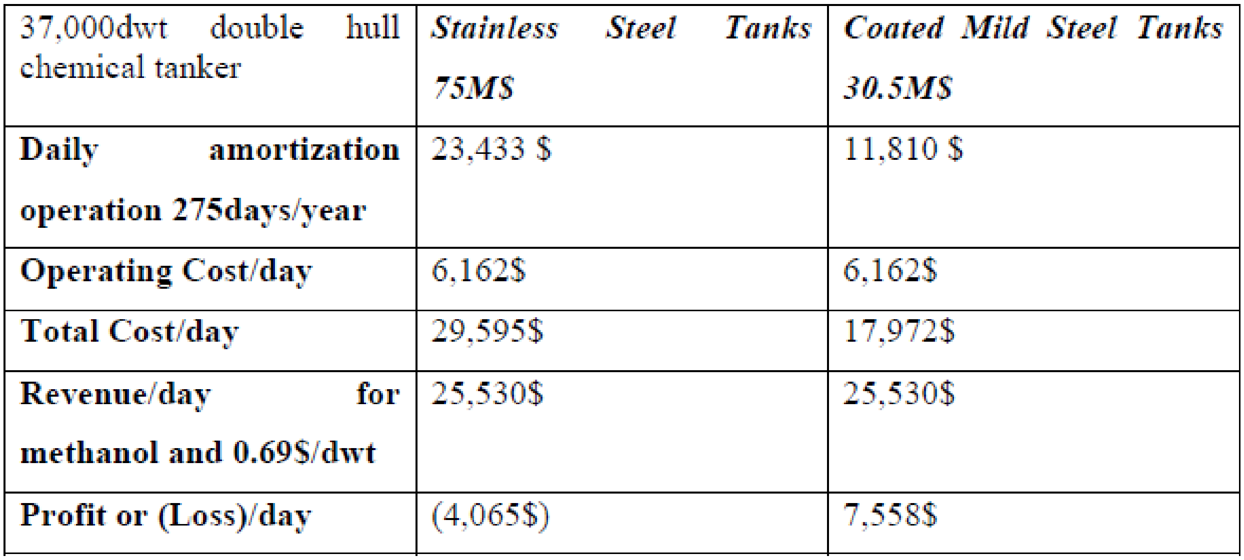
5.6 Material selection

The selection of the proper material for the construction of cargo tanks is not an easy task. The most important parameter for the selection is the cargo that is intended to be carried. Some cargoes, that are more corrosive, cannot be carried in mild steel tanks. On the other hand, stainless steel is not always the optimum choice against corrosion, as polymer coatings may have better results.

After the probable materials have been defined, economic criteria play the most important role in the final selection. A techno-economic analysis between stainless steel and coated mild steel is given by Giannakopoulos[24]. As seen in previous sections, stainless steel has very good corrosion resistant characteristics and can be used satisfactory for almost all types of cargoes (except strong hot acids, chloride solutions and generally solutions which contain halogens). However, it is an expensive metal and its quality can vary from supplier to supplier. Additionally, special skills are required for constructing large volume tanks.

In a case study that took place for a 37,000 DWT double hull chemical tanker, both options (stainless and mild-coated steel) were analyzed and compared. The vessel was assumed to carry methanol for 275 days per year, when at the same time the assumed interest over 20 years to be 6% and the operating cost for the both situations to be the same.

The survey initially shown that the tanker with stainless steel tanks would cost 75 million US$, almost the double than the one with coated mild steel tanks. All other parameters were estimated and are presented in Figure 5.21.



37,000dwt double hull chemical tanker	***Stainless Steel Tanks 75M$***	***Coated Mild Steel Tanks 30.5M$***
Daily amortization operation 275days/year	23,433 $	11,810 $
Operating Cost/day	6,162$	6,162$
Total Cost/day	29,595$	17,972$
Revenue/day for methanol and 0.69$/dwt	25,530$	25,530$
Profit or (Loss)/day	(4,065$)	7,558$

Figure 5.21 – Economic comparison of steels

What is indicated, is that in order to make profit, the stainless steel vessel should be hired at an increased rate of 1.09 USD/DWT/day. Therefore, the selection of the most appropriate cargo tank construction material, is significantly affected by the condition of the market at that time, or more specifically, by the prediction for the condition of the market at the lifetime period of the vessel.

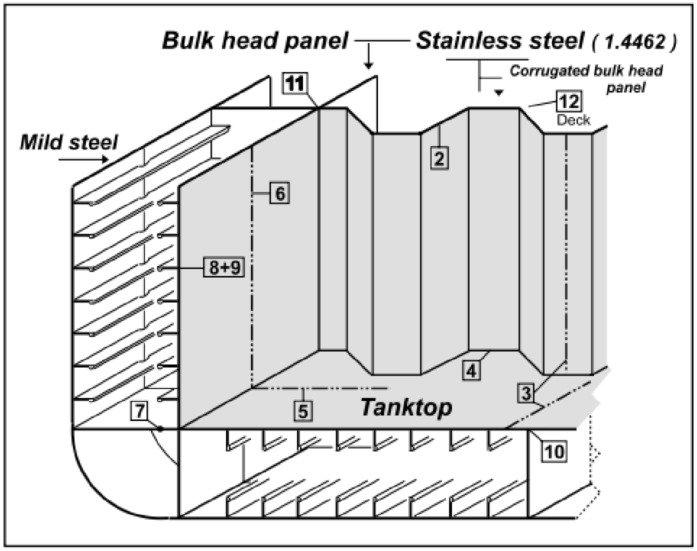


Figure 5.22 – Schematic cross section of a chemical tanker

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Chapter 6

Structural Configuration of Chemical Tankers

6.1 Introduction

The scope of this chapter is to explain and analyze the structural configuration of typical chemical tankers and of their structural components. For easier comprehension, several drawings of actual vessel constructions are included.

Before the analysis of the structural configuration takes place, some general design characteristics of the hull form of chemical tankers are presented, such as the typical block coefficient range and the common stem and stern arrangements. Furthermore, the effect on the design, of the specific gravity and the temperature of the cargo, and of the potential loading conditions, are mentioned.

Then, the structural configuration of the cargo tanks is explained, and the types of cargo tanks a chemical tanker may have are presented. Scantling methods and calculations as per classification societies for each tank type are also given. Additionally, special reference is been made to the saddle supports of the independent cargo tanks.

Subsequently, the structural configuration of the deck structure and the transverse and longitudinal bulkheads is analyzed. The analysis focus on corrugated bulkheads as this is the most common type used in chemical tankers. Design parameters of corrugated bulkheads and their effect in the design, types of corrugated bulkheads, scantlings, and other notes on the design are all included in this chapter.

Finally, a brief reference to the double hull and double bottom construction is been made.

6.2 General

The structural configuration and arrangements of chemical tankers are often similar to those of oil tankers. For existing chemical tankers arrangements may include a double bottom in way of cargo tanks, a double skin construction, or deck cofferdams or any combination of these. Certain more hazardous cargoes may also require tanks which are separate from the hull structure or are to be so installed that the tank structure is not subject to major hull stresses. In the latter cases the scantlings and arrangements may be similar to ships carrying liquefied gases.[1]

Like other modern tankers, chemical tankers are double hulled and longitudinally framed in way of the cargo area. The uniformity and continuity of the structure is maintained whenever possible. Generic guidelines for the local structural elements of double hull structures are followed when developing the structural design. Special attention is to be paid to design details in high stress areas. Fatigue life must be carefully considered because of the long design life of chemical tankers and the potential ramifications of cargo leaking from structures in the vessel's structure.

6.3 Hull form

The service speed of chemical tankers typically falls between 12 and 16 knots. This speed range, which is function of the markets governing economics, allows for the use of full hull forms similar to product tankers. Concern for ballast condition speed is minimal as chemical tankers rarely sail in ballast condition for long distances. Block coefficients for chemical tankers range from 0.80 to 0.85 with some smaller ocean-going vessels having finer hull forms with block coefficients below 0.80. Chemical tankers typically employ bulbous bows and trapezoidal sterns. Model tests and CFD analysis are employed when developing new chemical tanker hull forms.

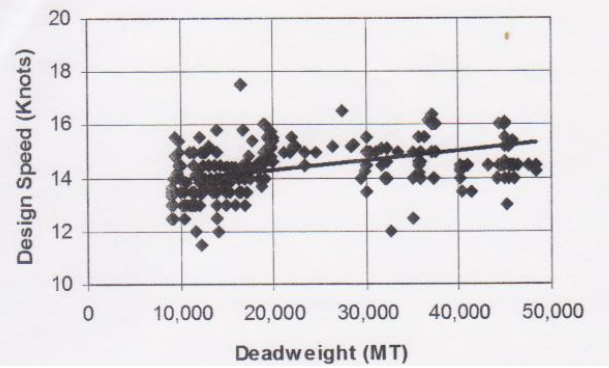


Figure 6.1

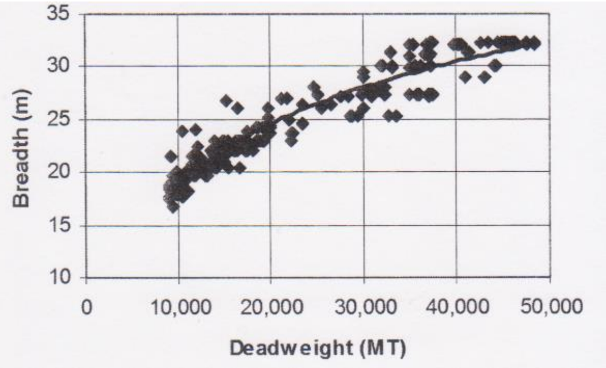


Figure 6.4

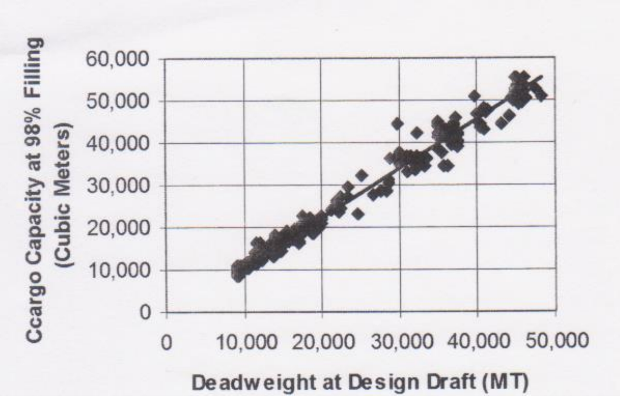


Figure 6.2

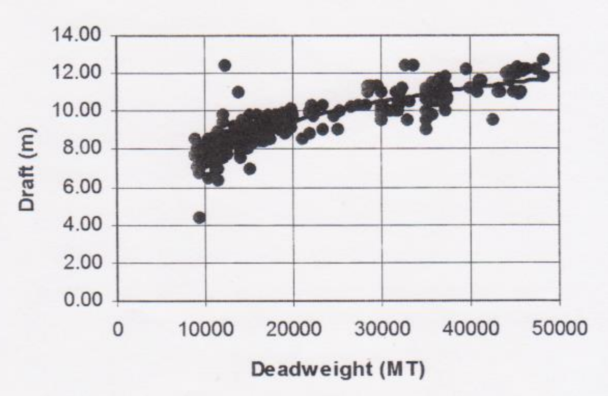


Figure 6.5

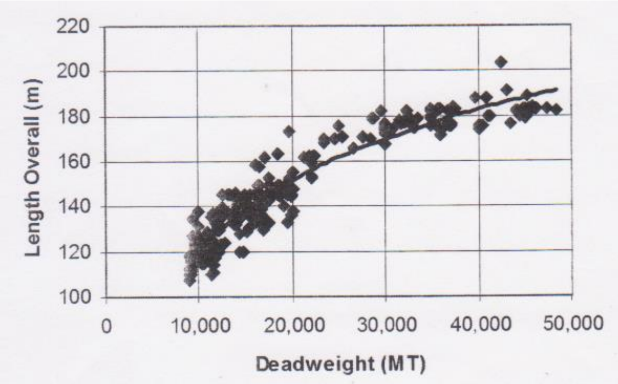


Figure 6.3

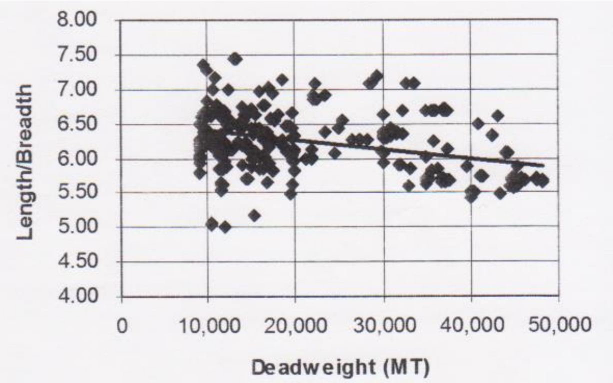


Figure 6.6

Figures 6.1 to 6.6 were developed from an analysis of approximate 500 chemical tankers ranging between 9000 and 50000 tons DWT that were constructed after 1990. Figure 6.1 clearly shows the speed range of 12 to 16 knots with large vessels tending to have higher service speeds.

Figure 6.2 illustrates the relationship between vessel deadweight and cubic capacity. The graph indicates that cubic capacity in cubic meters is greater than deadweight in metric tons. This relationship results from the majority of cargoes having a specific gravity less than 1.0. The data sampled had an average cubic to deadweight ratio of 1.13 with a minimum ratio of 0.92 and a maximum ratio of 1.48 with the larger vessels tending to have higher cubic to deadweight ratios.

Figures 6.2 through 6.5 show the relationships between deadweight and length, breadth, and draft. There are two definitive break points for the breadth of chemical tankers. The first break point is at approximately 23m, which is the maximum beam permitted in the St. Lawrence Seaway. The second breakpoint is at 32.3m, which is the beam restriction of the Panama Canal.

The graph of draft versus deadweight also reveals two breakpoints. The first is at 10m, which is related to the limiting drafts in both the United States Gulf of Mexico ports and ports in the Far East. The second break point is at approximately 12.25 m. Figure 6.6 shows that the length to beam ratio typically fall between 5.50 and 7.0.[2]

6.4 Hull structure

As it can be found in *Ship Design & Construction, Volume* 2 and in *Chemical Tankers: The quiet evolution*[3], the design of a chemical's tanker hull structure follows conventional practice but in way of the cargo tanks is complicated by the variability in the physical properties and carriage requirements of the cargoes to be carried and the numerous possible loading conditions. The design and analysis is also made more complex by the desire to have all cargo tank boundaries free of structural elements. The use of corrugated bulkheads in both longitudinal and transverse directions requires special attention in the design phase to avoid structural problems when the vessel is in operation. Adding to the scope of the analysis is the issue of mils steel, high strength steel, and stainless steel structural elements in the same design. Because of the complex nature of the analysis the naval architect must utilize finite element modeling techniques to properly evaluate the structural design.

The cargo characteristics that affect the structural design include the specific gravity of the cargo, the vapor pressure, and cargo temperature. Of these cargo characteristics the most important to the structural analysis are the cargo's specific gravity and cargo temperature. The impact of the cargo's vapor pressure is less pronounced because of the protection provided by the vessel's pressure vacuum (pv) valves and the tank pressure monitoring system. The importance of the cargo's temperature is related to the development of thermal stresses and the temperatures effect on the material properties of the structural members.

6.4.1 Cargo specific gravity

The specific gravity of a cargo dictates the hydrostatic loads that it will place on the structure of a cargo tank. The naval architect's dilemma when designing the structure of a chemical tanker is which specific gravity to use. Chemical cargoes currently being transported on ships have specific gravities ranging from below 0.7 to over 2.0.

The influence of specific gravity is well understood. It increases the pressure on cargo tank boundaries and may also increase the concentration of loading in the cargo tank area, thus affecting local scantlings, longitudinal hull bending moments and shear forces. Regulatory bodies may require that the water-test head be increased (to represent the actual cargo pressure plus a safety margin) and, for smaller ships, the tank test criteria can control local scantlings.

The design specific gravity is dependent on the trade in which the shipowner intends to employ the vessel. Designing the structure of a vessel to carry cargoes with highest specific gravity when the vessel will never be used in a trade where the highest density are carried will result in an unnecessary increase in acquisition costs and a reduction in the vessels deadweight because of the excessive structural weight. The selection of the design specific gravity must also take into account the range of cargoes that the vessels arrangements, cargo systems, and safety systems can support. The structural design affects the range of cargoes that a vessel can carry and the amount of operational flexibility incorporated in the design. Thus the design specific gravity cannot be selected without consideration for the vessel's design as a whole.

Partial filling of a cargo tank combined with the motions of the vessel results in cargo sloshing in the tank. The dynamic loads that result from the sloshing of cargo can be very large with their magnitude being dependent on several factors including the severity of the ship motions, the geometry of the tank, and the specific gravity of the cargo. The absence of structural members in the cargo tanks contributes to the sloshing problem, as structural members in tanks tend to damp the sloshing. To properly design the vessels structure, the dynamic loads caused by sloshing must be quantified and incorporated into the design process and analysis. The nature of ship's motions result in the dynamic sloshing loads being greatest on deck tanks. In the case of a deck tank, these loads affect both the strength of the tank and the structural arrangements that secure the tank to the deck.

In some instances the dynamic loads caused by cargo sloshing can be significantly large in certain loading conditions. Rather than designing the structure to withstand these forces, the designer has the option of placing limitations to the on the vessel operations. Sloshing curves can be developed for cargo tanks that communicate these limitations. The sloshing curves indicate the ranges of tank filling where the dynamic loads would be excessive for a given cargo specific gravity. For example a tank structure may be designed for a maximum specific gravity of 1.5 at 100% of capacity. However, because of the dynamic loads caused by the sloshing of the cargo, the sloshing curves may dictate that a cargo with a specific gravity of 1.5 cannot be carried in the tank at filling levels between 45 and 85% of capacity. The sloshing curves may also be used to provide guidance for partial loading of a tank wing cargoes whose specific gravities greater than the design limit.

The specific gravity which the vessel is designed for and the manner in which the dynamic loads will be addressed will greatly impact the operational flexibility of the vessel. The greater the design specific gravity and the fewer filling restrictions placed on the loading of cargo tanks, the higher the operational flexibility of the vessel. This flexibility comes at a cost of greater steel weight and increased acquisition costs.

6.4.2 Cargo temperature

Where cargoes are to be carried at a high temperature, the resultant thermal stresses may make it necessary to limit the hull bending moment so that an acceptable total stress is not exceeded. The temperature range of cargoes transported aboard a chemical tanker can be significant. Some specialized waxes must be heated to a temperature above 90°C while other cargoes may have to be cooled during transit. Ballast water adjacent to cargo tanks may be near 0°C in the North Atlantic during the winter months. The greater the temperature differential between structural components, the greater the magnitude of thermal stresses incurred by the structure. The thermal stresses will be related to temperature of the steel and are also proportional to the expansion which would have occurred without constraints. Differential expansion can impose a hogging bending moment on a ship's hull and the resultant stresses can be algebraically additional to those which are due to cargo weight and buoyancy loading. The constraints which contribute towards thermal stresses can be reduced by adopting transverse framing at ship side and longitudinal bulkhead, in preference to longitudinal framing, but these arrangements are only practicable for small ships.

The development of significant thermal stresses is also exacerbated by the use of both stainless and mild steel structural components, as the thermal expansion of some stainless steel is significantly greater than mild steel. These thermal stresses must be accounted for in the design and analysis of the vessels structure.

Elevated temperatures also impact the mechanical properties of structural materials. For example the maximum design stress for 2205 duplex stainless steel is reduced by over 20% when it's raised from room temperature to 100°C. This degradation of mechanical properties caused by high cargo temperatures must be taken into account when designing and analyzing the structure.

Because of the effects of elevated cargo temperature on the vessel's structures operational restrictions may have to be placed on a vessel in terms of the combination of high cargo temperatures and high specific gravity. For example, a tank designed for a maximum cargo specific gravity of 1.85 may be limited to a maximum cargo specific gravity of 1.5 when cargo temperatures exceed 60°C.

Other factors influencing the thermal stresses are the heating arrangements and the cargo viscosity. For example, if the cargo is heated through ducts integral with the inner bottom, the temperature of the structure in this area will be higher than the cargo temperature, a situation which cannot arise when separate heating coils are used. Cargoes such as bitumen at temperatures about 150°C without being unduly concerned about thermal stresses, provided the heat source is not adjacent to the steel structure. Where very high temperatures are contemplated for cargoes which remain entirely fluid, independent tanks are required.

6.4.3 Loading Conditions

The nature of the chemical tanker trade and the range of different cargoes carried by these vessels produce a wide range of loading conditions in which a chemical tanker may be expected to operate. During any leg of a voyage, a chemical tanker is likely to sail with some cargo tanks full, while others are partially filled, and others are completely empty. Ballast may be loaded in any of a number of ballast tanks to achieve a desired trim or heel condition. The cargoes and their properties can vary from one cargo tank to the next. All of these variables can change from voyage to voyage creating different loading conditions. A vessel's operational flexibility is tied directly to the range of loading conditions that's its structural design can accommodate. In order to provide the level of operational flexibility required in the intended trade the naval architect needs to work with the shipowner to develop an appropriate range of loading conditions for which the structure is to be designed. If the loading range is made excessively large the vessel's structure will be over-designed leading to excess steel weight and higher vessel acquisition costs. Alternatively, if the loading range is too narrow then the operational flexibility will be limited.

To allow for the structural design to be developed and analyzed the range of loading conditions must be reduced to a manageable number of worst-case load conditions. These worst-case conditions must take into account all of the cargoes that the vessel is designed to carry. Once the worst-case loading conditions are established the structure can be designed to meet the demands placed on it by this limited number of worst-case conditions. If the range of loading conditions is not well-defined before the structure is designed, it may not permit the vessel to meet the commercial needs of the shipowner. Therefore, an early definition of the loading conditions is crucial.

After the vessel is designed, the issue of loading conditions ceases to be a design issue and becomes an operational issue. To ensure that the vessel is never operated beyond the designed range of loading conditions, a chemical tanker must be outfitted with a loading manual and a loading computer that can be used by the cargo officer to evaluate planned loading arrangements. When evaluating a loading scenario, the cargo officer must evaluate the loading condition over the length of the voyage to ensure that at no time during the voyage will the structure be over stressed because of cargo stowage and operations.

6.5 Cargo tanks

6.5.1 General

The design of chemical tankers' cargo tanks is affected in a great way by the chemical cargoes they are about to carry. As described earlier in chapter 2, chemical cargoes are characterized by various chemical properties which are sometimes very significant to the product's behavior. In addition, chemical cargoes are hazardous cargoes that can pose a great threat to the people, the environment or the vessel itself, if not treated in a right way. For that reason, the cargo tank design of a chemical tanker is a very complicated issue in matters of structural design and configuration, materials and coatings that are to be used, and – most of all – cargo systems that shall be implemented in order to monitor and regulate the behavior of the cargo.

When two different chemical products come in contact, there is a possibility that they react in an unwanted and most probably dangerous way. For that reason, cargo tanks shall be properly cleaned so that all residues from the previous cargo are removed, before the new cargo is loaded. This removal would be greatly incommoded by the integral structural design of the tank, like stiffeners and girders. This leads cargo tanks in chemical tankers to be completely free of structural components, which are instead placed on the deck.

Figure 6.7 – Chemical tanker cargo tank

6.5.2 *Cargo tank types*

Chemical tankers may have different types of cargo tanks, depending on the cargo each tank will contain. There are three types of cargo tanks which are described in the IBC Code[4] as follows:

1. Independent – Gravity (1G)
2. Independent – Pressure (1P)
3. Integral – Gravity (2G)

Independent tanks are cargo-containment envelopes which are not contiguous with, or part of, the hull structure. An independent tank is built and installed so as to eliminate whenever possible (or in any event to minimize) its stressing as a result of stressing or motion of the adjacent hull structure. An independent tank is not essential to the structural completeness of the ship's hull. On chemical tankers, independent tanks typically taking the form of deck tanks.

On the other hand, the boundaries of an integral tank are formed by the hull structure and the subdivisions of the hull in the cargo area. Integral tanks are parts of the ship's hull and may be stressed in the same manner and by the same loads which the contiguous hull structure is stressed. As part of the hull, the integral tanks contribute to the structural completeness of the ship's hull.

Gravity tanks are designed for a maximum pressure of 0.7 bar gauge at the top of the tank and can be both of integral or independent type. On the other hand, pressure tanks are designed for pressure greater than 0.7 bar gauge and can only be independent tanks.

Integral tanks – and more specifically integral gravity tanks - are most commonly used in chemical tanker vessels, rather than independent tanks, as they are capable of carrying the majority of the cargoes covered by the IBC code. Pressure tanks are less commonly used and they are more commonly found in other types of vessels. There is no such type as pressure integral tank.

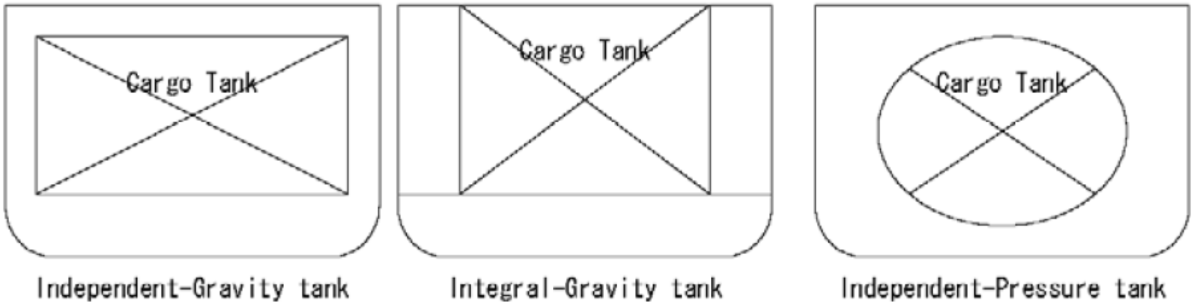


Figure 6.8 – Chemical tanker cargo tank

6.5.3 *Structural configuration of cargo tanks*

The structural configuration of the cargo tanks in a chemical tanker, differs depending on the tank type. As there are no specific structural rules for chemical tankers, their structural design follows the methods used in other vessels' type design and more specifically in the oil tankers and the LNG. Integral tanks resemble to the oil and product carriers' tanks, when independent pressure tanks follow the rules used for the Liquefied Gas Carrier tanks structural design. For the independent gravity tanks the design is simplified, as the loads are easy to be analyzed and lead to the respective scantlings.

6.5.3.1 Gravity tanks scantlings

As given by DNV[5], for integral tanks the thickness requirement for plates exposed to lateral pressures, is given as follows:

$$t = \frac{15.8\, k_a\, s \sqrt{p}}{\sqrt{\sigma f_1}} + t_k \quad \text{(mm)}$$

$$t_{min} = t_0 + \frac{kL}{\sqrt{f_1}} + t_k \quad \text{(mm)}$$

ka = correction factor for aspect ratio of plate field
= (1.1 – 0.25 s/*l*)2
= maximum 1.0 for s/*l* = 0.4
= minimum 0.72 for s/*l* = 1.0
s = stiffener spacing in m
p = maximum lateral pressure in kN/m^2
σ = allowable local stress in N/mm^2 for mild steel
t_0, k, f1 = as given in relevant chapters of the rules
t_k = corrosion addition

For independent tanks the thickness requirements are given as per below:

$$t = \frac{C\, k_a\, s \sqrt{p}}{\sqrt{\sigma}} + t_k \quad \text{(mm)}$$

C = factor depending on boundary conditions of plate field, normally taken as 15.8 for panels with equally spaced stiffeners.

ka = correction factor for aspect ratio of plate field
= (1.1 – 0.25 s/ l)2
= maximum 1.0 for s/ l = 0.4
= minimum 0.72 for s/ l = 1.0
s = stiffener spacing in m.
l = stiffener span in m.
p = design lateral pressure in kN/m^2.

For stiffeners exposed to lateral pressure, the section modulus requirement is generally given as function of bending moments and nominal allowable bending stress as follows:

$$Z = \frac{1000\, l^2 s\, p\, w_k}{m\, \sigma f_1} \qquad (cm^3)$$

p = lateral pressure in kN/m^2
l = length of the member in m
s = spacing in m
m = bending moment factor
w_k = section modulus corrosion factor in tanks as given in the rules
σ = allowable stress in N/mm^2 for mild steel
f1 = material factor

6.5.3.2 Pressure tanks scantlings

The design of an independent pressure tank is a more complicated issue than this of a gravity tank, as there are much more complex systems with much more parameters that need to be taken into consideration. The DNV[6,7] proposes[8] that the rules and design procedures that are used for independent pressure tanks' design of Liquefied Gas Carriers shall also be used for the design of same tanks in chemical tankers.

The pressure tanks are usually of cylindrical or spherical type. During their design and scantling calculations, special attention shall be given to the tanks' ends, as the welded parts and joints placed in that area are the most dreadful parts to be cracked or damaged due to the extreme internal pressure of the tank. Pressure tanks in chemical tankers are most commonly made of stainless steel. The minimum nominal thickness for tank shells made of stainless steel as per DNV is 3mm.

For cylindrical shells, their thickness should not be less than:

$$t = \frac{pR}{10\sigma_t e - 0.5p} + c \quad (mm)$$

For spherical shells, their thickness should not be less than:

$$t = \frac{pR}{20\sigma_t e - 0.5p} + c \quad (mm)$$

R = inside radius of shell or shell section
e = joint efficiency taking values between 0.6-1.0 depending on vessel's type.

For cylindrical shells, their thickness should not be less than:

$$t = \frac{pD_C}{20\sigma_t e - 0.5p} \frac{1}{\cos\alpha} + c \quad (mm)$$

D_C = internal diameter at the large end of the cone
a = the half apex angle of the section

The calculating pressure p, which is the pressure used for the purpose of determining the thickness of the vessel section or component under consideration, is normally to be taken as the design pressure with additional pressure due to static head of the fluid exceeding 3% of the design pressure. The calculating pressure, p, is the greater of:

$$p_d \text{ and } p_d + \left(\frac{\rho g_0 h}{100} - 0.03p_d\right)$$

r = density of fluid in t/m3
g0 = standard acceleration of gravity = 9.81 m/s^2
h = vertical distance from load point to top of pressure vessel in m.

In special cases, the calculations are also to be carried out with a calculating pressure taking dynamic loads due to the ship's motions from wave actions into account. The calculating pressure shall be:

$$p = p_d + \left[\frac{\rho g_0 h}{100}\left(1 + \frac{a_v}{g_0}\right) - 0.03p_d\right]$$

av = the most probable largest combined vertical acceleration in 10^8 wave encounters (probability level Q = 10^{-8}).

The nominal design stress σ_t for stainless steel is defined as the lowest of:

$$\frac{R_{p1,0}}{1.5} \text{ and } \frac{R_m}{2.7}$$

where the $R_{p1,0}$ and R_m are given for different grades of rolled steel as per below:

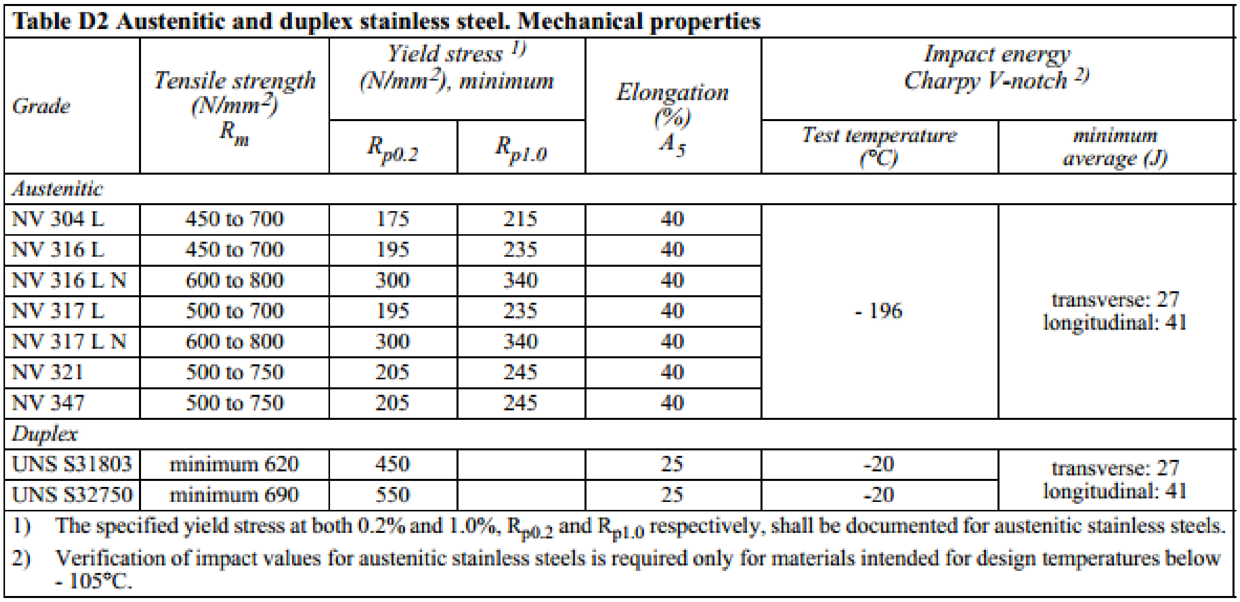


Table D2 Austenitic and duplex stainless steel. Mechanical properties

Grade	*Tensile strength (N/mm^2) R_m*	*Yield stress [1] (N/mm^2), minimum*		*Elongation (%) A_5*	*Impact energy Charpy V-notch [2]*	
		$R_{p0.2}$	*$R_{p1.0}$*		*Test temperature (°C)*	*minimum average (J)*
Austenitic						
NV 304 L	450 to 700	175	215	40	- 196	transverse: 27 longitudinal: 41
NV 316 L	450 to 700	195	235	40		
NV 316 L N	600 to 800	300	340	40		
NV 317 L	500 to 700	195	235	40		
NV 317 L N	600 to 800	300	340	40		
NV 321	500 to 750	205	245	40		
NV 347	500 to 750	205	245	40		
Duplex						
UNS S31803	minimum 620	450		25	-20	transverse: 27 longitudinal: 41
UNS S32750	minimum 690	550		25	-20	

1) The specified yield stress at both 0.2% and 1.0%, $R_{p0.2}$ and $R_{p1.0}$ respectively, shall be documented for austenitic stainless steels.

2) Verification of impact values for austenitic stainless steels is required only for materials intended for design temperatures below - 105°C.

The thickness of the large end of a cone/cylinder or cone/cone junction and adjoining parts of the shells within a distance L from the junction shall be determined by the following formula:

$$t = \frac{pD_0k}{20\sigma_t e} + c + c_1 \quad \text{(mm)}$$

Do = outside diameter of the conical section, see Figure 5.9

e = joint efficiency of junction or of circumferential welds located within a distance L from the knuckle

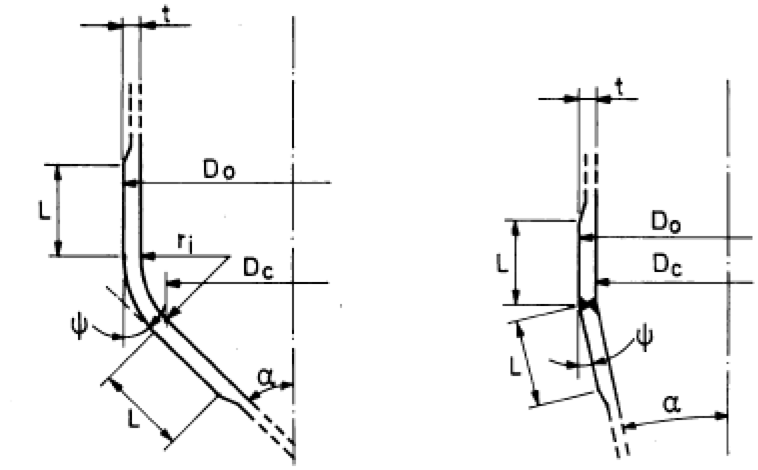
L = length equal to:

$$0,5\sqrt{\frac{D_0(t-c)}{\cos\psi}} \quad \text{(mm)}$$

c1 = 0 for t - c/Do>= 0.005

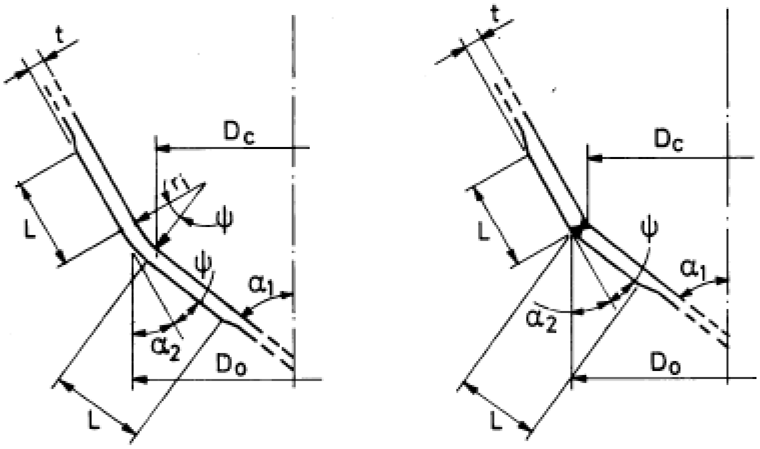
= 1 mm for t - c/Do < 0.005

k = a factor taking into account the stress in the junction.



(a) CONE/CYLINDER WITH KNUCKLE

(b) CONE/CYLINDER WITHOUT KNUCKLE



(c) CONE/CONE WITH KNUCKLE

(d) CONE/CONE WITHOUT KNUCKLE

Figure 6.9 – Junction arrangements

However, in any case the thickness of the junction or knuckle and the adjacent parts shall not be less than that for the cone determined previously.

Finally, the thickness of dished ends without stays, concave to the pressure side, shall not be less than:

$$t = \frac{pD_0}{20\sigma_t e}K + c \quad \text{(mm)}$$

However, the thickness t shall not be less than the thickness required for a seamless, un-pierced, cylindrical shell of the same diameter and material, except where the end plate is a complete hemisphere.

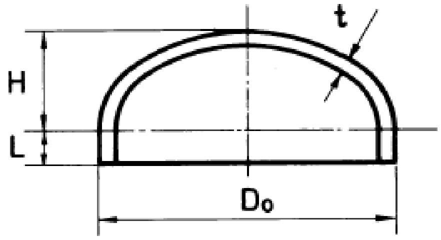


Figure 6.10 – Elliptical end

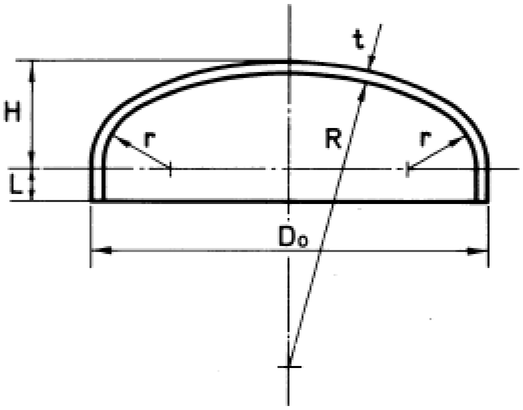


Figure 6.11 – Torispherical end

6.5.4 Cargo tank saddles

While the design of the pressure tanks is governed by a wide set of rules, the method of support is left pretty much up to the designer. The correct design of the supports is of major importance, as their contribution to the vessel's safe operations is significant. All the forces, stresses and moments that are applied to the cargo tanks due to the vessel's movement and acceleration are transferred from the ship's hull to the tank's shell through these structures. As a matter of fact, they need to withstand extended, and in some cases extreme, static and dynamic forces without failure.

Horizontally kept cylindrical pressure tanks are generally supported on twin saddle supports. When a cylindrical vessel acts as its own carrying beam across two symmetrically placed saddle supports, one-half of the total load will be carried by each support. This would be true even if one support should settle more than the other. This would also be true if a differential in temperature or if the axial restraint of the supports should cause the vessel acting as a beam to bow up or down at the center. This fact alone gives the two-support system preference over a multiple-support system.

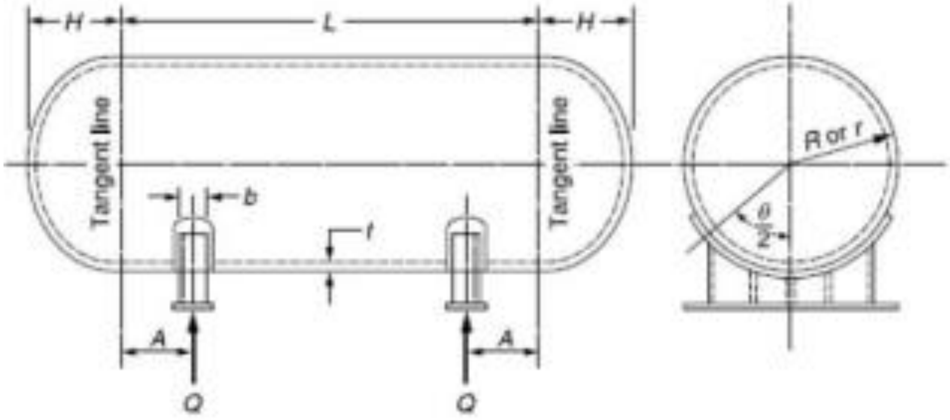


Figure 6.12 – Pressure tank and tank saddles

The contact angle and the saddle's width are two parameters that should be defined during the design process. The contact angle of each saddle should always be more than 120°, except in cases of very small tanks. In certain cases, a larger contact angle should be used. The impact of the saddle's width is not a controlling factor, so a nominal width of 12 inches is used for steel. This width however should be increased in case of extremely heavy tanks, and in certain cases it may be desirable to reduce this width for small tanks.

Another important parameter during the design of the supports is the location of the saddles. Thin-wall tanks of large diameter are best supported near the heads provided they can support their own weight and contents between supports and provided the heads are stiff enough to transfer the load to the saddles. Thick-wall tanks too long to act as simple beams are best supported where the maximum longitudinal bending stress in the shell at the saddles is nearly equal to the maximum longitudinal bending stress in the shell at the saddles is nearly equal to the maximum longitudinal bending stress at mid-span, provided the shell is stiff enough to resist this bending and to transfer the load to the saddles. Where the stiffness required is not available in the shell alone, ring stiffeners must be added at or near the saddles.

Another aspect that must always been taken into account during the design of cargo tank saddles is the high temperature of the pressurized cargo. The temperature of the tank during the vessel's operation is much higher than the temperature during its installation. This leads to a differential in displacement between the supports due to the temperature change that needs to be considered in design. In most of the cases, the design of support requires adequacy to operate in a severe thermal environment during normal operation as well as to sustain some thermal transients.

Usually saddles are welded to the outer periphery of the pressure tank. In a horizontal pressure tank with saddle support a high localized stress at the interface of the tank and saddle is generated. This highest localized stress is termed as circumferential stress whose intensity is very high at the horn part of the saddle and tank.

In some cases vessel and saddle support contact is of loose-fitting type. In this case there is a narrow gap or space between the saddle support and vessel, due to which it becomes very difficult for maintenance at that part which causes corrosion.

During the design procedure, and prior to their construction and implementation, cargo tank saddles are simulated via finite element methods and programs. These programs allow the designer to estimate the maximum loads that the saddles are about to suffer and to check which parts of the construction will be the most affected, and in that way to lead to the structural optimization of the construction. [9,10]

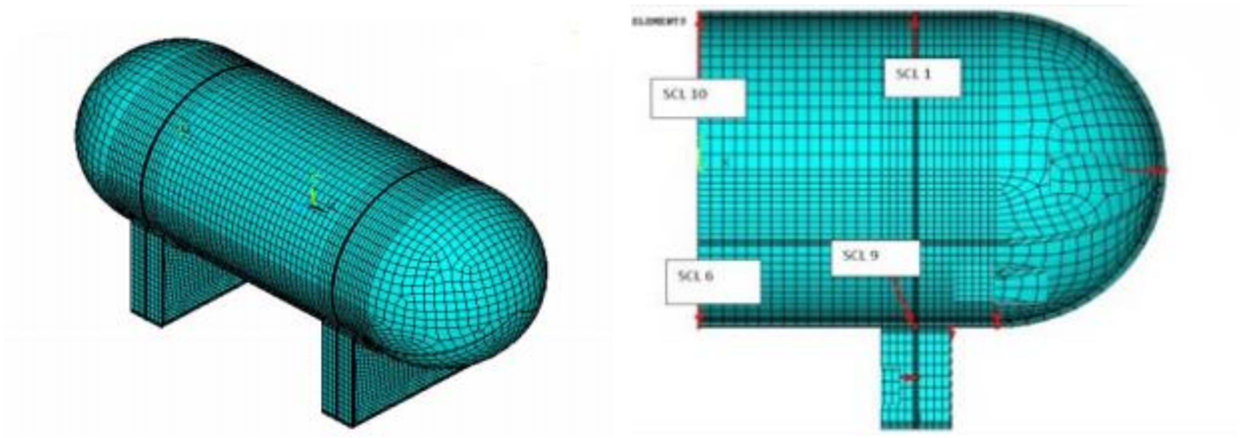


Figure 6.13 – Tank and saddles simulation

6.5.5 Testing of cargo tanks

After the construction of the tank, it is a mandatory requirement that all tank welds shall be tested for crack detection via non-destructive testing methods, such as ultrasonic or radiographic testing[11]. Most of the testing is to be placed at weld crossings and highly stressed connections, as there the possibility of crack formation is highly increased.

The testing shall be carried out to a specific portion of the weld's length which is different according to vessel's Ship type. Independent tanks are also checked more extensively than the integral tanks as they have more welding junctions.

As defined by DNV, testing for Ship type 1 and 2 vessels should be as below. For Ship type 3 vessels, the testing procedures that take place in Oil carriers shall be carried out.

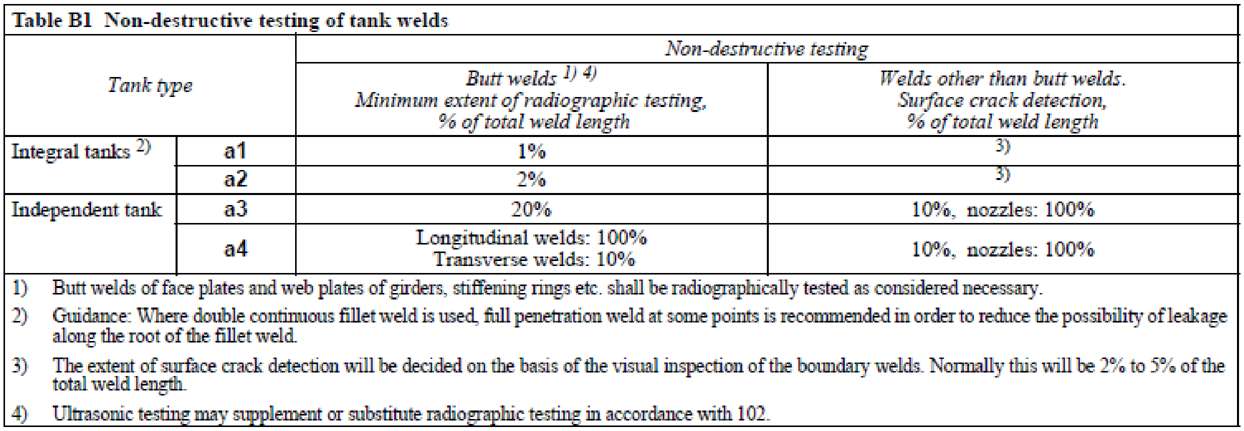


Table B1 Non-destructive testing of tank welds

Tank type		*Non-destructive testing*	
		Butt welds 1) 4) *Minimum extent of radiographic testing,* *% of total weld length*	*Welds other than butt welds.* *Surface crack detection,* *% of total weld length*
Integral tanks 2)	a1	1%	3)
	a2	2%	3)
Independent tank	a3	20%	10%, nozzles: 100%
	a4	Longitudinal welds: 100% Transverse welds: 10%	10%, nozzles: 100%

1) Butt welds of face plates and web plates of girders, stiffening rings etc. shall be radiographically tested as considered necessary.
2) Guidance: Where double continuous fillet weld is used, full penetration weld at some points is recommended in order to reduce the possibility of leakage along the root of the fillet weld.
3) The extent of surface crack detection will be decided on the basis of the visual inspection of the boundary welds. Normally this will be 2% to 5% of the total weld length.
4) Ultrasonic testing may supplement or substitute radiographic testing in accordance with 102.

Figure 6.14 – Non-destructive testing of tank welds

In addition to the non-destructive testing methods, each cargo tank may be tested separately when complete by filling the tank with water to a head 2.45 m above the highest point of the tank excluding the hatchways, and by filling the cofferdam to the top of the hatch. Water testing on the building berth or dry dock may be undesirable owing to the size of flooded tanks which gives rise to large stresses on the supporting material and structure. Testing afloat is therefore permitted, each tank being filled separately until about half the tanks are full when the bottom and lower side shell in the empty tanks are examined. Water is then transferred to the empty tanks, and the remainder of the bottom and side shell is inspected. This testing may take place after the application of protective coatings, provided that welds have been carefully examined beforehand.

6.6 Deck structure

As described in *Ship Design & Construction, Volume 2* [12], the deck structure of a chemical tanker varies depending on location. In way of the ballast tanks and forward and aft of the cargo area we find a conventional deck structure, resembling to other common types of commercial vessels, characterized by longitudinal framing with deck longitudinals and girders welded to the underside of the deck plating.

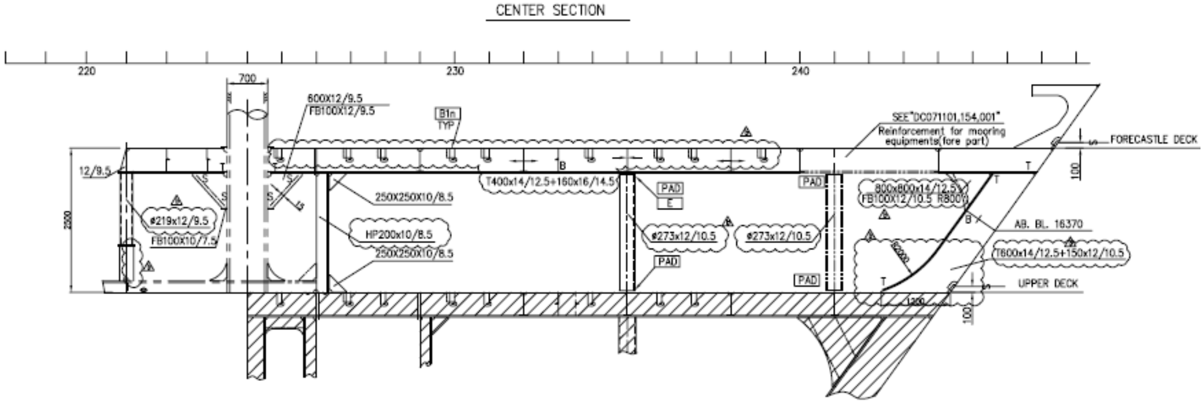


Figure 6.15 – Forecastle deck structure – profile view

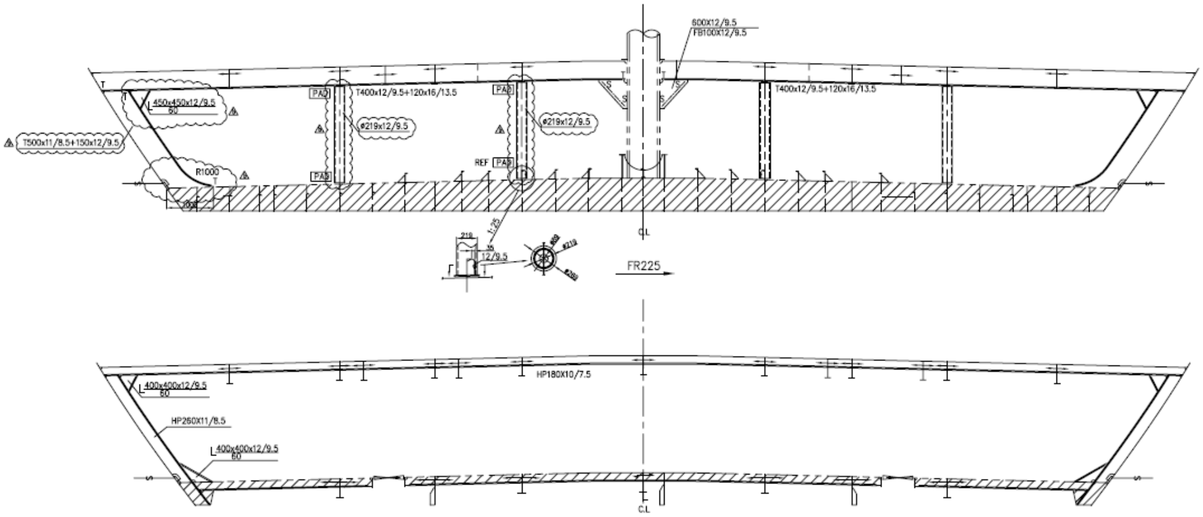


Figure 6.16 – Forecastle deck structure – section view

In way of the cargo tanks the deck structure is different. Due to the need to remove all structural components from the inside of the cargo tank boundaries in order to facilitate and accelerate the tank cleaning procedures of the loading – discharging cycle, all deck longitudinals and deck girders are placed on the top side of the deck plating. With this arrangement the web frames are also placed on the top of the deck plating in way of the cargo area. To maintain structural continuity it is important so that the framing on top of the deck plating lines up with the longitudinal and transverse bulkheads located below the deck plating.

An alternative to the extremely framed deck is the corrugated deck. This arrangement eliminates all deck longitudinals and girders in way of the cargo tanks by using transversely corrugated deck plating. The web framing still runs atop the deck plating in such an arrangement. This approach is not as common as the externally framed deck but has been used in smaller ocean-going chemical tankers.

One aspect that plays a significant role in the design of a chemical tanker's deck structure is the large amount of openings in the deck plating in way of the cargo area. The number of these openings in chemical takers is significantly greater compared to other cargo vessels, as each cargo tank has numerous deck openings as the main tank hatch, tank-cleaning hatches, penetrations for ullaging and sampling equipment, penetrations for temperature, level, and pressure sensing devices, and openings for cargo pumps and piping. These openings can greatly reduce the strength of the main deck structure and structural reinforcement such as doubler plates and local stiffening are provided. Furthermore, the openings should be staggered and elliptical n shape with their major axes in the longitudinal direction.

One means of strengthening the main deck is the addition of a deck trunk running along the main deck at the centerline, from the poop deck to the forecastle. The deck trunk is designed as a continuous structural member that adds to the hull's section modulus. The trunk acts as a shelter for the piping run along the deck, providing these components with protection from the elements and reducing routine maintenance tasks, such as painting and chipping deck piping. The top of the trunk serves the function of the catwalk providing unimpeded access to the bow and a location for the hose-handling crane and firefighting equipment. An enclosed space of this type is required to be mechanically ventilated in accordance with the IBC code, and also results in increased steel weight and acquisition costs.

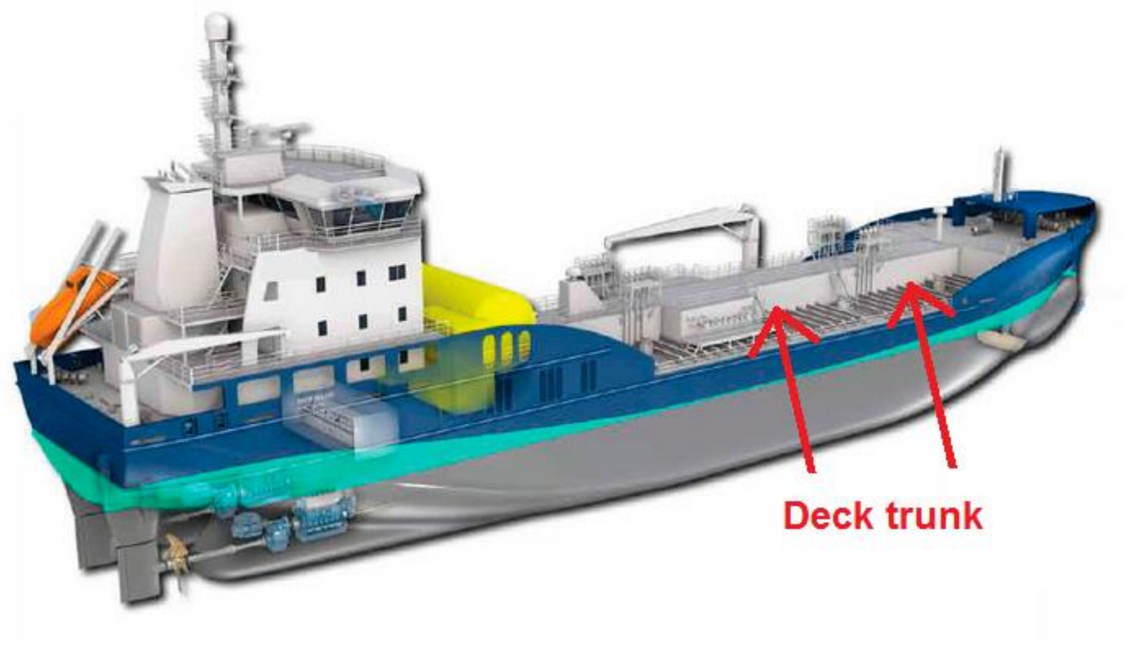


Figure 6.17 – Deck trunk on a chemical tanker

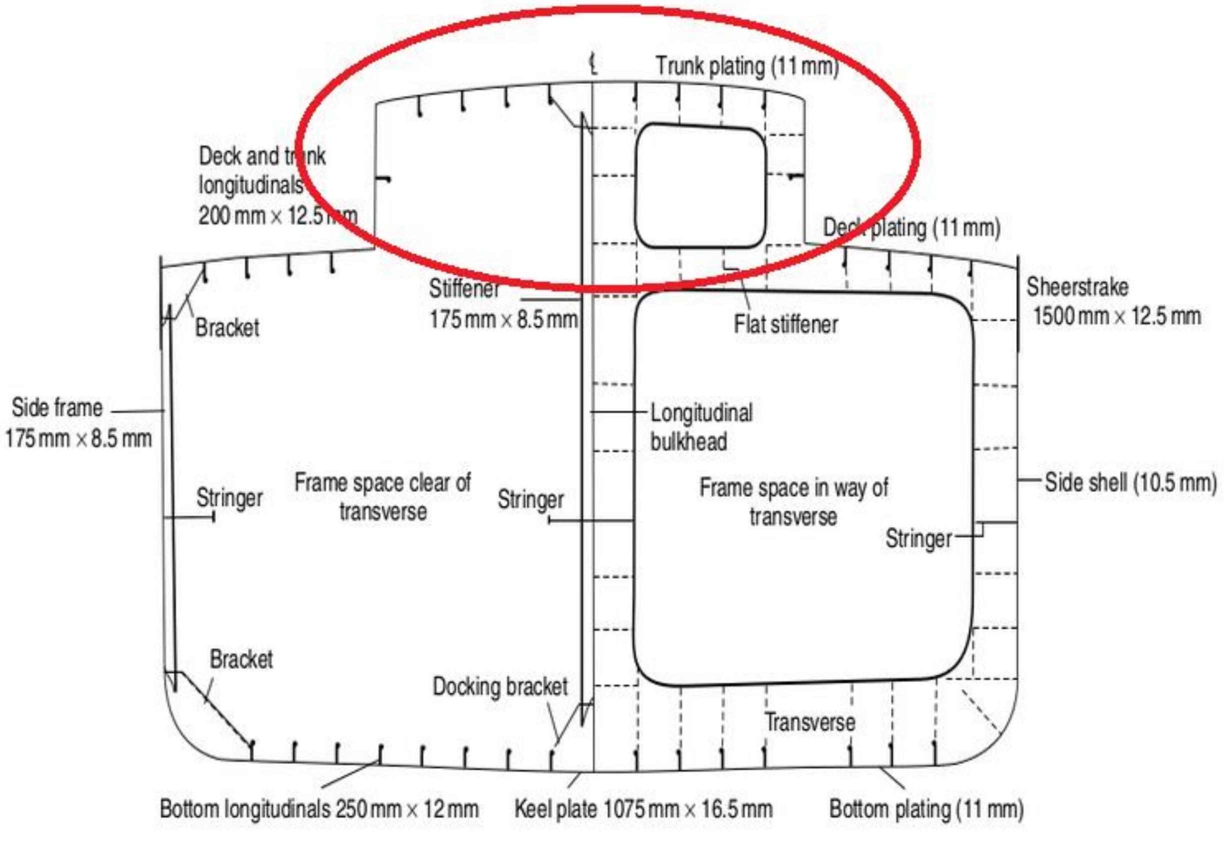


Figure 6.18 – Deck trunk midship view

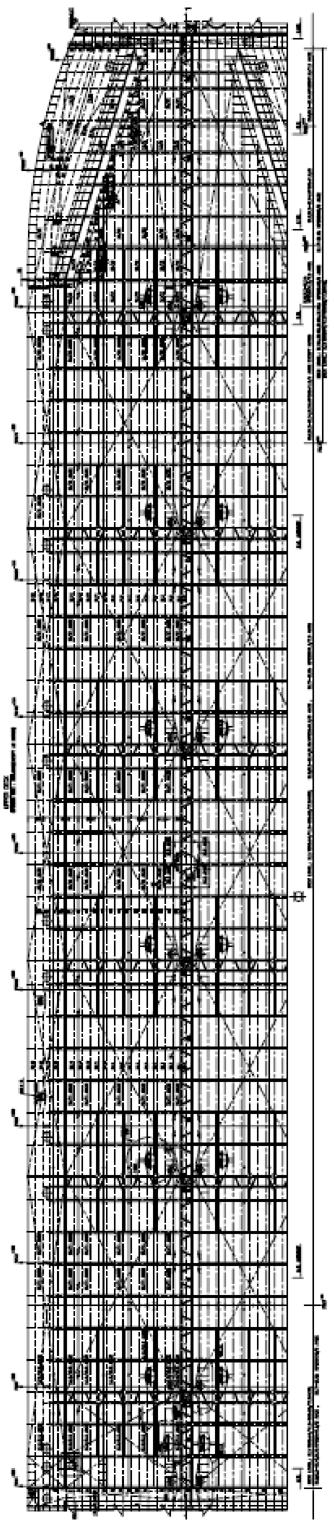


Figure 6.19(a)–Upper deck structure top view

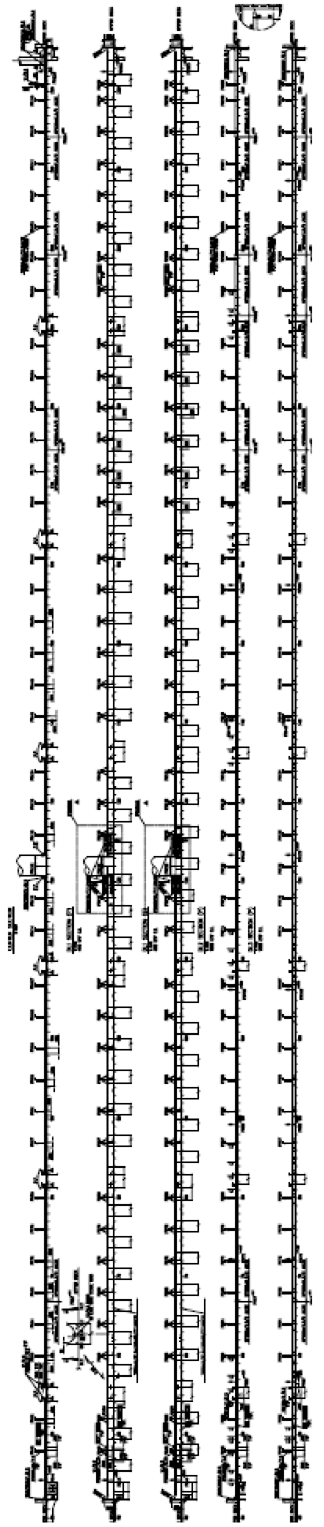


Figure 6.19(b)-Upper deck structure profile view

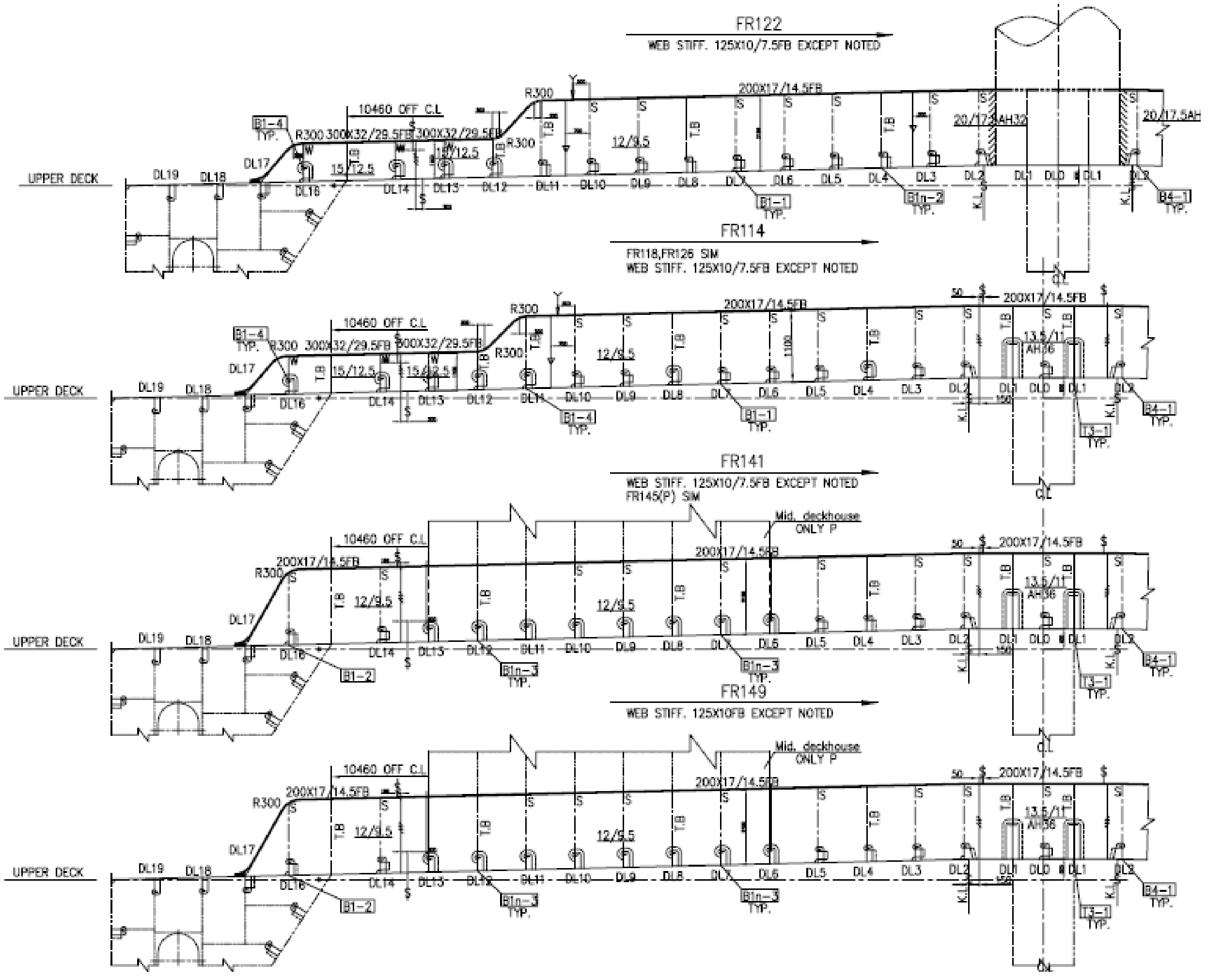


Figure 6.20 – Upper deck structure in C.O.T. area of a 16500DWT chemical tanker, transverse view in different sections

6.7 Bulkheads

6.7.1 General

Each and every cargo vessel is divided into spaces via vertical partitions arranged either transversely or longitudinally known as transverse and longitudinal bulkheads respectively. The function of bulkheads is mainly to divide the main hull into different compartments and to limit the extend of flooding, and hence of loss of buoyancy, in case of a damage to the external shell plating. However bulkheads in a vessel offer additional benefits, such as preventing spread of fire from one compartment to another, contributing to the longitudinal strength of the ship (longitudinal bulkheads) and preventing racking and torsional distortion on the vessel (transverse bulkhead).

Bulkheads are either watertight or non-watertight although such terms as oil tight and gas tight bulkheads have been also used. Transverse watertight bulkheads divide the main hull into many different watertight compartments. Watertight bulkheads are attached to the shell, the deck, and the bottom or tank top by welding. Non watertight bulkheads are any other types of bulkhead which are non watertight such as centerline wash bulkhead in the peak tanks, partial bulkheads in the accommodation spaces, stores and engine spaces.

The number of transverse bulkheads in a ship is dependent on the length of the ship. However all ships must have a collision or fore peak tank bulkhead, an aft peak tank bulkhead and a bulkhead at each end of the engine room.

6.7.2 Corrugated bulkheads

The selection of types of cargo tank bulkheads in the design stage of a commercial vessel depends on various considerations for ship's design. From the regulatory point of view, when a chemical tanker is designed to carry noxious liquid substances (NLS) under the IBC Code, the maximum quantity of residue permitted after unloading is strictly restricted. Moreover, the cargo tank surfaces must be of a suitable type for effective washing by means of rotary water jets so that the risk of marine pollution by the discharge of NLS after cargo tank washing can be minimized.

The above creates the need of a tank structure with as many plane surfaces as possible, and without any shadow areas where cargo can be stored and become difficult to remove by washing procedures. The conventional type of the plain bulkheads consisted of flat plates and strengthened with horizontal stiffeners is not suitable for that purpose, as the large web frames and stiffeners provided on the surface of the bulkhead easily become complicated shadow objects.

To solve this problem, corrugated bulkheads have been applied to chemical and product tankers to convert the cargo tank boundaries into more easily accessible plane surfaces. Such plane surfaces, of course, contribute to minimizing the amount of remaining cargo itself after unloading and also help facilitate easier coating and inspection of corrugated bulkheads as a result.

However it is not uncommon to find also plane stiffened bulkheads in a chemical tanker. Due to cargo segregation reasons, the use of a cofferdam between two cargo tanks is sometimes required. This cofferdam produces a plane bulkhead in each tank, as the stiffeners can be placed in the void side. Bulkheads in the ballast tanks are also of the plane type.

Corrugated bulkheads consist of welded or single corrugated plates and are stronger than flat plates without stiffeners if subjected to bending moments or pillar loads along the corrugations. In addition to the advantages they offer in tank cleaning, they are also preferred due to their lower mass, and therefore decreased steel weight, the fewer corrosion problems they face, and the simplified service and maintenance they need. Properly designed, constructed and maintained corrugated bulkhead structures can give many years of safe and satisfactory service. On the other hand the complexity of structural configuration and difficulties of manufacture can lead to significant defects occurring which may be costly to repair.

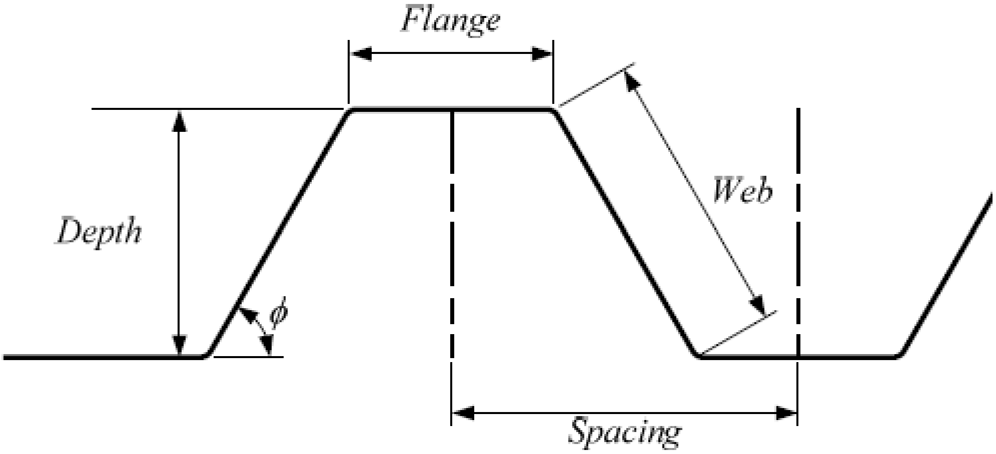


Figure 6.21 – Corrugation terminology

Corrugations can either be fabricated or cold formed (Figure 6.22). Fabricated corrugations are produced by welding web and flanges together. Cold-formed corrugations are produced from a single sheet of material and pressed into the corrugation shape by mechanical means.

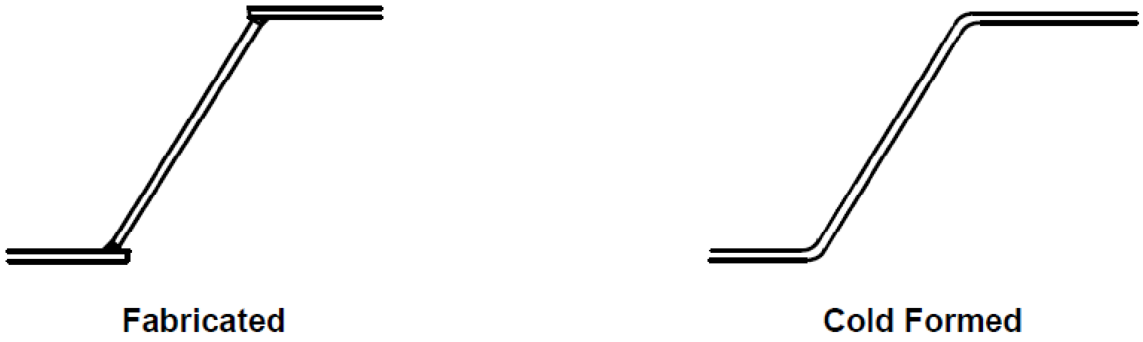


Figure 6.22 – Types of corrugation

Another type of bulkhead that is used in order to maintain cargo tanks free of structural elements is this of the double plate. Double plate bulkheads consist of two plane plates put in parallel, and a layer of a lighter and less strong material placed between them. Double plate, or sandwich, bulkheads however are less common than corrugated bulkheads as they consume valuable revenue-generating volume. The area between the two plates is also difficult to inspect and maintain. Furthermore, the space between the plates can collect dangerous cargo or cargo vapors because of leaks. Such leaks are difficult to detect.

6.7.3 Types of corrugated bulkheads

There are two main groups of categorization for corrugated bulkheads, based on the direction of the corrugations[13]: the horizontally corrugated bulkheads and the vertically corrugated bulkheads. Vertically corrugated bulkheads can be found without stools, with lower stools only, or with both lower and upper stools, depending on the size of the vessel. Both types of orientations can be used in either longitudinal or transverse bulkheads.

6.7.3.1 Vertically corrugated bulkheads

Vertically corrugated bulkheads take three basic forms as illustrated in Figure 6.23. Each configuration presents various challenges in ensuring continuity of strength and load transfer to surrounding structures.

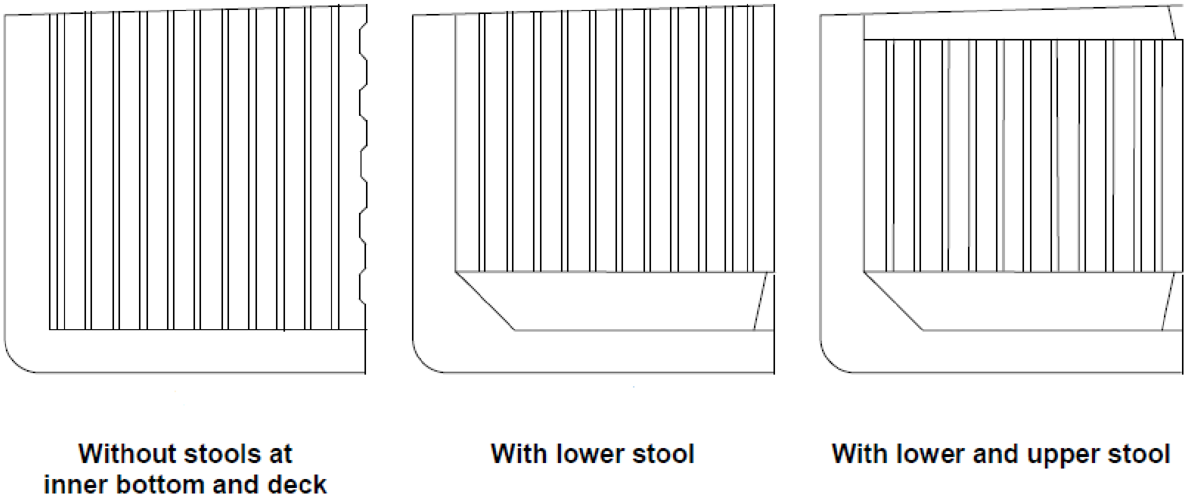


Figure 6.23 – Configurations of vertical corrugated bulkheads

Without stools at inner bottom and deck

This type of bulkhead is most commonly used in small chemical and product tankers not exceeding 40,000t DWT, and can only be used for vessels with moulded depth less than 16m, provided the requirements stipulated in the Common Structural Rules are complied with. Due to the absence of stools, the cargo tank volume is significantly increased. An additional advantage of non-stool bulkheads is that the gas freeing procedure of the tank becomes much simpler, as the risks associated with the formation of gas pockets in way of stools, shedder plates etc. is eliminated.

As there are not stools for the bulkhead to step and supported on it, support structure for the corrugation flanges is commonly provided under the inner bottom, by floors/girders fitted in the same plane as the flanges with load from the corrugation web transmitted through shear of the weld connection to the inner bottom, as can be seen in Figure 6.24. For highly stressed connections support of the corrugation webs below the inner bottom by means of aligned brackets/carlings may also be arranged.

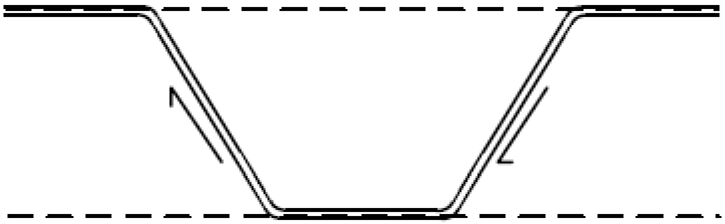


Figure 6.24 – Inner bottom support non-stool bulkheads

With support stools at inner bottom

For chemical tankers exceeding 40,000DWT vertical bulkheads are supported by lower stools. This means that the corrugated plate of the bulkhead does not meet directly the top barrier of the inner bottom, but steps on a fabricated stool, which is a box type structure as shown in Figure 6.25. The reason to place these stools is that due to large size of the vessel the span of the corrugations is increased, and so the design stresses may be exceeded. By supporting the bulkhead on the stool, the span is significantly reduced. Also, the loads are transferred in a more sufficient way via the stool construction to the surrounding structure. Finally, the stool provides appropriate shear and torsional rigidity to the lower end of the corrugation.

These stools may be of rectangular or non-rectangular cross section depending on the height of stool. The lower stool consists of shelf plate, side plates and internal web plates providing primary support for the stool boundaries. The shelf plate provides a foundation for the corrugation and facilitates load transfer from the corrugation web to the structure below through shear and also from the corrugation flanges to the stool side plates through transmission of out of plane stress.

The flanges of the corrugations are to be aligned with the side plating of the stools. For highly stressed connections support of the webs below the shelf plate by means of aligned brackets/carlings may also be arranged.

The side plates of the stool may be vertically or horizontally stiffened. Horizontal stiffening is convenient for longitudinal bulkhead stools as it provides more efficient buckling capacity to resist hull girder bending loads. Vertical stiffening is normally adopted for transverse bulkhead stools because of the simpler fabrication process, the better buckling strength and improved load transfer to the double bottom structure.

For strength or cleaning reasons, brackets or shedder plates may be arranged at the lower part of the corrugation. Special attention is to be made for the welds between those bracket and shedder plates with the bulkhead. In some cases the small volume created between the shelf plate and the shedder plate has been filled with a suitable compound compatible with the products carried by the vessel.

The stools are usually used as parts of the double bottom ballast tanks, or – less commonly – as void spaces. For that reason adequate access is required, as well as sufficient drainage and ventilation. As the size of the openings shall fulfil some minimum requirements as defined by the IBC code, special consideration must be given during the design procedure. One particular design issue is that the openings in the shelf plate leads to a substantial reduction in the local cross sectional area. This can be offset by an increase in the thickness of the local plate.

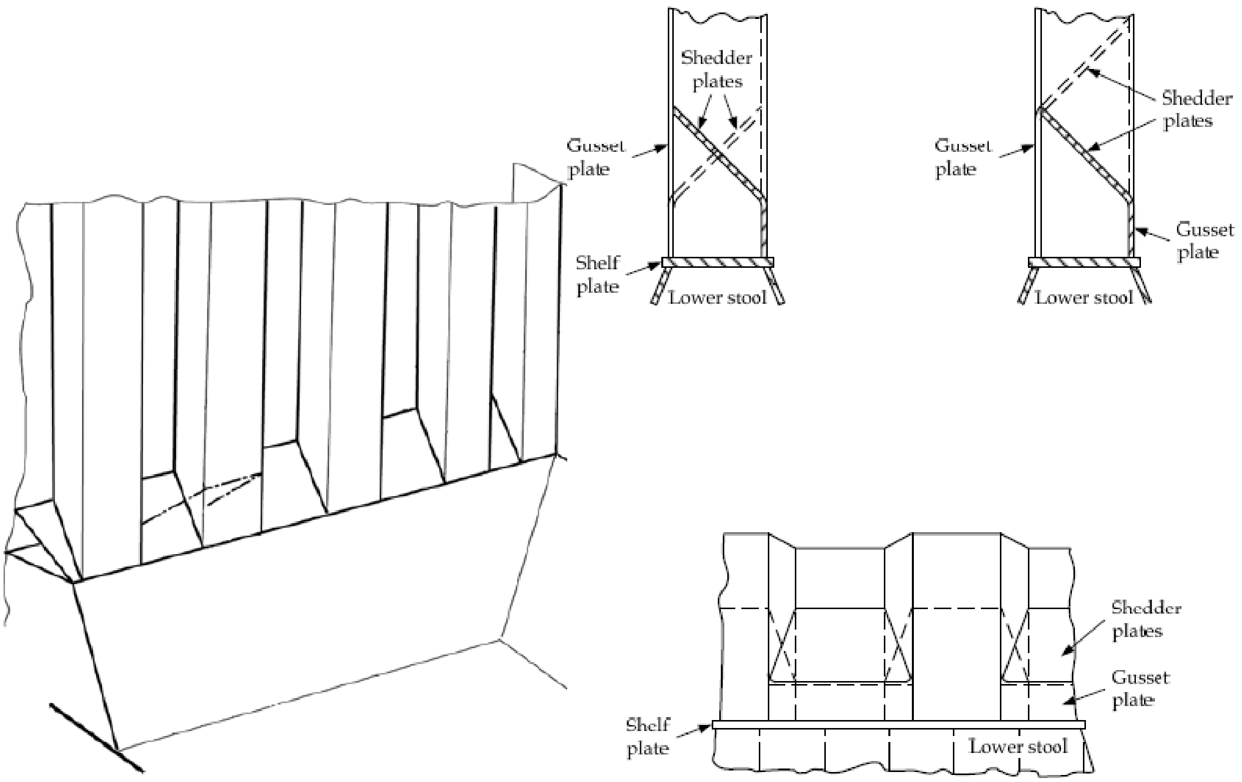


Figure 6.25 – Vertical corrugated bulkhead lower stool

Regarding the bulkhead – deck interface there are two main types of support structure used, which are the same both for non – stool bulkheads and bulkheads with lower stool.

In the first type, a rigid support consisted from girders or transverses is provided for the upper end of the corrugation. This structure is located above deck and must be aligned with the bulkhead beneath (Figure 6.26 (a)). On some of these designs, additional partial girder structure is incorporated to form a grillage structure in way of the bulkhead, with the aim to reduce relative deflection, between adjacent deck transverses (Figure 6.27).

In the second type, there is very limited additional support to the bulkhead above the main deck. This provides a relatively flexible support, thereby attracting less load (and therefore local stress) to the upper end of the corrugation but bigger deflection in rotation (Figure 6.26 (b)).

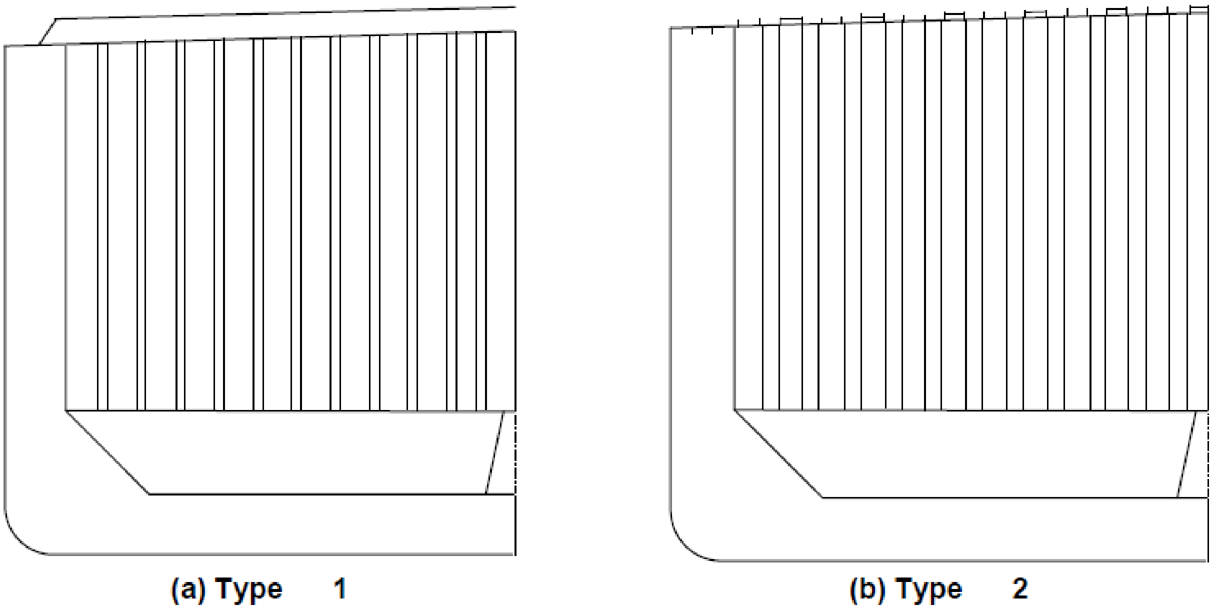


Figure 6.26 – Vertical corrugated bulkhead upper support

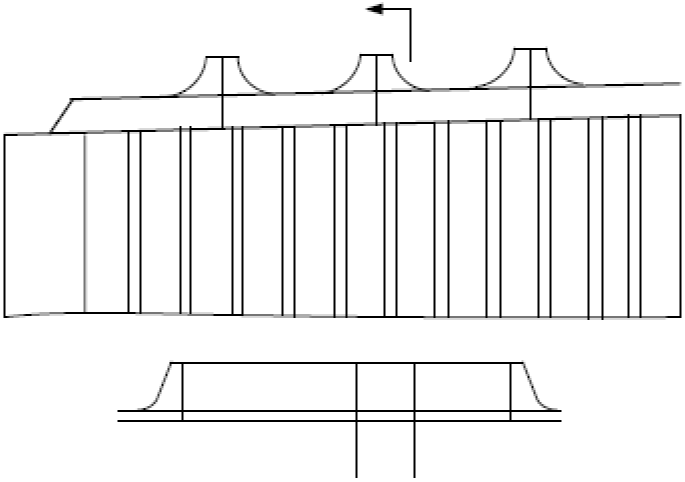


Figure 6.27 – Partial girder arrangement

With support stools at inner bottom and deck

For the same reasons that lower stools are used in vessels reaching the 40,000t DWT (reduce span of corrugations, provide appropriate shear and torsional rigidity, etc), a combination of upper and lower stools is been used for even bigger vessels reaching the Aframax size. However chemical tankers do not reach this size, so the use of this type of bulkheads is limited to the oil/product tankers and the bulk carriers.

6.7.3.2 Horizontally corrugated bulkheads

Unlike the vertical ones, horizontal corrugated bulkheads are of one type without any stools. However, and unless the span (breadth of tank) is too small, some form of symmetrical vertical primary supporting member is normally provided to give adequate shear rigidity for overall vessel strength and support for the corrugations when loaded on one side. Backing structure is also normally provided to support the corrugation flanges. For longer corrugation spans, this will take the form of substantial web structures, whilst for small spans, inter-costal stiffening may be sufficient. However, as this stiffening may incommode the tank's washing operations, it is not preferable for all types of chemical tankers and transported products.

Horizontally corrugated bulkheads allow the variation of their thickness in the direction of the vessel's depth. In that way the weight of the construction can be reduced, when at the same time the increased thickness of the bottom corrugations can lead to a stronger construction without the need to use web frames and stiffeners.

In case that horizontally corrugated bulkheads are used as longitudinal bulkheads, they are subjected to longitudinal hull girder bending and therefore need to be stiffened at regular intervals in order to provide adequate shear and out of plane rigidity. For this purpose vertical primary supporting members are normally arranged. The extreme end of longitudinal bulkheads is to be terminated at an effective bulkhead and also needs to be arranged with substantial transition brackets for the purpose of efficient load transfer and to avoid abrupt structural changes.

6.7.3.3 Application in chemical tankers

Both horizontally and vertically corrugated bulkheads are used in chemical tankers. When it comes for longitudinal bulkheads horizontal corrugation is usually preferred rather than vertical, as its contribution to the longitudinal strength of the vessel is much more significant. Vertical corrugation may though be used in longitudinal bulkheads with negligible results, however it is not recommended as it would need greater plate thickness and additional stiffening that would lead to some unpleasant side effects such us increased weight and cost, and less plain surfaces. An additional issue, is that the vessel may need to be trimmed slightly to ensure complete drainage of the cargo to the pump well.

On the other hand, vertical corrugated bulkheads are most commonly used for the construction of transverse bulkheads. Vertically corrugated bulkheads can be of a much larger size without the need for stiffening, than a comparable horizontally corrugated bulkhead, contributing for this reason to the target for a component-free cargo tank.

From statistical data[14] for approximately 700 chemical tankers built in the period 1990-2009 and having corrugated bulkheads, it comes that about 85% of the corrugated bulkheads designs consisted of vertically corrugated type and only the remaining 15% comprised horizontally corrugated ones. The decision though depends on the designer who needs to examine all aspects and conclude to the most effective option for the project, as well as on the shipyard's facility and fabrication procedure.

6.7.4 Bulkheads design

As the role of the bulkheads in a vessel is crucial for its safety, its strength, cargo separation and operations and structural continuity, it is essential that their design are governed by a set of rules while simultaneously new efforts are made for further improvement. One great tool in this effort is the study of damages that have occurred in existing bulkhead constructions, and the attempt to eliminate these damages in the future through advanced design. An additional tool is the use of Finite Elements Methods through which the designer can detect parts of the initial design that need to be amended. All the above contribute to stronger and more resistant constructions that will require less maintenance and will develop as less defects as possible.

6.7.4.1 Initial design and scantlings

Some fundamental rules regarding the design of corrugated bulkheads can be found in IACS CSR for Double Hull Oil tankers[15]. Although not all chemical tankers are to be constructed according to these rules, the main design principles of corrugated bulkheads should be the same for all tankers. The main points that can be summarized from those rules are presented below:

- In general, corrugated bulkheads are to be designed with the corrugation angles, φ, between 55 and 90 degrees (Figure 6.28)

- For ships with a moulded depth equal to or greater than 16m, a lower stool is to be fitted for vertical corrugated bulkheads. In that case:

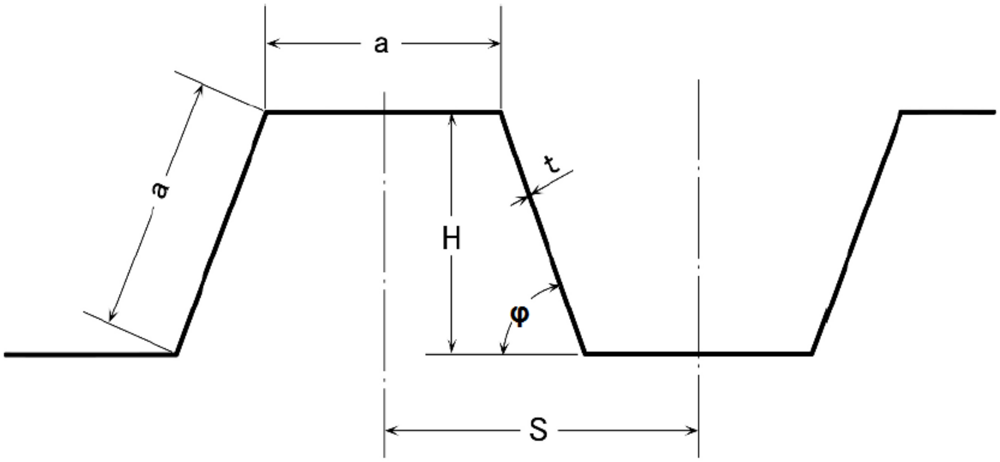


Figure 6.28 – Definition of Parameters for Corrugated Bulkhead

- Where gussets with shedder plates or shedder plates (slanting plates) are fitted at the end connection of the corrugation to the lower stool or to the inner bottom, appropriate means are to be provided to prevent the possibility of gas pockets being formed by these plates.
- The lower stool is to be fitted in line with the double bottom floors or girders.
- The side stiffeners and vertical webs (diaphragms) within the stool structure are to align with the structure below, as far as is practicable, to provide appropriate load transmission to structures within the double bottom.
- The extension of the stool top plating beyond the corrugation is not to be less than the as-built flange thickness of the corrugation.
- The ends of stool side vertical stiffeners are to be attached to brackets at the upper and lower ends of the stool.
- Continuity is to be maintained, as far as practicable, between the corrugation web and supporting brackets inside the stool. The bracket net thickness is not to be less than 80% of the required thickness of the corrugation webs and is to be of at least the same material yield strength.
- Scallops in the diaphragms in way of the connections of the stool sides to the inner bottom and to the stool top plate are not permitted.

- For ships with a molded depth less than 16m, the lower stool may be eliminated. In that case:
- Double bottom floors or girders are to be fitted in line with the corrugation flanges for transverse or longitudinal bulkheads, respectively.
- Brackets/carlings are to be fitted below the inner bottom and hopper tank in line with corrugation webs.
- The inner bottom and hopper tank in way of the corrugation is to be of at least the same material yield strength as the attached corrugation.

- The upper ends of vertical stiffeners on supporting double bottom floors or girders are to be bracketed to adjacent structure.
- Cut outs for stiffeners in way of supporting double bottom floors and girders in line with corrugation flanges are to be fitted with full collar plates.
- Scallops in brackets, gusset plates and shedder plates in way of the connections to the inner bottom or corrugation flange and web are not permitted.

The above points as set by CSR, together with many additional points that are not included in this section, consist a fixed and solid basis for the design and construction of corrugated bulkheads and provide the structural continuity that is required to avoid faults of the construction during its life. It is obvious here, that the structural behavior of the bulkhead when subjected to loads and stresses, is in a great way related to the structural configurations of its neighbor compartments such as the double bottom and the deck structure. Therefore its design procedure should be part of the global design procedure of the vessel, and not a standalone issue.

Another decision that needs to be made during the design phase is the thickness of the corrugated plates. Suggestions for scantlings are also given in the CSR, however as there are not particular CSR rules for chemical tankers, each class may have its own ones. The below scantlings calculations are as proposed by the DNV[16] and the following definition of spacing applies:

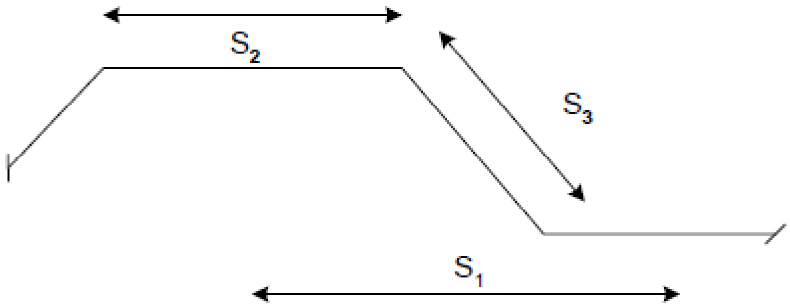


Figure 6.29 – Definition of Spacing for Corrugated Bulkhead

s = s1 for section modulus calculations
= 1.05 s2 or 1.05 s3 for plate thickness calculations in general
= s2 or s3 for plate thickness calculation when 90° corrugations.

In general for bulkheads the thickness requirements are given as described in Chapter 6.5.3.1 for cargo tanks scantlings. In corrugated bulkheads formed by welded plate strips, the thickness in flange and web plates may be differing. The thickness requirement then is given by the following modified formula:

$$t = \sqrt{\frac{500\,s^2\,p}{\sigma} - t_n^2} + t_k \qquad \text{(mm)}$$

t_n = thickness in mm of neighboring plate (flange or web), not to be taken greater than t.

The thickness should also not be less than:

$$t = 5.0 + \frac{k\,L_1}{\sqrt{f_1}} + t_k \qquad \text{(mm)}$$

k = 0.03 for longitudinal bulkheads except double skin bulkheads in way of cargo oil tanks and ballast tanks in liquid cargo tank areas
= 0.02 in peak tanks and for transverse and double skin longitudinal bulkheads in way of cargo oil tanks and ballast tanks in liquid cargo tank areas
= 0.01 for other bulkheads.

In longitudinal bulkheads within the cargo area the thickness shall not be less than:

$$t = \frac{1000 s}{120 - 3\sqrt{L_1}} + t_k \qquad \text{(mm)}$$

The scantling methods presented above may differ for vessels registered under other than DNV classes but in any case there will be some particular scantling rules that need to be followed. In case of plane bulkheads the conventional design method of a plate under lateral pressure is been used, when for corrugated bulkheads some additional calculations may need to take place. In any case, what it matters is that the plate thickness and the section modulus of the bulkhead, corrugated or not, is sufficient to ensure the local and global strength of the construction against the loads it is predicted to face.

The section modulus of a corrugated section is a function of the thickness of the plate and the geometrical characteristics of the corrugations. For a known required section modulus, and for a defined plate thickness, the geometry of the corrugations can be defined. For the parameters as per Figure 5.28, the section modulus is calculated by the following type:

$$a \sin\theta = H$$

$$a \cos\theta = S - a$$

$$Z = \frac{2atH}{3}$$

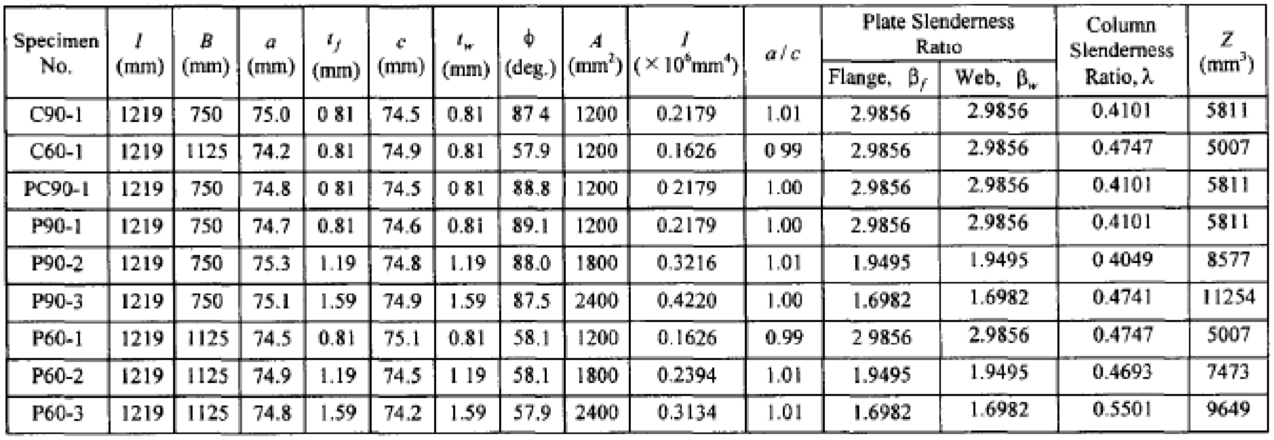
6.7.4.2 Parameters that affect the behavior of corrugated bulkheads

After a study[17] that has taken place regarding the ultimate strength and the behavior of corrugated bulkheads, it has come out that factors such as the corrugation angle, the plate thickness and the loading, play a significant role to the collapse and post-collapse behavior of the construction.

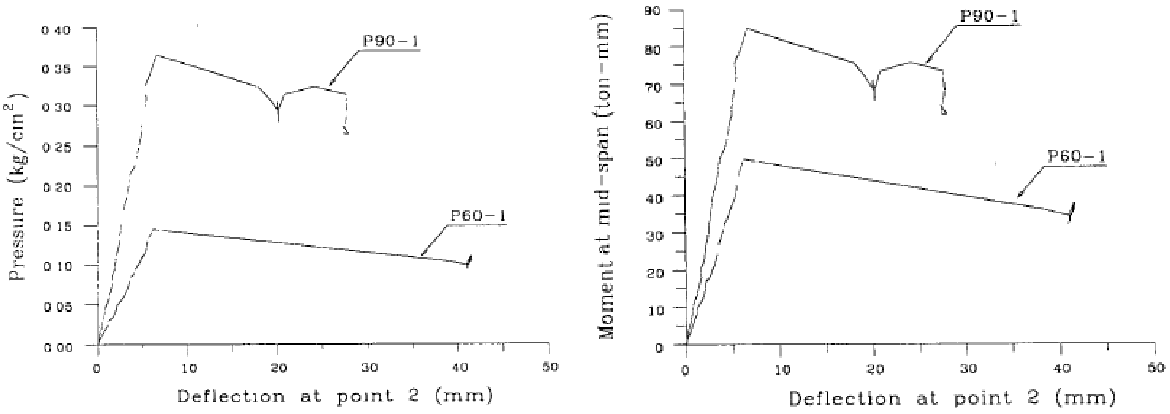
The researchers performed tests to nine mild steel corrugated bulkheads of different corrugation angles and thicknesses by applying to them loads such as lateral pressure, axial compression, and a combination of those. The bulkheads were models constructed with plate bending and not welding, and the loads were applied through compressed air and not water pressure. What was measured was the initial deflection, the initial distortions of the corrugation angle and the vertical deflection of the models during the load effect.

Effects of corrugation angle

Figure 6.30 shows the influence of the corrugation angle on the collapse behavior of corrugated bulkhead models under static lateral pressure. Figure 6.30 (a) represents the relationship between the average pressure intensity and the deflection of the central corrugation (at point 2, see Figure 6.31) for the two corrugation angles of the test models. Figure 6.30 (b) shows the mid-span bending moment versus lateral deflection curves for a single central corrugation as a beam, where it is assumed that the corrugation ends are simply supported.



Specimen No.	l (mm)	B (mm)	a (mm)	t_f (mm)	c (mm)	t_w (mm)	ϕ (deg.)	A (mm^2)	I ($\times 10^6$mm^4)	a/c	Plate Slenderness Ratio		Column Slenderness Ratio, λ	Z (mm^3)
											Flange, β_f	Web, β_w		
C90-1	1219	750	75.0	0.81	74.5	0.81	87.4	1200	0.2179	1.01	2.9856	2.9856	0.4101	5811
C60-1	1219	1125	74.2	0.81	74.9	0.81	57.9	1200	0.1626	0.99	2.9856	2.9856	0.4747	5007
PC90-1	1219	750	74.8	0.81	74.5	0.81	88.8	1200	0.2179	1.00	2.9856	2.9856	0.4101	5811
P90-1	1219	750	74.7	0.81	74.6	0.81	89.1	1200	0.2179	1.00	2.9856	2.9856	0.4101	5811
P90-2	1219	750	75.3	1.19	74.8	1.19	88.0	1800	0.3216	1.01	1.9495	1.9495	0.4049	8577
P90-3	1219	750	75.1	1.59	74.9	1.59	87.5	2400	0.4220	1.00	1.6982	1.6982	0.4741	11254
P60-1	1219	1125	74.5	0.81	75.1	0.81	58.1	1200	0.1626	0.99	2.9856	2.9856	0.4747	5007
P60-2	1219	1125	74.9	1.19	74.5	1.19	58.1	1800	0.2394	1.01	1.9495	1.9495	0.4693	7473
P60-3	1219	1125	74.8	1.59	74.2	1.59	57.9	2400	0.3134	1.01	1.6982	1.6982	0.5501	9649



(a) (b)

Figure 6.30 – Effects of corrugation angle in collapse behavior

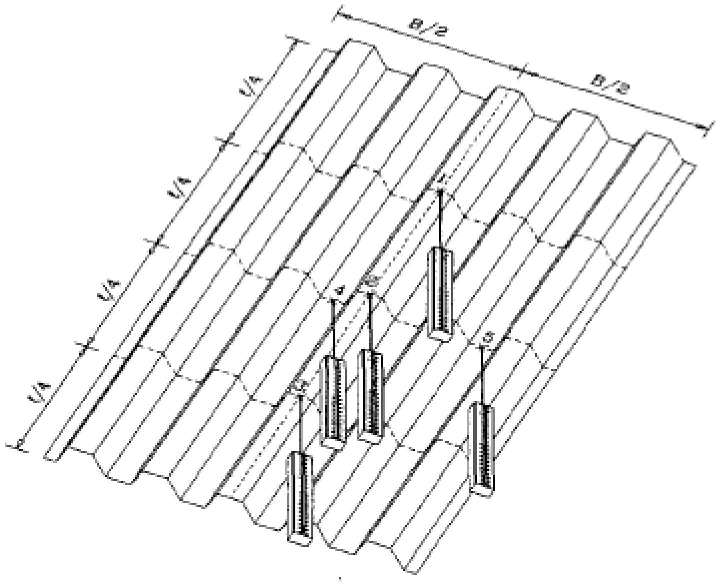


Figure 6.31 – Measurement points in test models

What comes out from the above test is that the ultimate collapse pressure load for the corrugated bulkhead with φ = 60 deg is only one third of the model with φ = 90 deg. As a matter of fact the thickness of a bulkhead with 60 deg corrugations should be increased compared to a bulkhead with 90 deg corrugations, in order to compensate the lower resistance to lateral pressure. This however would lead to increases weight, making the trapezoidal corrugation profile bulkhead a much heavier construction than the rectangular profile one.

Another study reveals the effect of the corrugation angle to the section area – and as a result to the steel weight – of the bulkhead per unit breadth. For a range of angles as shown in Figure 6.32, and for the rest design parameters predefined, it becomes clear that the minimum sectional area per unit breadth comes for a corrugation angle of 65 deg.

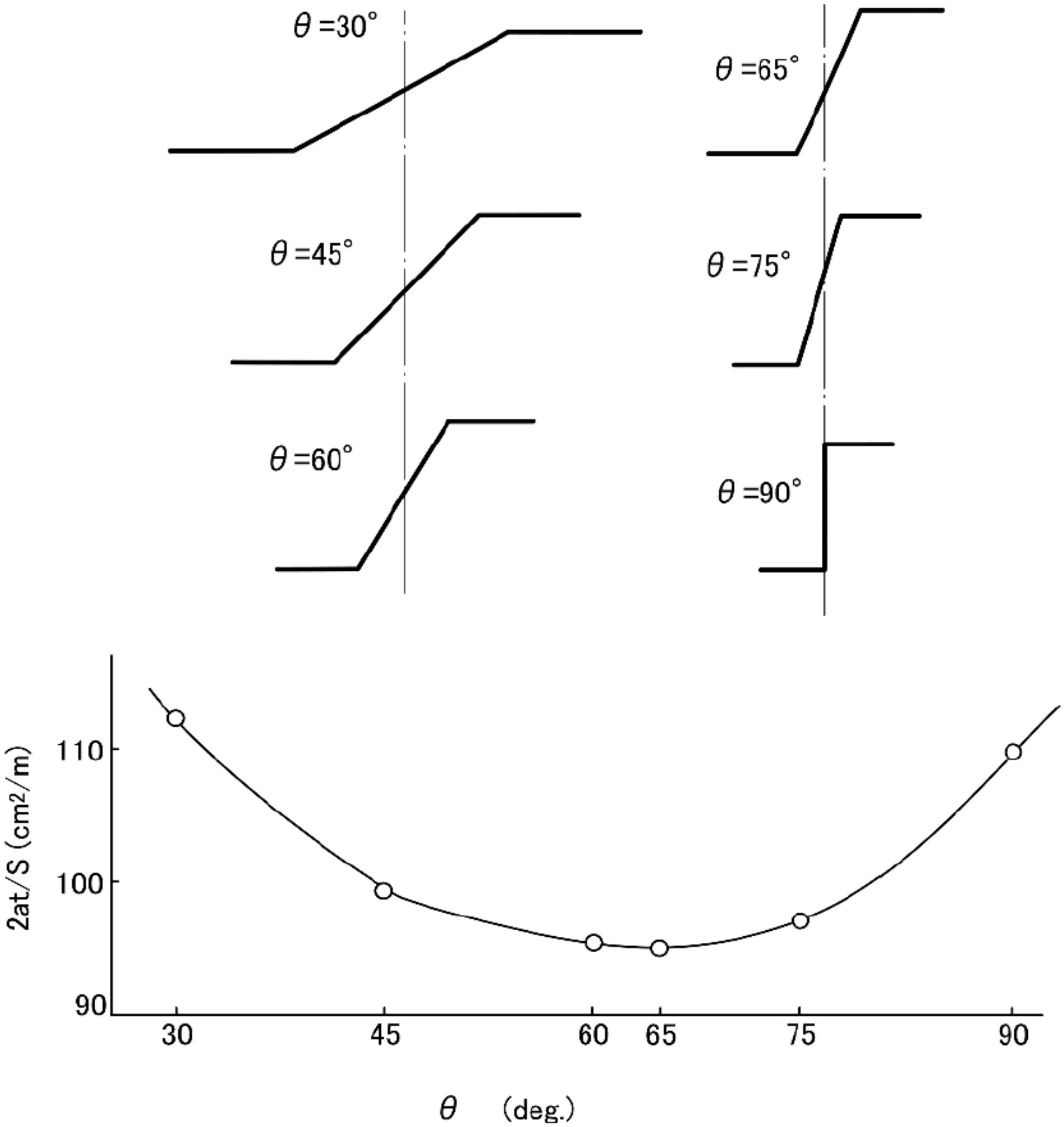
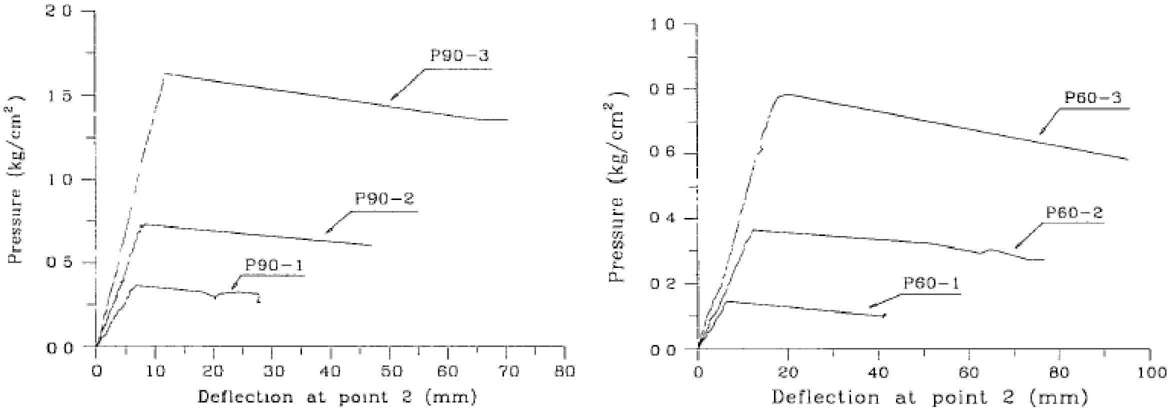


Figure 6.32 – Sectional are per unit length of corrugated bulkhead vs. inclination of web plate

The same study reveals that a corrugated bulkhead without horizontal stiffener and with corrugation angle of 65 deg weights almost the half in comparison with a flat plate bulkhead with stiffener space equal to 0.67 m which results to the same section modulus.

Effects of plate thickness

Figure 6.33 shows the effects of plate thickness on the collapse behavior of corrugated bulkhead models under lateral pressure for φ = 90 deg and 60 deg respectively. An increase in the plate's thickness leads to a significant increase in the collapse strength of the corrugated bulkhead. This increase is irrelevant of the corrugation angle.



(a) (b)

Figure 6.33 – Effects of thickness in collapse behavior

Figure 6.34 indicates the variation of the ultimate bending strength of a single corrugation with increase in the plate (flange and web) slenderness ratio for the two kinds of corrugation angle, namely φ = 90 deg and φ = 60 deg. It can be seen that with increase in the thickness of corrugation flange/web, the ultimate bending moment for a single corrugation with φ = 90 deg increases at a faster rate than that for φ = 60 deg. This leads again to the conclusion that a rectangular corrugation profile would be more efficient than a trapezoid one.

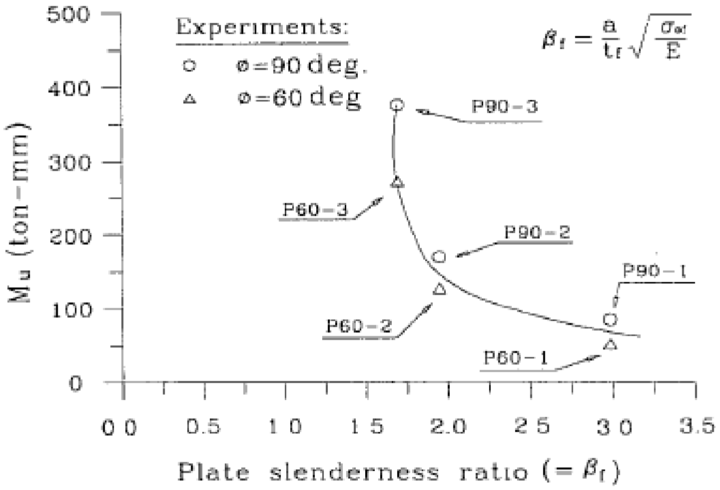


Figure 6.34 – Ultimate bending moment

<u>Effects of axial compressive loads</u>

Figure 6.35 shows the collapse behavior of the corrugated bulkhead models under axial compression, for the two different corrugation angles. It can be seen that axial compressive loads increase without occurrence of local buckling of flange up to the ultimate strength of the whole corrugated bulkhead model, and unloading follows after collapse, but due to the internal contact of walls the internal forces can rise again. The latter is a typical crushing response which is observed in thin-walled structures under excessive compressive loads, such as those for instance in ship collision.

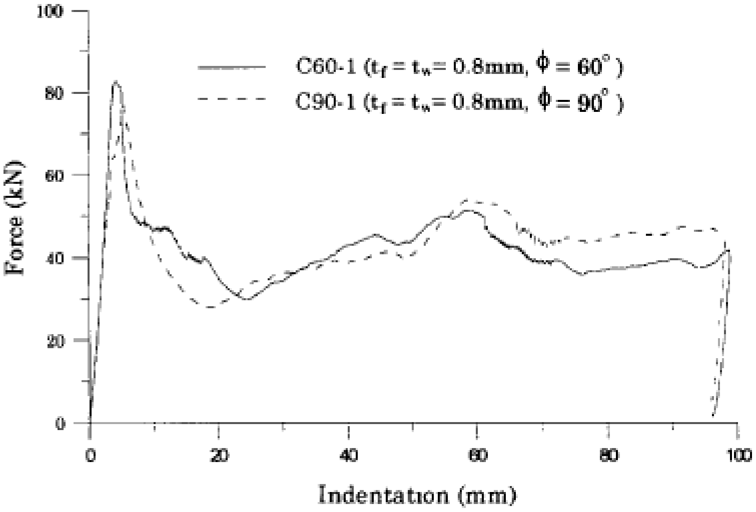


Figure 6.35 – Collapse behavior of corrugated bulkheads under axial compression

Effects of combined lateral pressure and axial compressive loads

Figure 6.36 shows the ultimate strength interaction relationship for the corrugated bulkhead models subject to combined axial compression and uniform lateral pressure. It can be seen that an application of a relatively small axial force to a corrugated bulkhead that is subjected to lateral pressure may decrease the collapse strength of the bulkhead down to almost the half. Although the axial forces applied on a vessel (mostly because of the still water sectional shearing forces) are negligible, special care should be given to this factor during the design, as their effect could be significant.

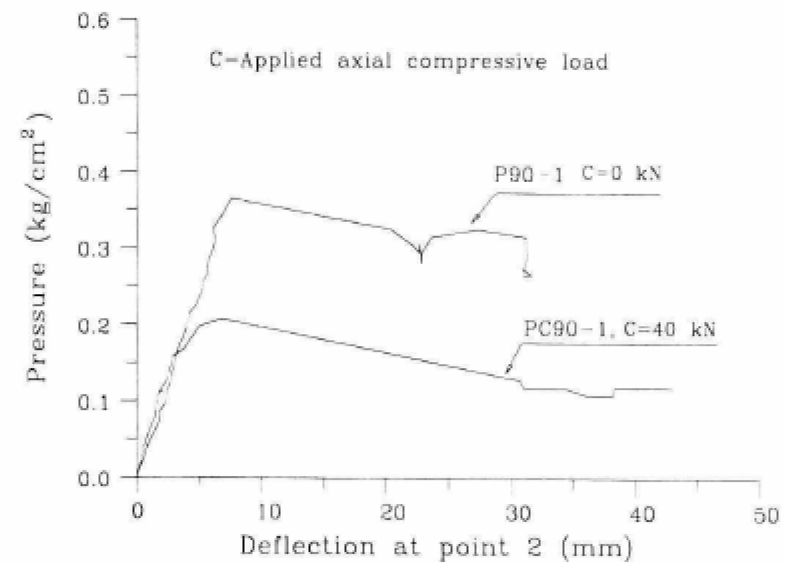


Figure 6.36 – Collapse behavior of corrugated bulkheads under combines lateral pressure and axial compression

6.7.5 *Damages in corrugated bulkheads and effect in design*

One of the most successful ways to improve and optimize the design of a construction is to detect and analyze damages and defects that developed to similar constructions in the past in order to find ways to eliminate them in the future. It is crucial that these damages are categorized, so that we find out which of them were created by the same cause. One detailed categorization of damages in corrugated bulkheads of tanker vessels, together with design innovations to eliminate them, are given in *Corrugated Bulkhead Design for Tankers*[18].

6.7.5.1 Types of damage

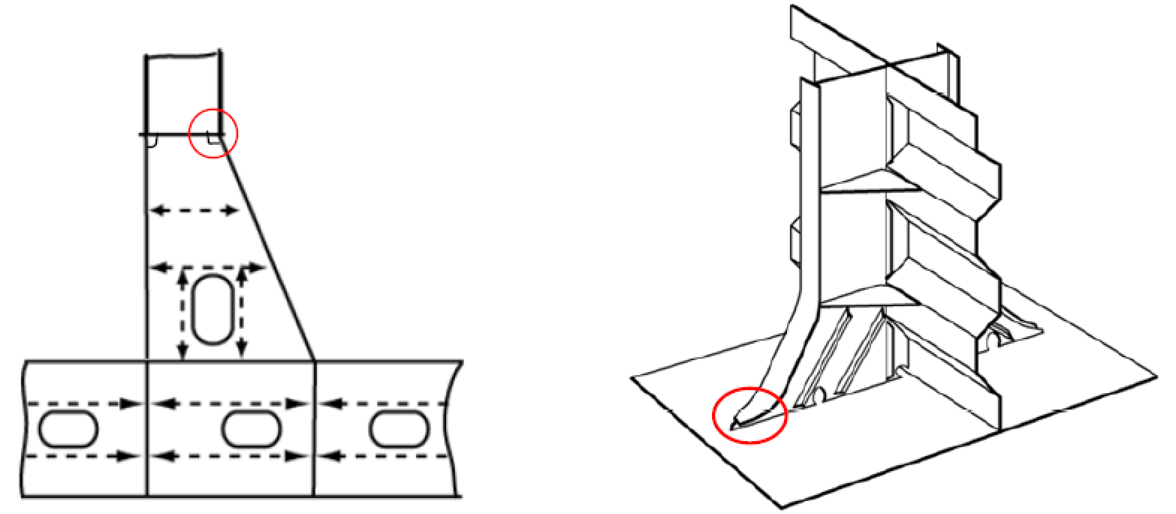
Damages caused by welding defects

It has been reported in several occasions, that cracks have been developed in the welding between the vertically corrugated bulkhead and the inner bottom plate. At this area, and especially at the corner of the corrugation, the stresses applied are transferred from the overall corrugation span, and are extremely intense. As a matter of fact, in case there are any overlapping or undercutting of welding at that point, and due to the high local stresses concentration, the circumstances exist for a crack to be developed.

This type of damage is developed in bulkhead construction without lower stool, where the corrugated plate comes to direct contact with the inner plate of the double bottom, therefore it is most often observed in small tankers that use non stool bulkheads. Due to chemical tankers small size compared to the oil tankers, this is a type of damage that need to be taken into account during the design procedure.

Damages of scallops or brackets toes at stress concentration area

Two areas that are vulnerable to cracks creation are the scallop at the corner of the lower stool diaphragm just below the vertically corrugated bulkhead and the bracket toe of the vertical web provided on the horizontally corrugated bulkhead. These cracks are initiated by the stress concentrations resulting from the scallop and shape of the bracket toe. The first of the two may pose a threat for big chemical tankers that are implemented with vertical transverse corrugated bulkheads with lower stool, when the second may appear to all chemical tankers that use horizontally corrugated bulkheads for longitudinal strength.



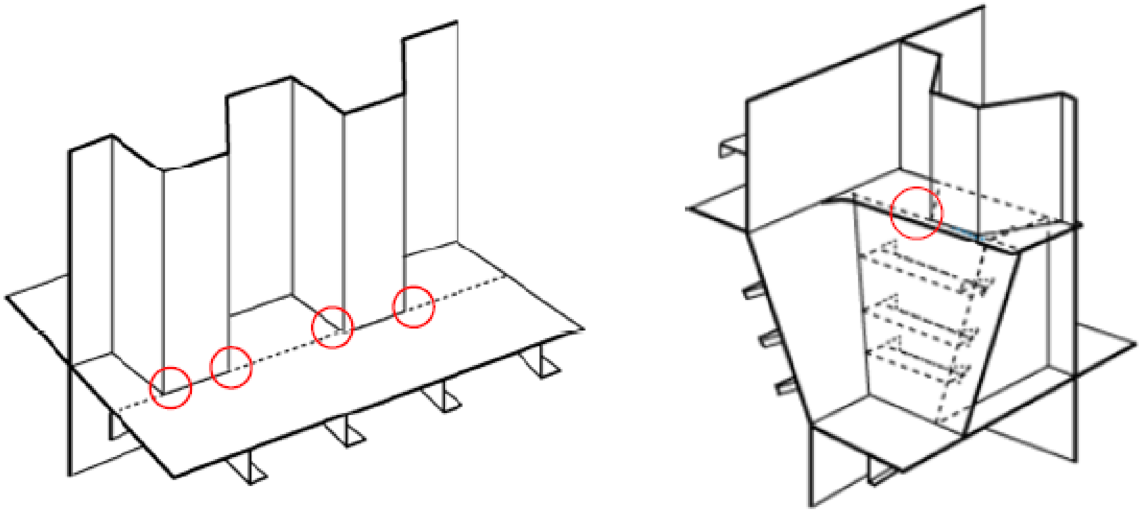
(Vertically corrugated bulkhead)

(Horizontally corrugated bulkhead)

Figure 6.37 – Cracks at scallop and bracket toe

Damages due to luck of supporting structures

Several damages that have been noticed in corrugated bulkheads have been caused by the lack of supporting structures. If the structural components of the bulkhead are not properly edged and supported, then the possibility of cracks formation is increased. Two typical examples are the damages in the connection between the vertically corrugated bulkhead with the inner bottom plate (without lower stool), and the damage in the connection between the vertically corrugated bulkhead with the lower stool top plate.



(Direct connection to inner bottom)

(With lower stool)

Figure 6.38 – Cracks due to lack of supporting structures

In case the corrugated plated is edged directly to the inner bottom plate, for constructions without lower stool, then appropriate backing structure should be provided to the bottom plate, so that there is sufficient transfer of the loads through this structure. In case this backing structure is absent, there will be stress concentration to the area where the bulkhead meets the bottom plate, as the loads will have no way to escape, with high possibility of constructional failure.

On the other hand, if a lower stool is provided, both flanges of corrugated plate can be supported by the stool plate directly. However, even in that case, and if the slanted stool plate is not sufficient to transfer the load, or the fitting angle of the supporting structure is not the required in order to avoid unacceptable stress concentrations, cracks formation may take place.

Both of these deformations are likely to happen in a chemical tanker transverse corrugated bulkhead. Their effect though may be significant, as not only they affect the structural strength of the compartment, but they also create cracks and cavitation where chemical cargo may be trapped and cannot be easily removed.

Damages due to lack of continuity

However, even though effective supporting structure is provided, crack formation may take place at the end connections of vertically corrugated bulkhead. This may occur due to differences in the thickness and the welding length between the corrugation and its supporting structure.

For the purpose of effective transmission of loads from the corrugated bulkhead to the underneath supporting structures, it is considered that the adequate continuity of plate thickness and welding length are also important factor of the design.

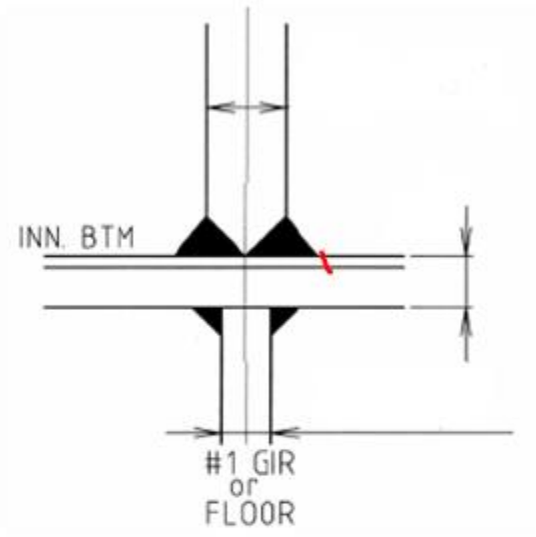


Figure 6.39 – Crack due to lack of continuity

6.7.5.2 *Impact of damage experience in the design*

Design of supporting structures

In order to avoid damages caused by lack of sufficient support beneath the bulkhead, supporting structures are placed in appropriate locations into the double bottom. The mere existence of these structures however is not always enough to eliminate potential damage, as their type and structural characteristics play a significant part in the way they will reduce the stresses concentration. Therefore, supporting structures shall not only exist, but also need to be designed in a proper and effective way.

Recent studies have indicated the relation between the length of the supporting structure and the stress reduction. What comes from these studies, is that the length of the stiffener located under the corrugated flange, should be at least half the depth of the corrugation depth, in order to offer sufficient stress reduction. Supporting structures such as floor/girders underneath the corrugation flange are also suitable, however not necessary if the condition above is satisfied.

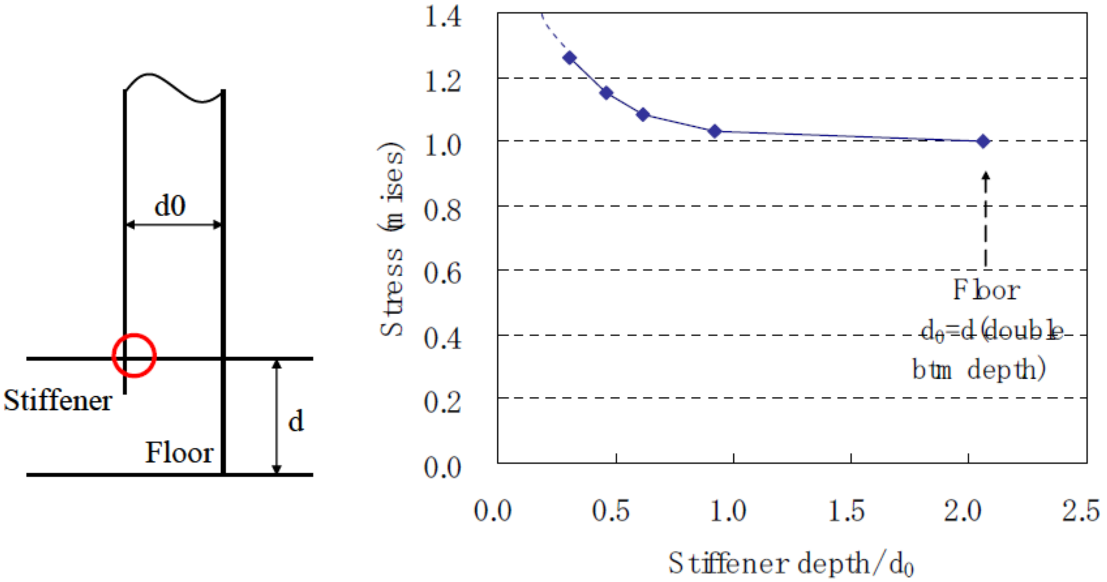


Figure 6.40 – Relative stress by depth of supporting structure

Full penetration welding

In order to avoid the stress concentration and minimize the risk of cracking at the lower end of corrugated bulkheads, full penetration welding is been applied at the corner of the corrugation instead of fillet penetration welding. The two welding types are shown in Figure 6.41.

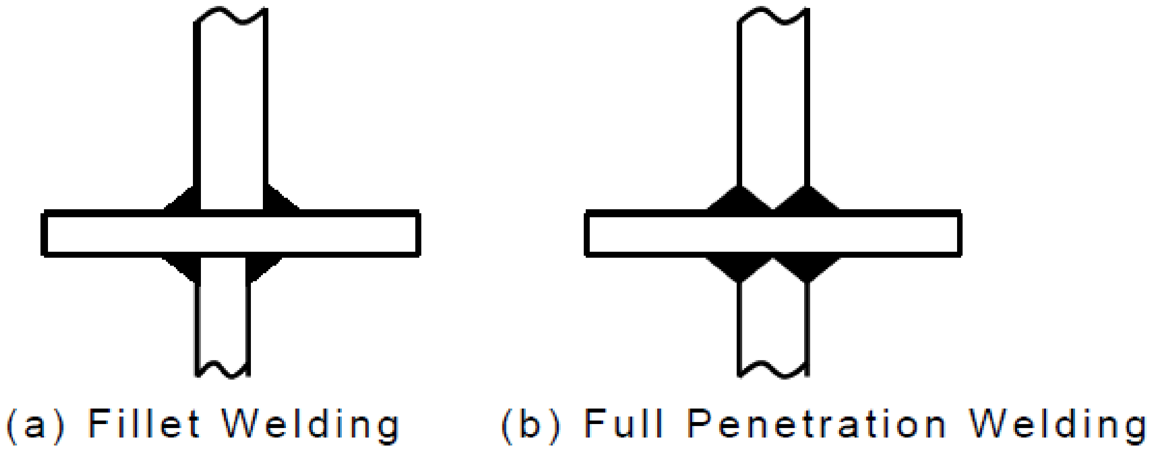

(a) Fillet Welding (b) Full Penetration Welding

Figure 6.41 – Welding types

The use of full penetration welding drastically decreases the stress concentration at the corner of the corrugation toward the center of the corrugation flange and web. In addition, it almost eliminates the risk of unexpected gaps existence which could lead to potential cracking and failure.

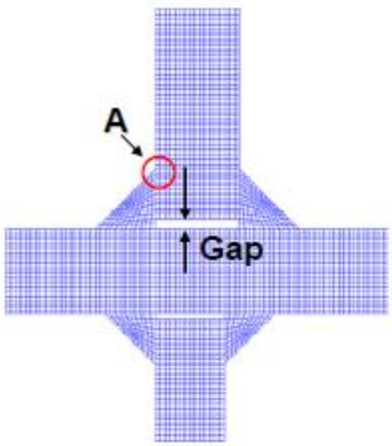


Figure 6.42 – Gaps in fillet welding

In the following pages transverse and longitudinal corrugated bulkheads drawings of a 16,500 DWT chemical tanker are displayed.

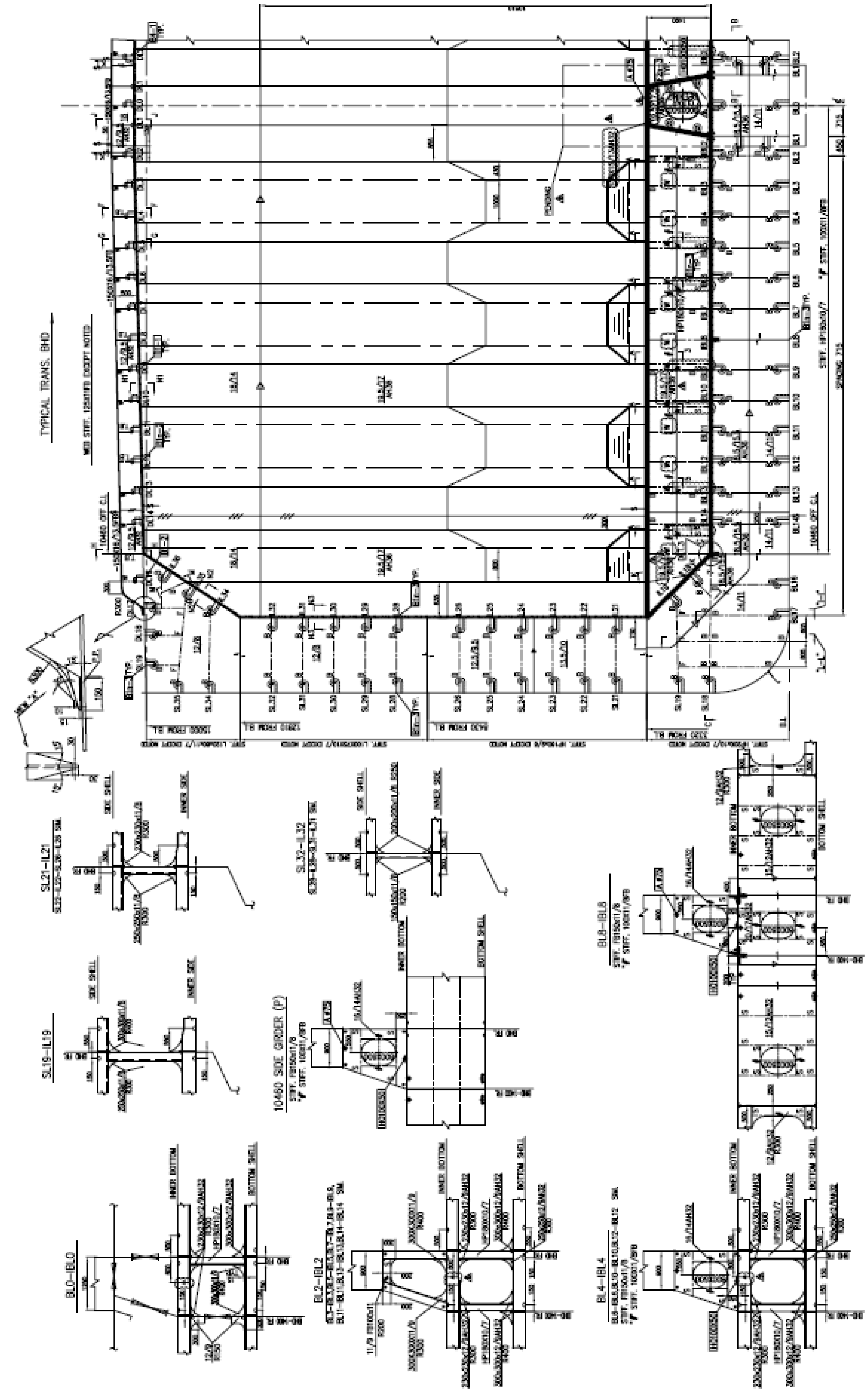


Figure 6.43 – Typical transverse bulkhead

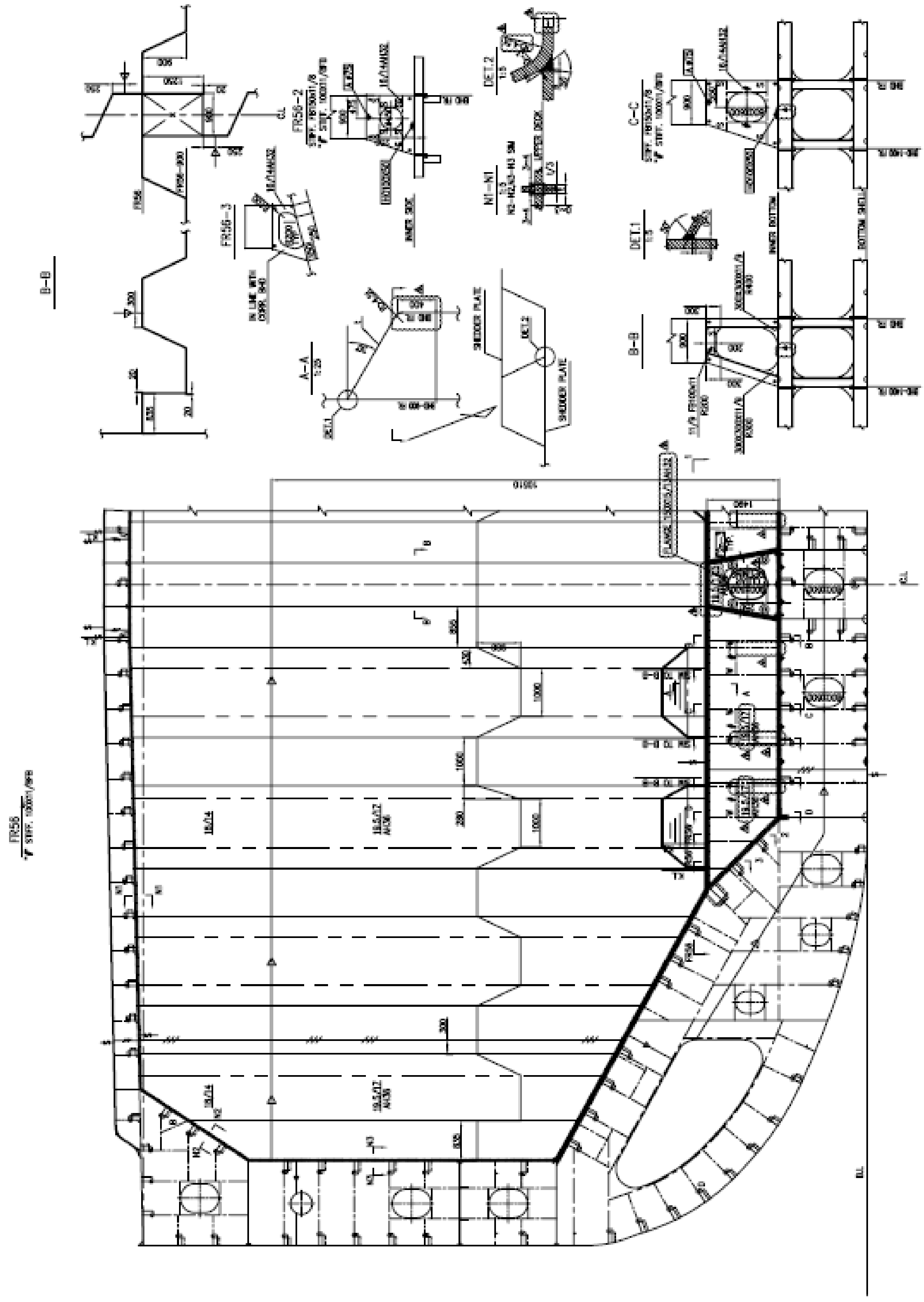


Figure 6.44 (a) – Watertight transverse bulkhead of a 16,500 chemical tanker, fr.56

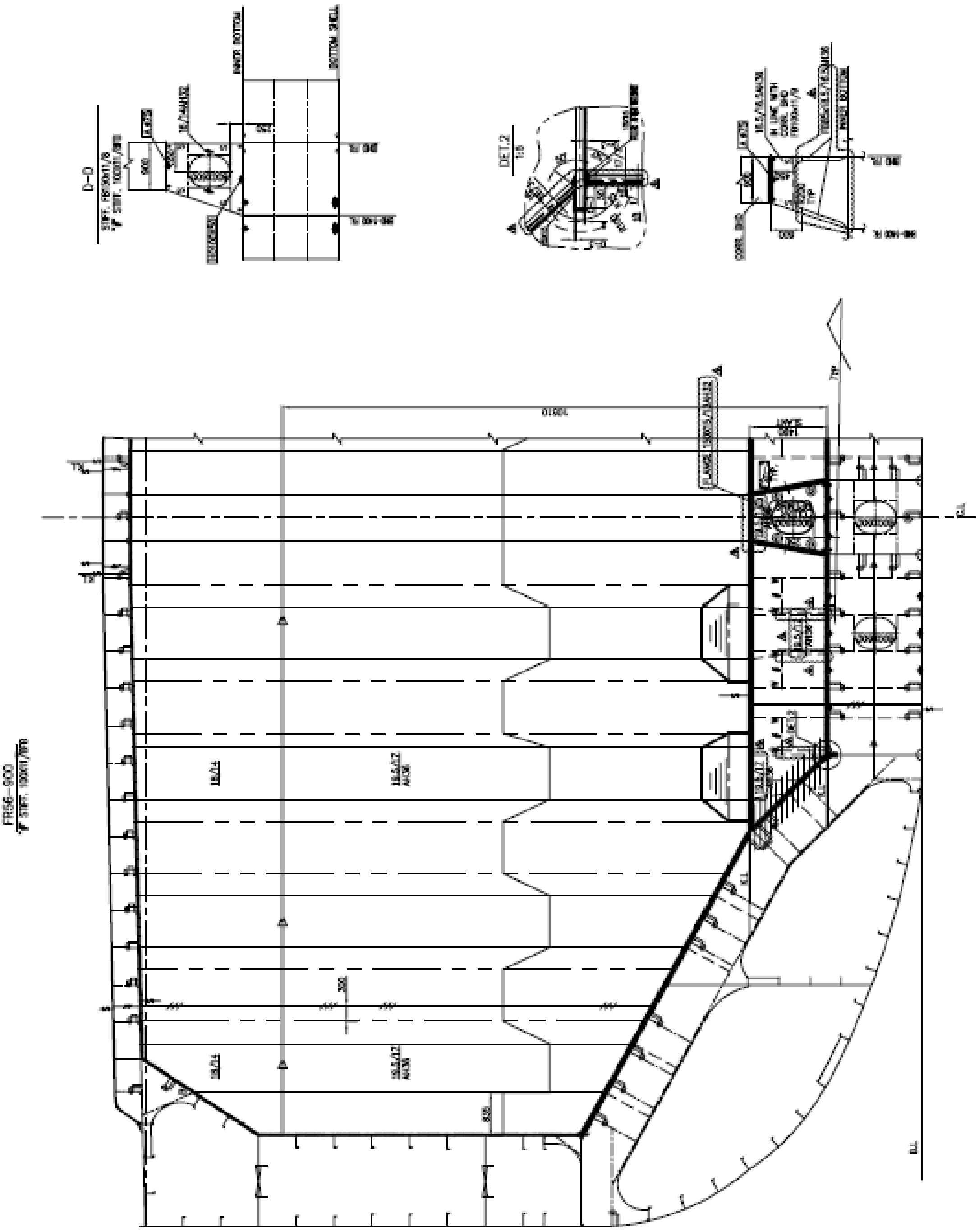


Figure 6.44 (b) – Watertight transverse bulkhead of a 16,500 chemical tanker, fr.56

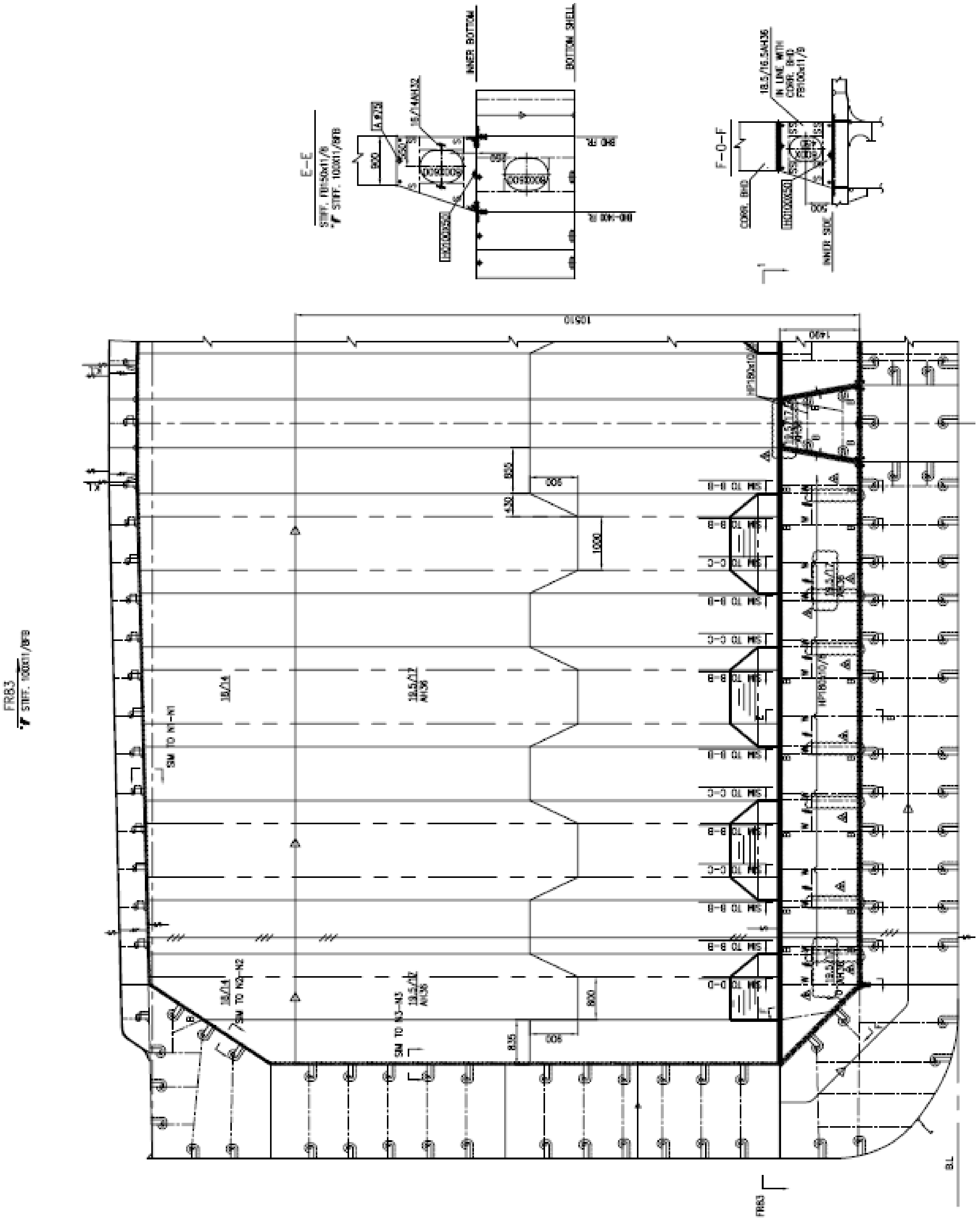


Figure 6.44 (c) – Watertight transverse bulkhead of a 16,500 chemical tanker, fr.83

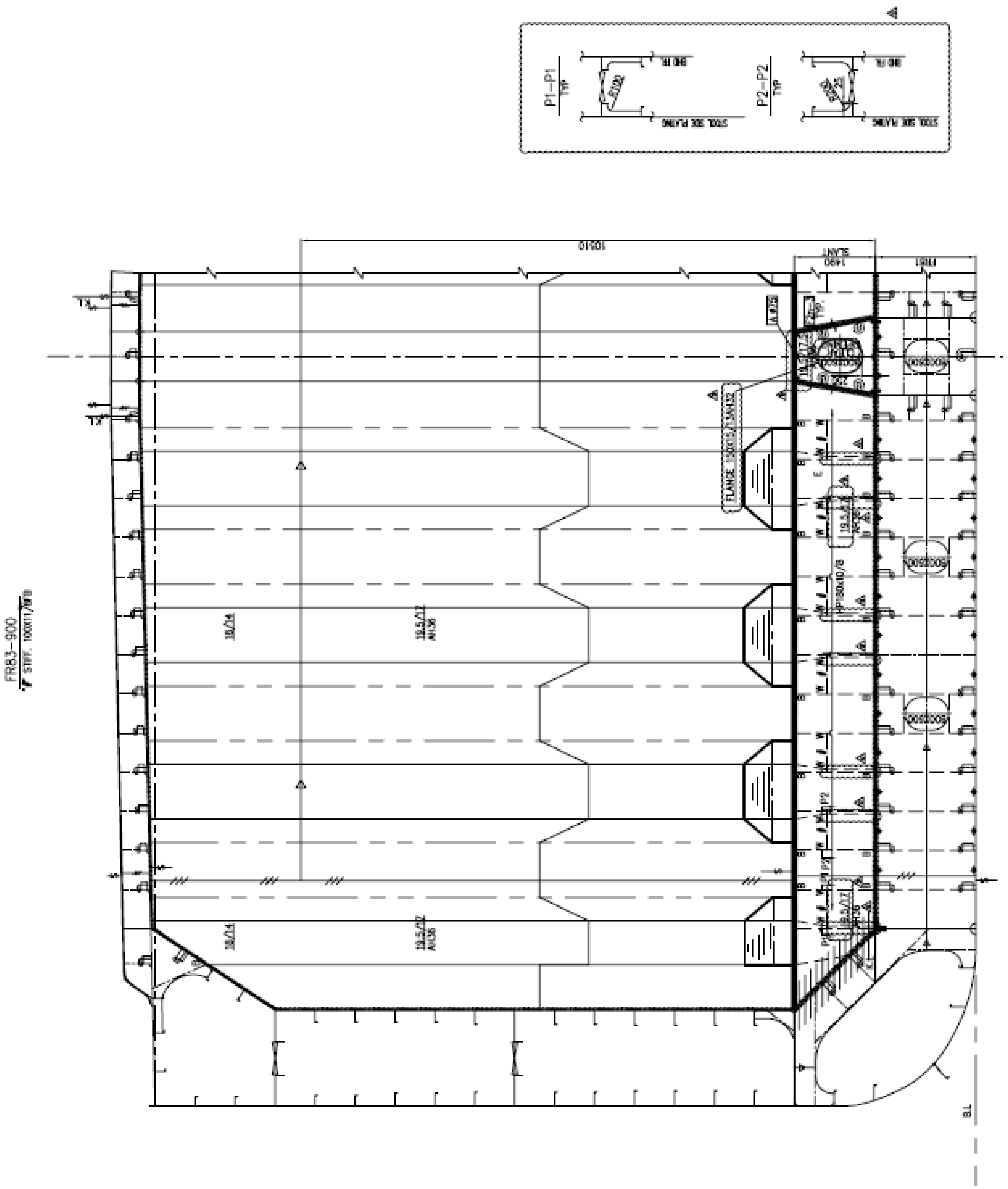


Figure 6.44 (d) – Watertight transverse bulkhead of a 16,500 chemical tanker, fr.83

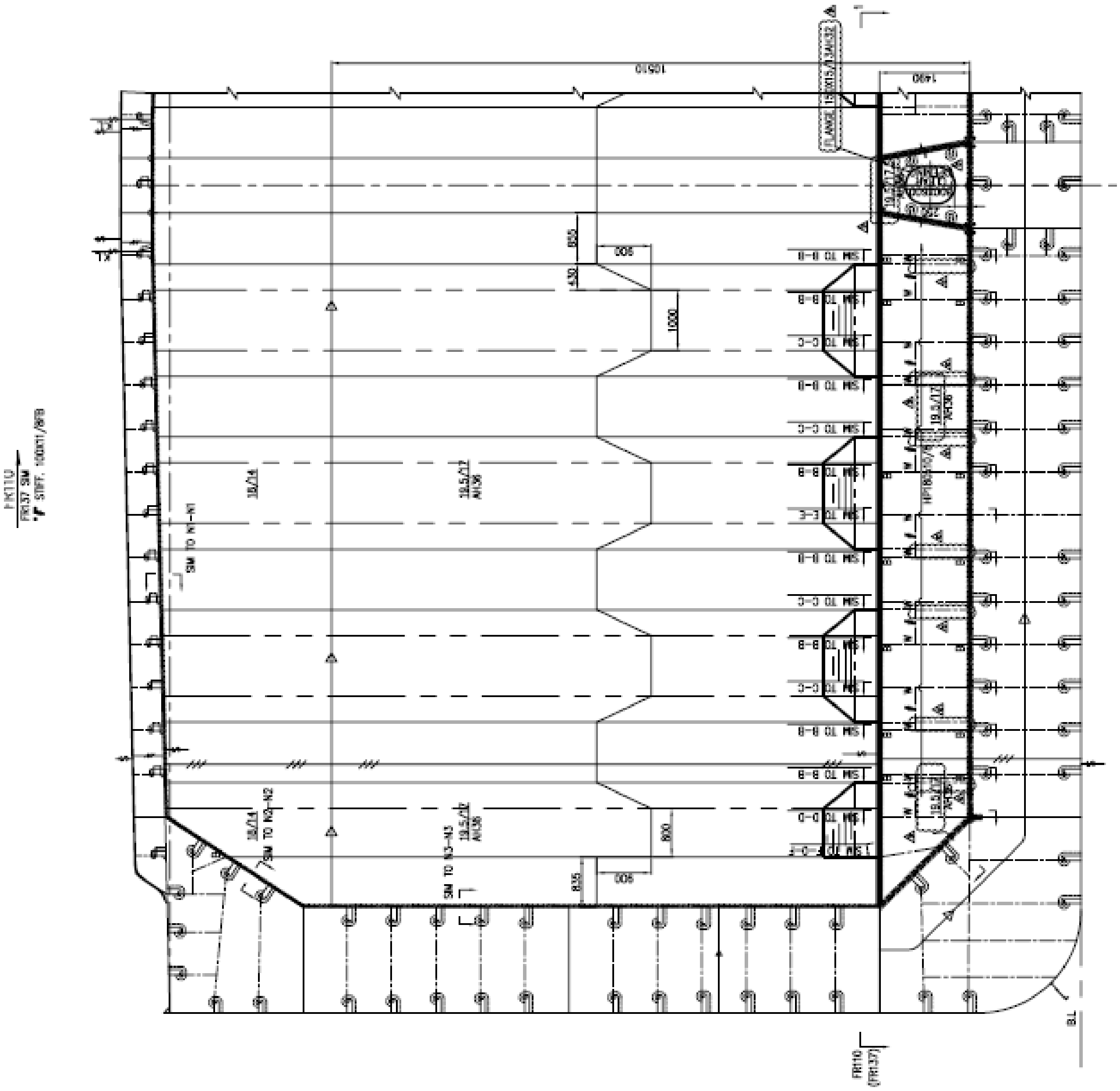


Figure 6.44 (e) – Watertight transverse bulkhead of a 16,500 chemical tanker, fr.110

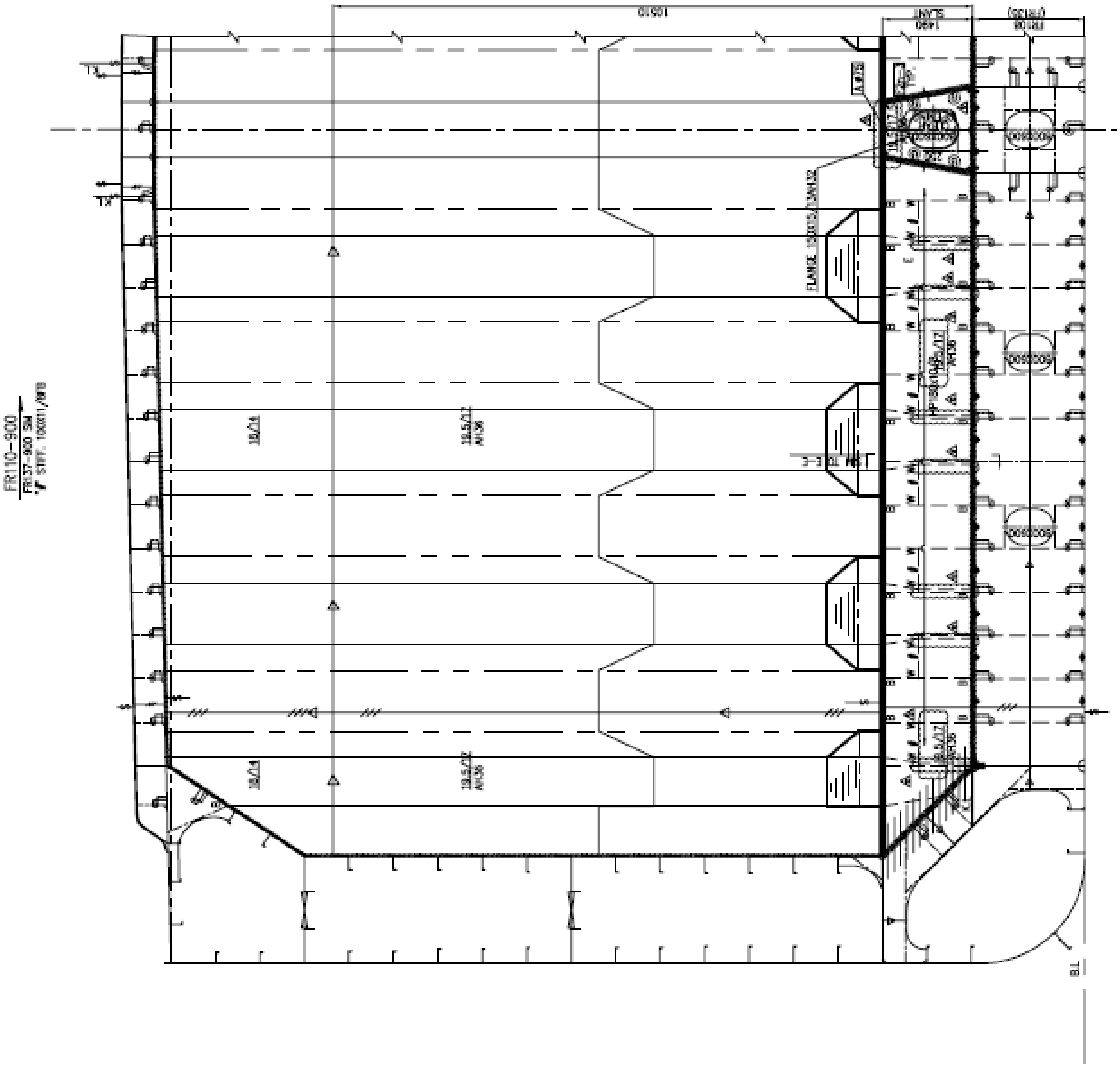


Figure 6.44 (f) – Watertight transverse bulkhead of a 16,500 chemical tanker, fr.110

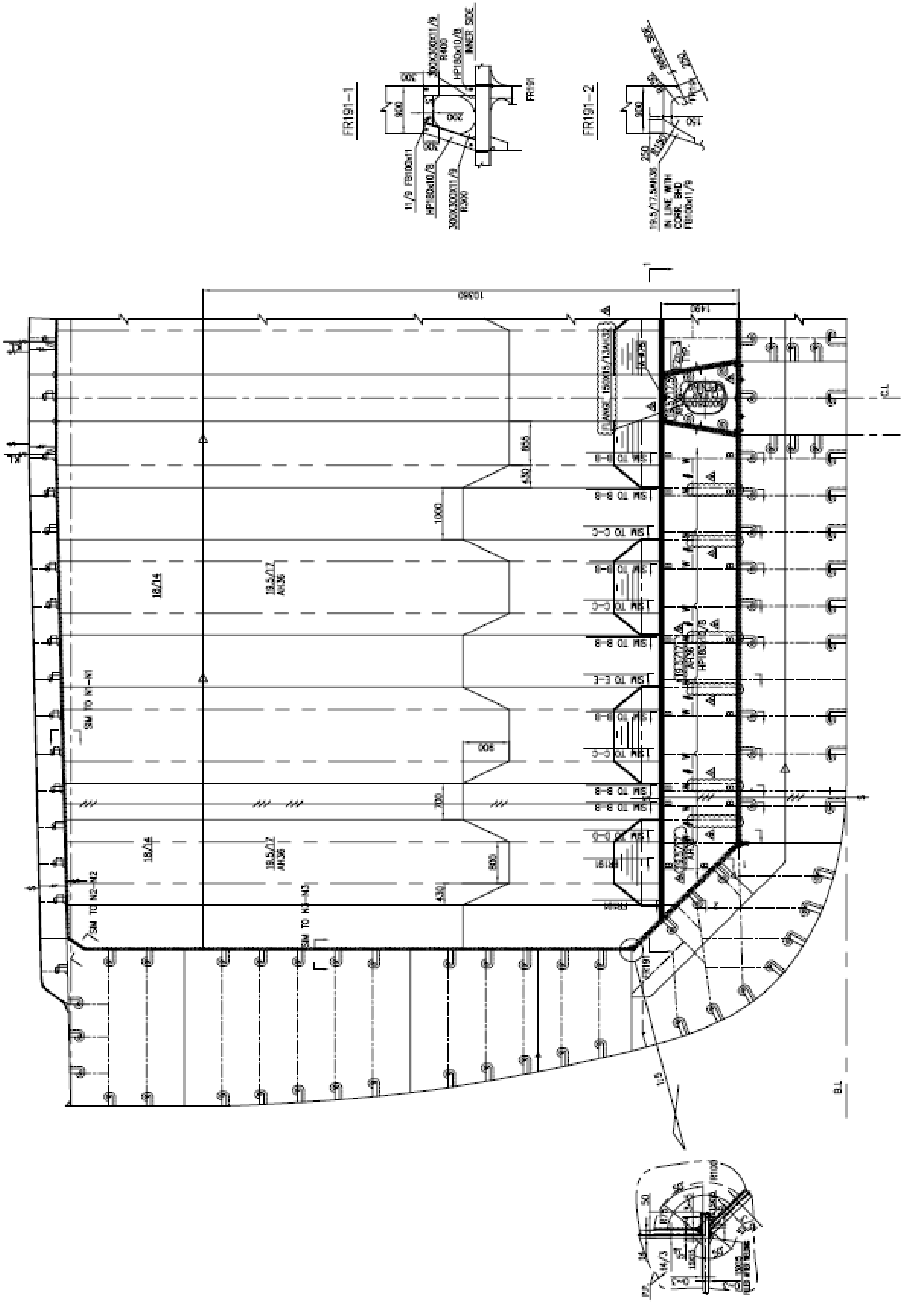


Figure 6.44 (g) – Watertight transverse bulkhead of a 16,500 chemical tanker, fr.191

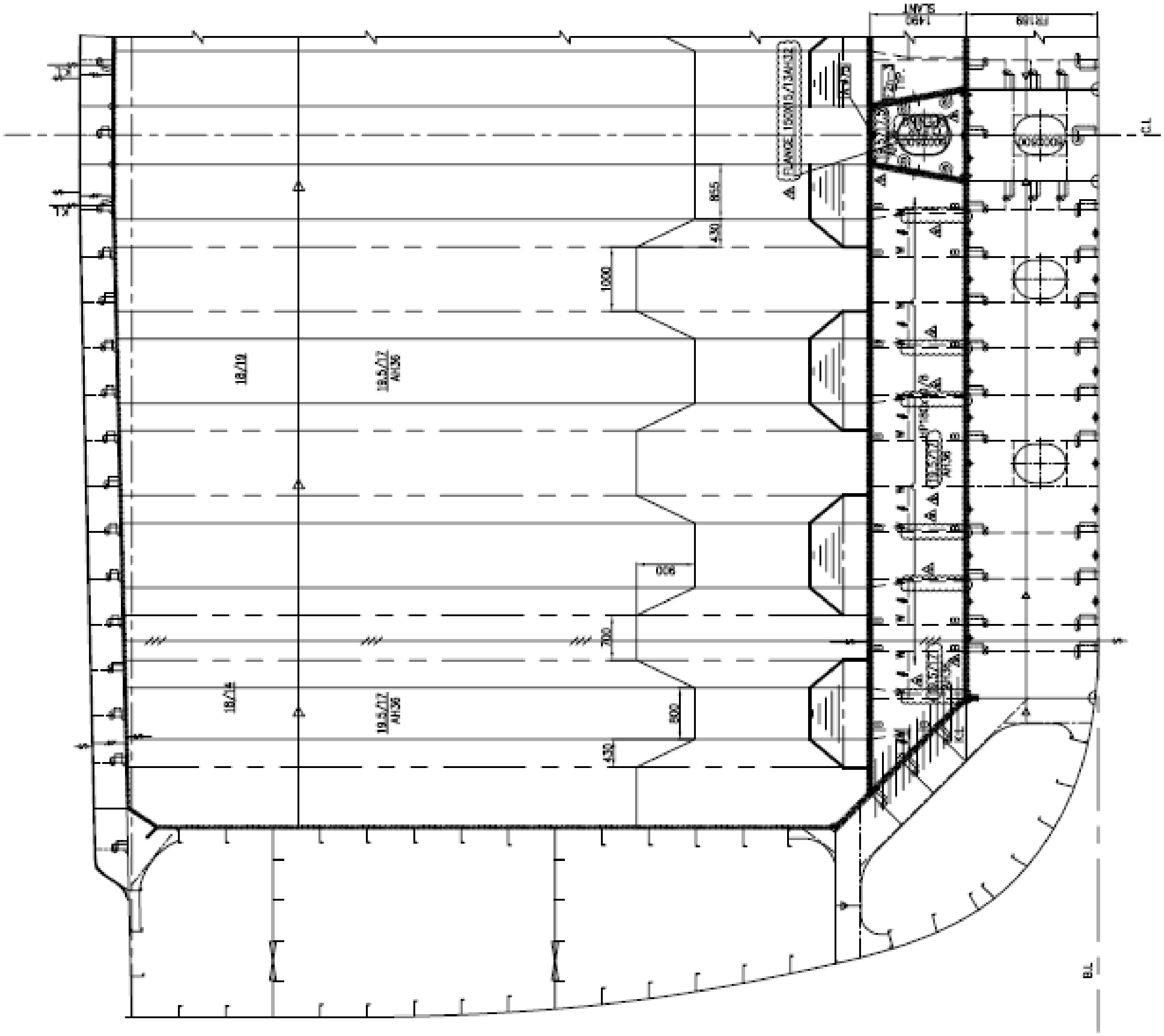


Figure 6.44 (h) – Watertight transverse bulkhead of a 16,500 chemical tanker, fr.191

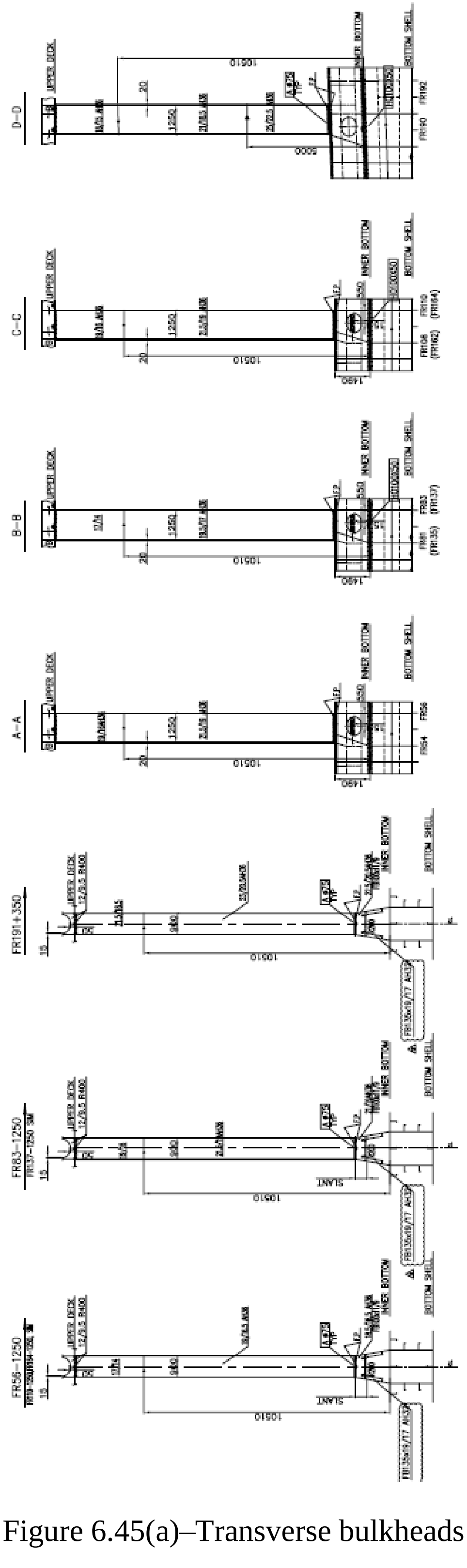


Figure 6.45(a)–Transverse bulkheads profile view

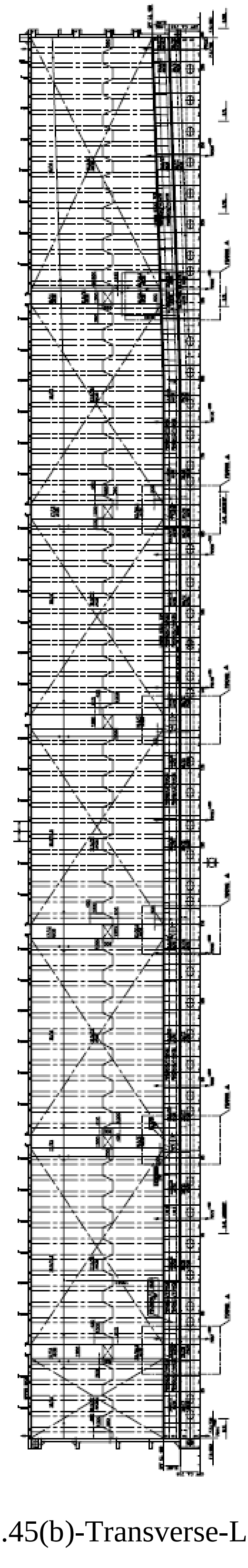


Figure 6.45(b)-Transverse-Longitudinal bulkheads collaboration, profile view

6.8 Double hull

The main reasons that double bottom and double side constructions are applied to chemical tankers are to avoid spill of the hazardous chemical cargo to the marine environment, and to increase the safety of the vessel in case of collision. Sufficient water and oil tightness has to be provided in the inner hull plate of a chemical tanker, so that, under no circumstances, may chemicals leak into the double hull, or ballast water leak into the cargo tank. In the case of the double bottom of a chemical tanker, a weak connection between the outer shell and the inner hull plate is preferable so that the inner hull plate is not directly affected by a load applied to the outer shell plate.

In order to facilitate and accelerate the cargo tank cleaning procedures, it is optimum to retain the cargo tanks free of structural elements. For that reason, all inner bottom and inner side shell stiffeners, are placed in the double hull side.

The double side structure on a chemical tanker, is made up of horizontal stringers and side shell and inner shell longitudinals. The double bottom structure is made up of longitudinal floors and bottom shell and inner bottom shell longitudinals in the double bottom. The inner side shell joins the inner bottom shell via a sloped hopper structure, which adds stiffness and strength to the connection. A typical web frame can be seen in the web frame section of Figure 6.46. The web frame is reinforced between each horizontal girder by vertical stiffeners and has access openings between each horizontal girder. The horizontal stingers in the double side and the floors in the double bottom also have access openings cut in them.[19]

As given by Okumoto[20], the main problem caused by the application of double hull side structure on tankers, is the rigidity unbalance between the vertical webs on the side shell and the longitudinal bulkhead

In the case of a single hull side structure, the rigidities of the vertical webs on the side and the longitudinal bulkhead are well balanced and they are effectively connected by cross tie. However, in the case of a double hull side structure the rigidity of the vertical web on the side shell is far bigger than the rigidity of the vertical web on the longitudinal bulkhead.

As it is not efficient to connect two members with different rigidities by a cross tie, the cross tie is placed in the center tank instead of the side tanks. In this arrangement, the vertical webs connect two identical longitudinal frames, which are of the same scantling and rigidity.

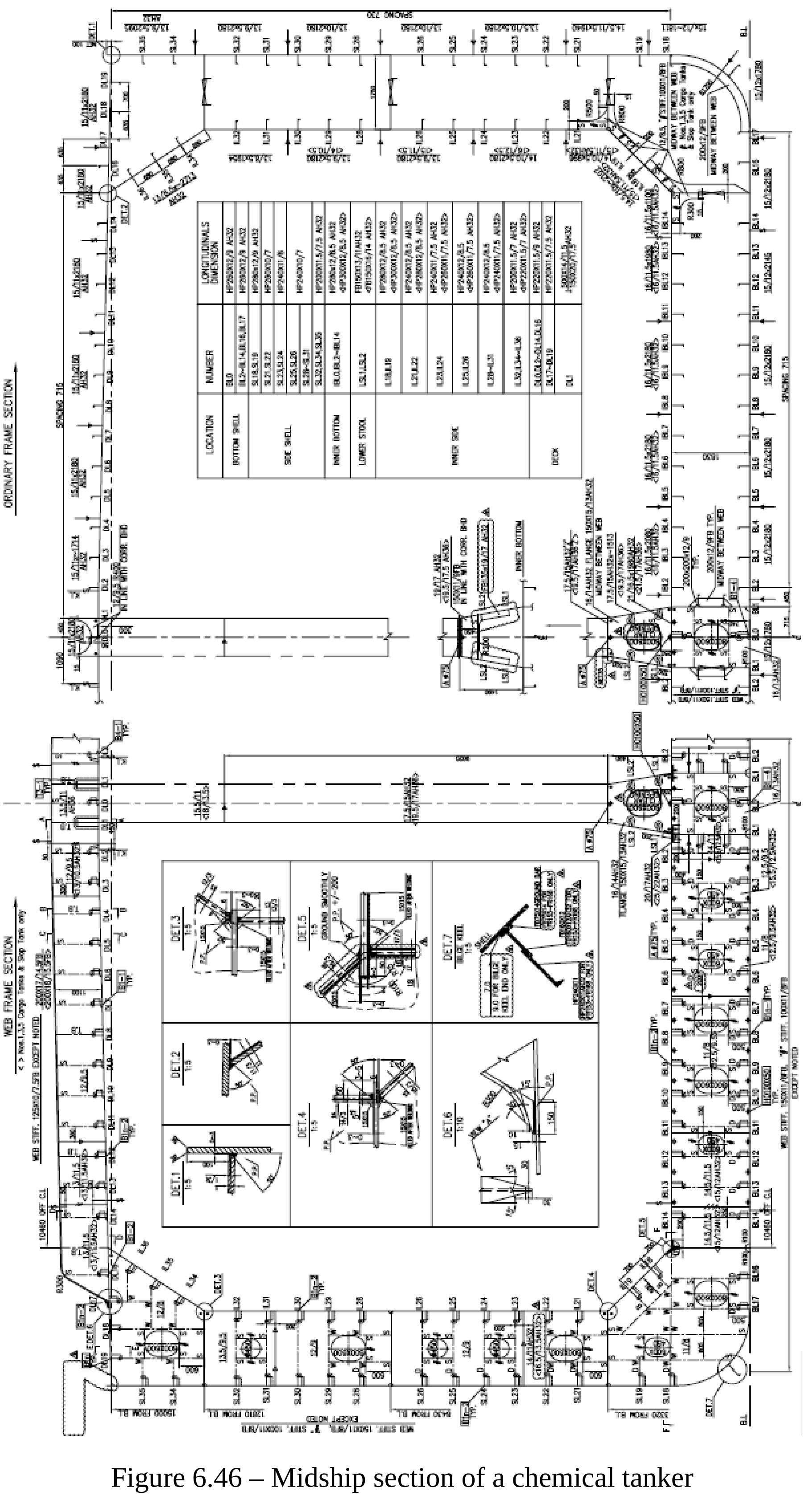


Figure 6.46 – Midship section of a chemical tanker

In the following pages, double bottom and double side construction drawings of a 16,500 DWT chemical tanker are displayed:

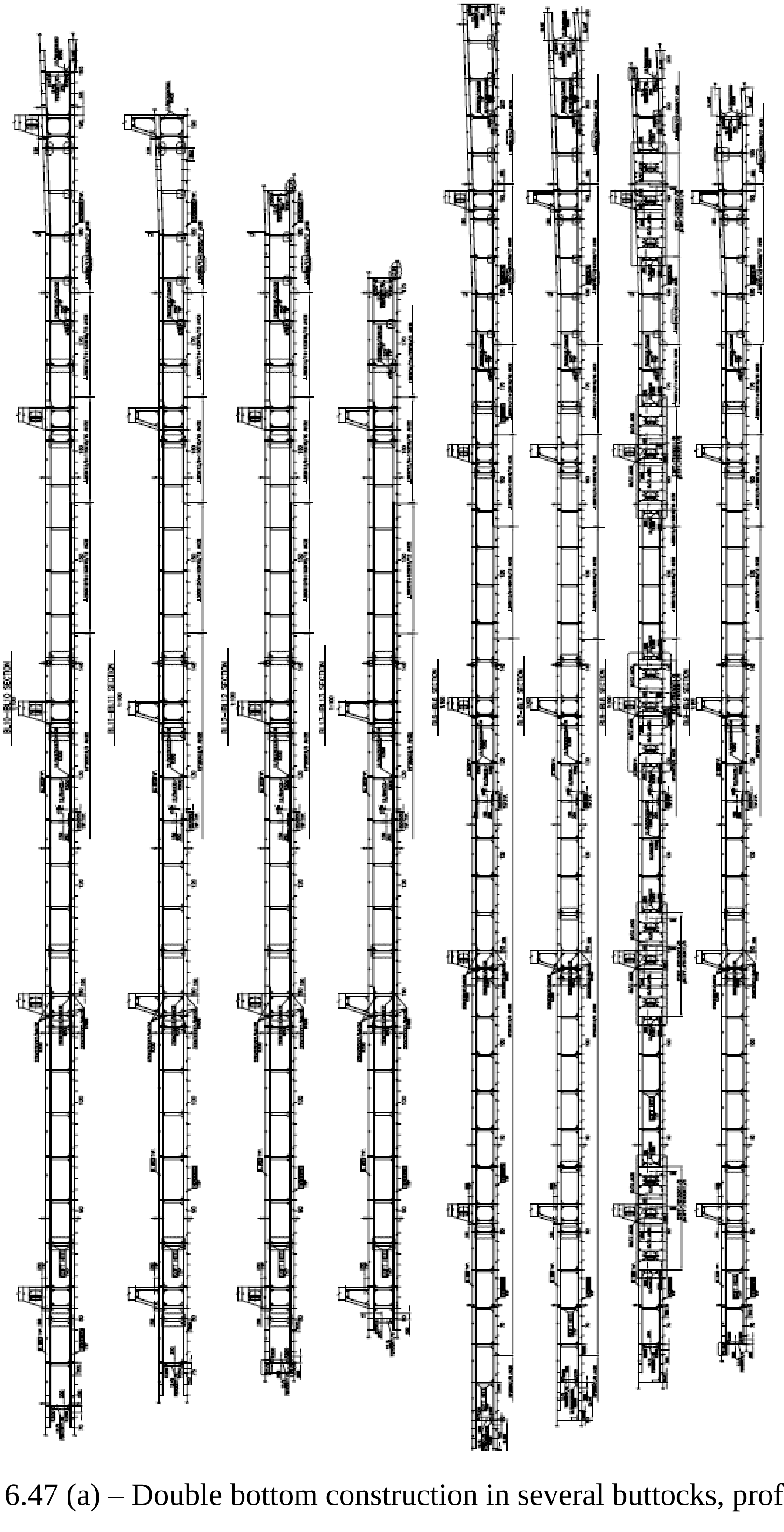


Figure 6.47 (a) – Double bottom construction in several buttocks, profile view

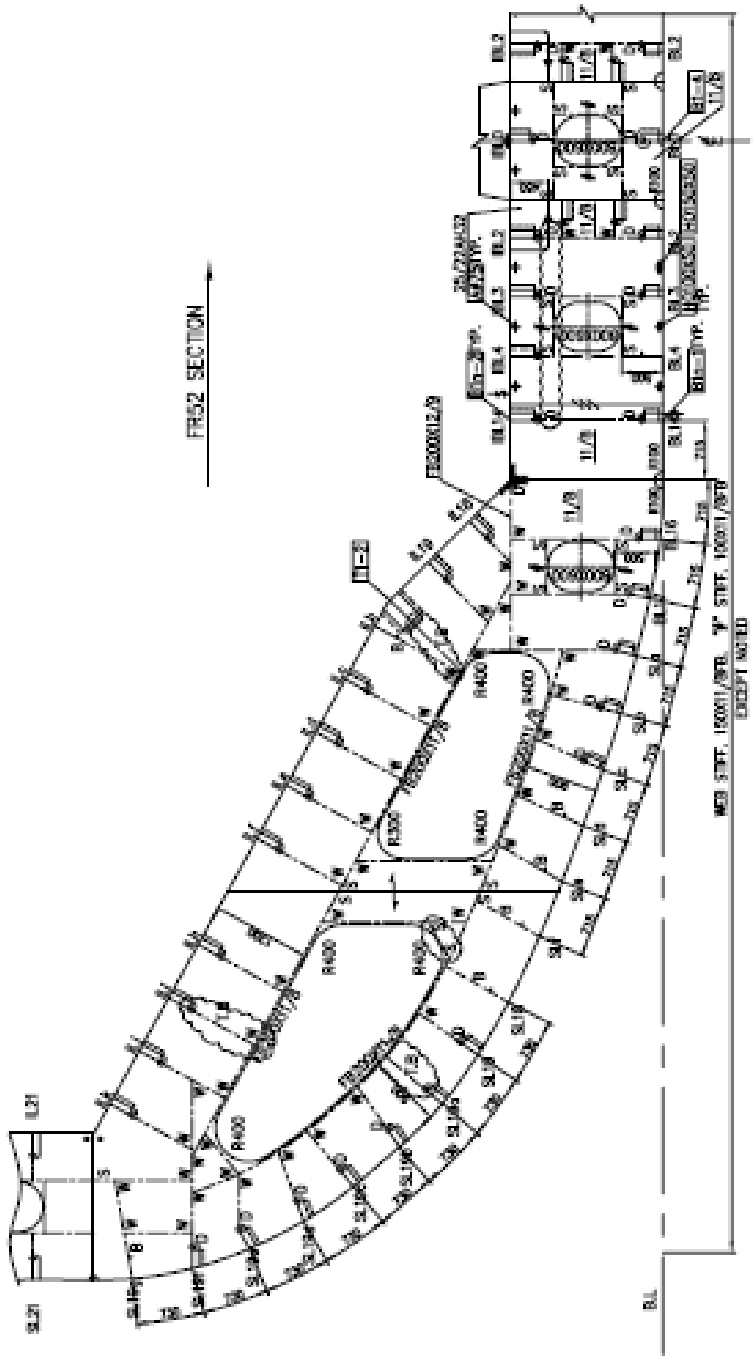


Figure 6.47 (b) – Double bottom construction fr.52, transverse view

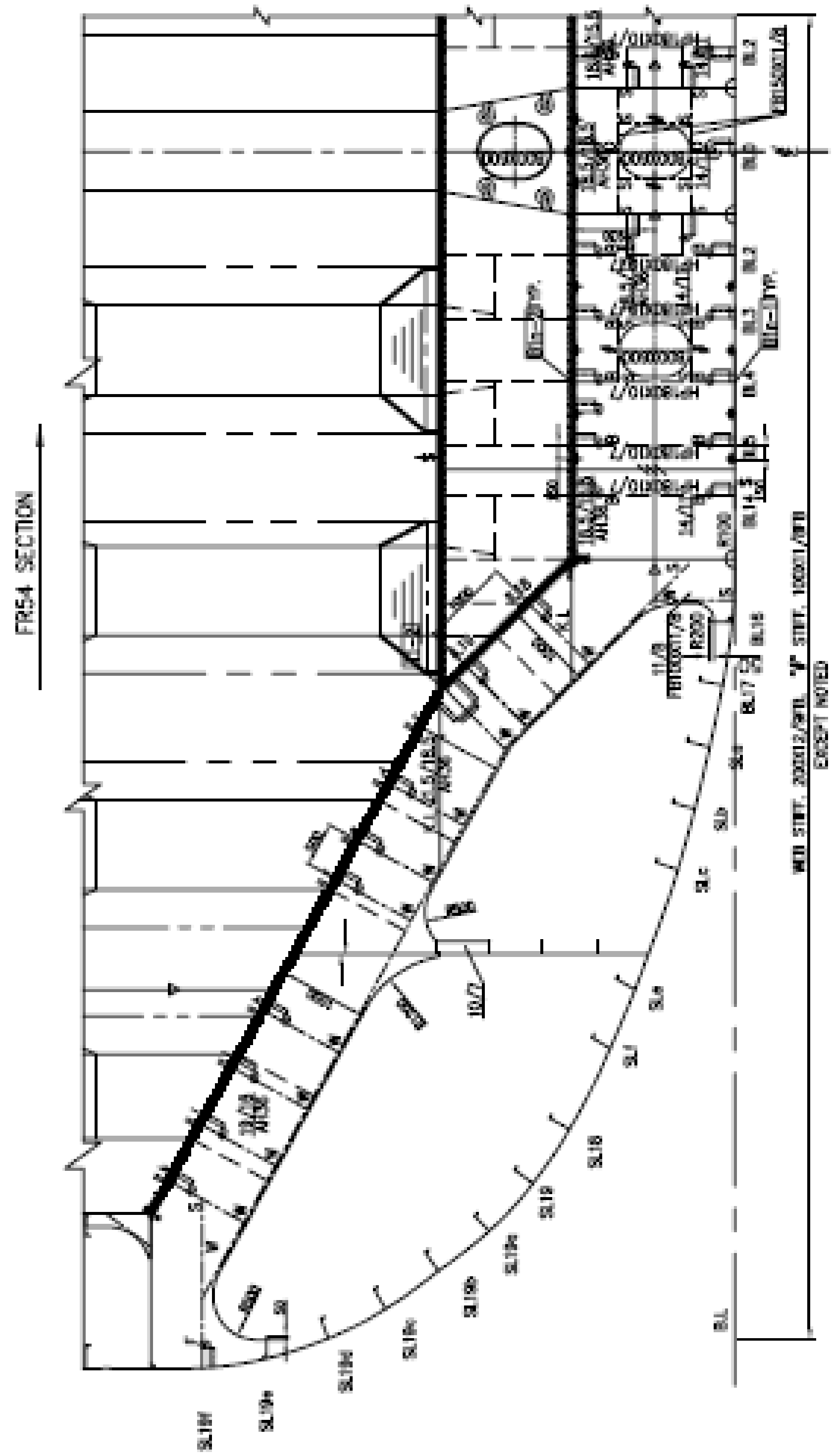


Figure 6.47 (c) – Double bottom construction fr.54, transverse view

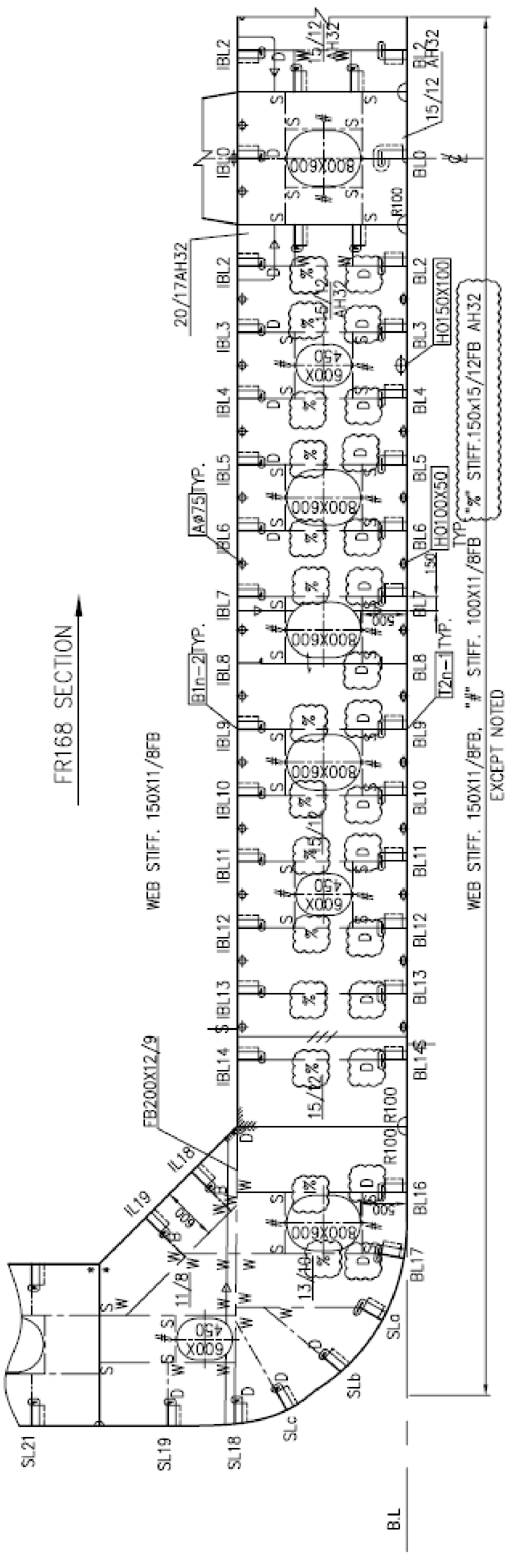


Figure 6.47 (d) – Double bottom construction fr.168, transverse view

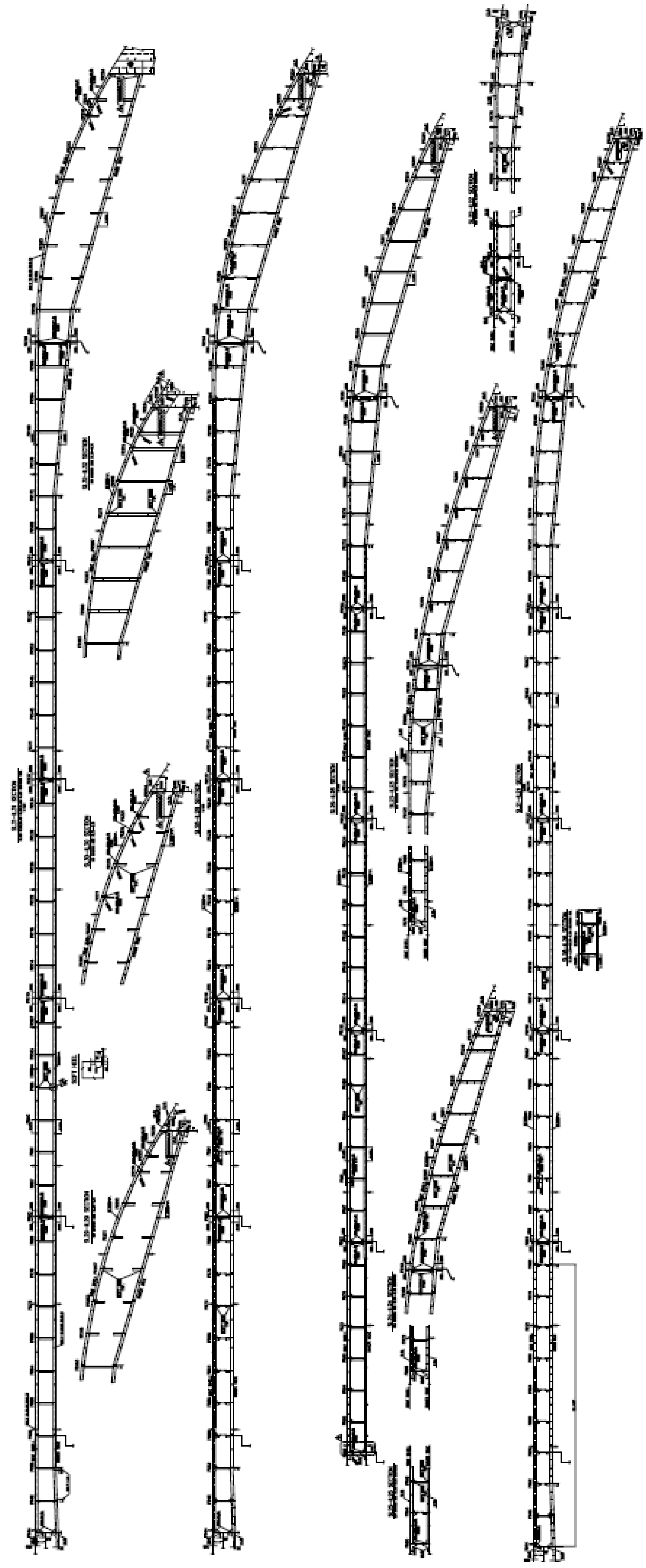


Figure 6.48 (a) – Double side construction in several waterlines, top view

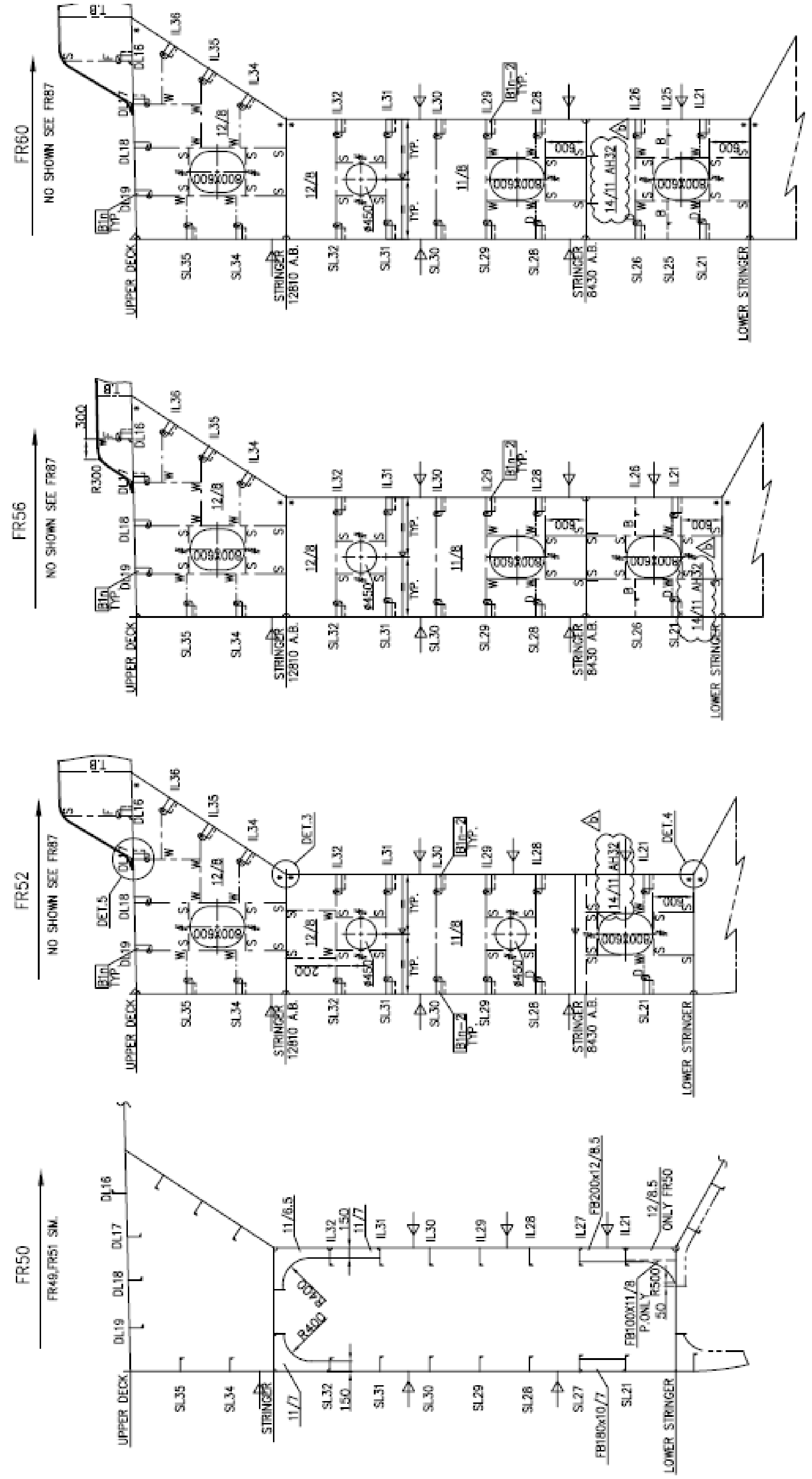


Figure 6.48 (b) – Double side construction in several frame sections, transverse view

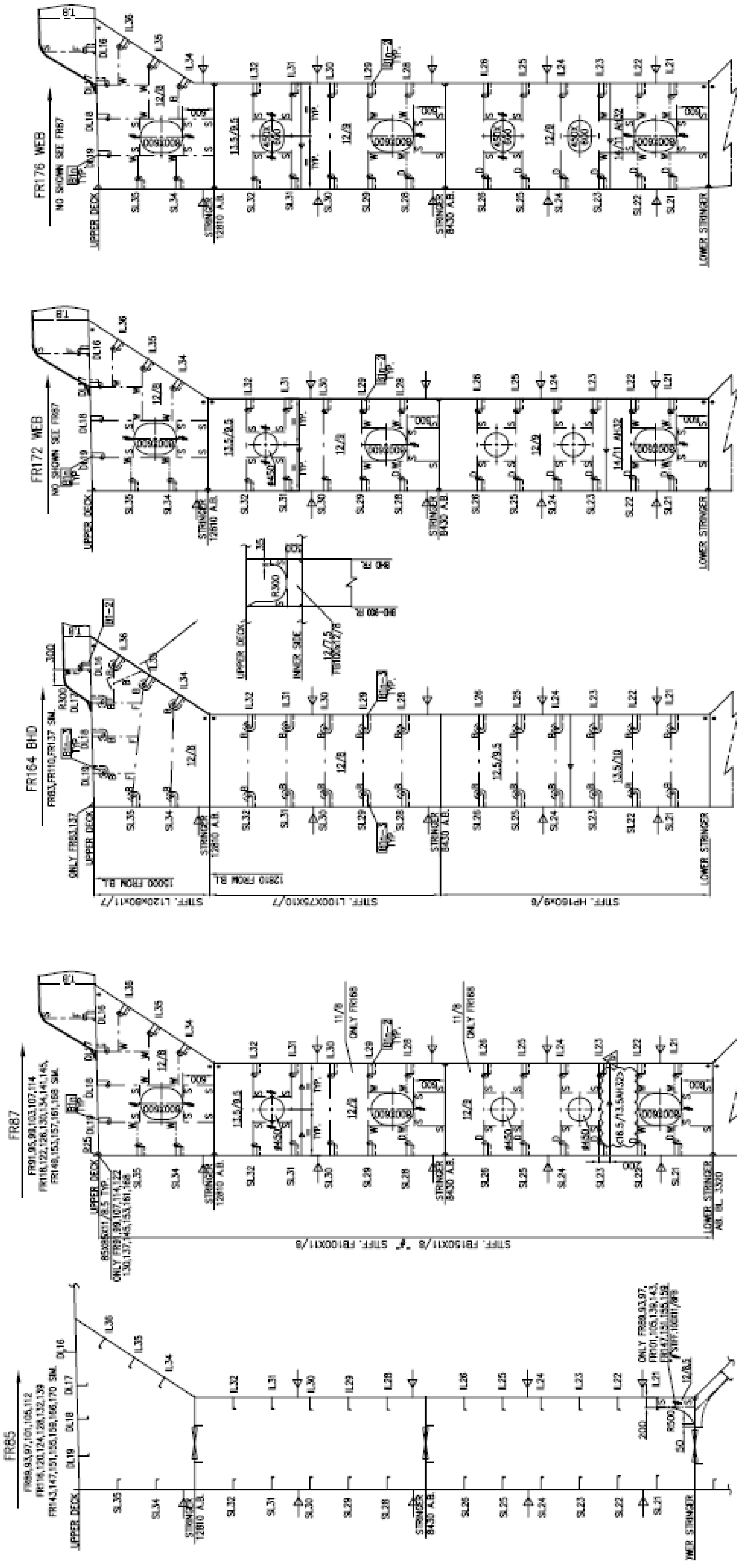


Figure 6.48 (c) – Double side construction in several frame sections, transverse view

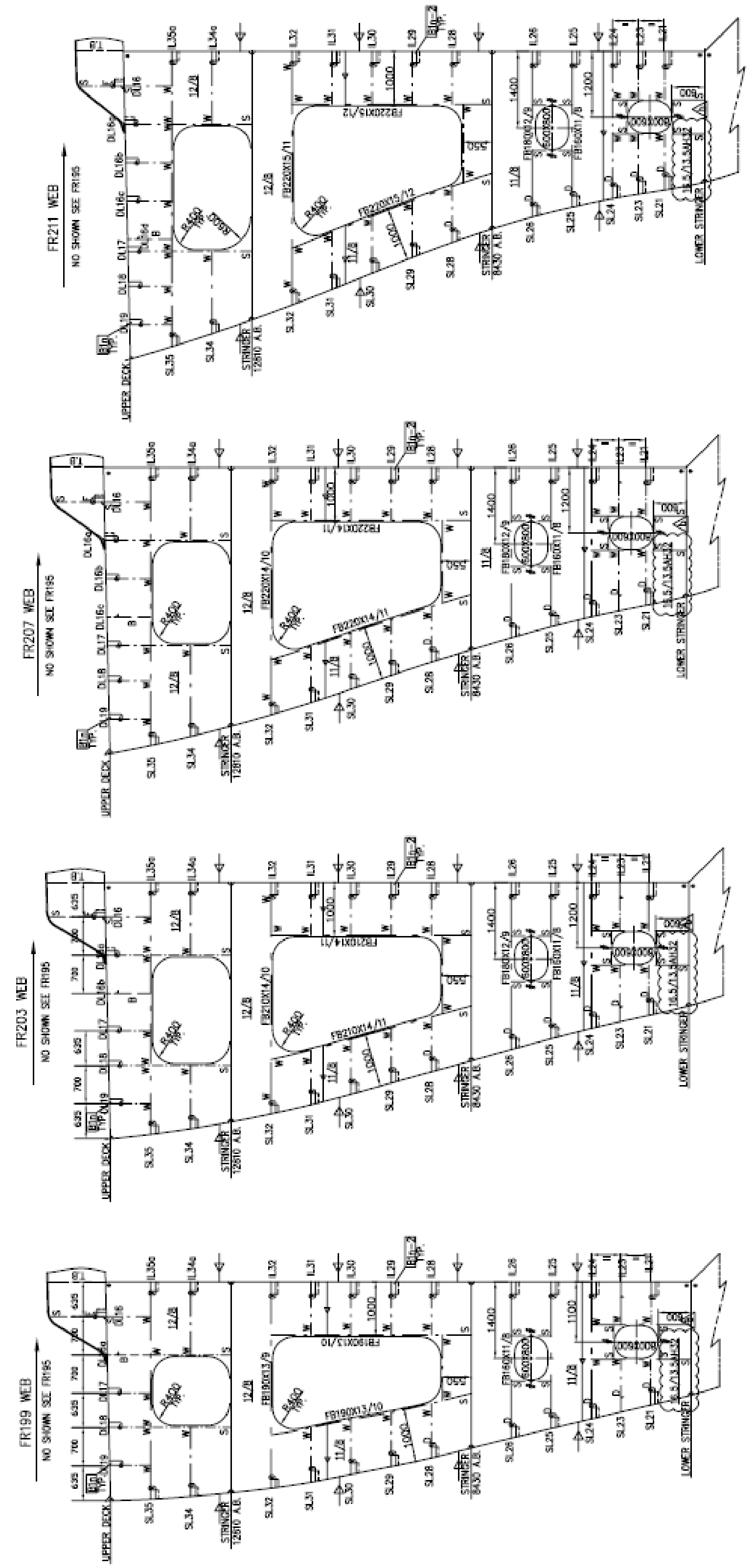


Figure 6.48 (d) – Double side construction in several frame sections, transverse view

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Chapter 7

Cargo Systems

7.1 Introduction

What differentiates modern chemical tankers from product and crude oil tankers, is the amount of sophisticated cargo systems that are installed on board, for the handling and monitoring of the several cargoes. A vessel's cargo system, together with its cargo tank arrangement and safety systems determines the cargoes that a vessel can or cannot carry. The scope of this chapter is to present these cargo systems, and the potential impact they may have on the vessel's structural design.

First, a review is been made to the cargo piping and cargo manifolds arrangements. The method to calculate the piping scantlings is also provided, as per the IBC Code's minimum thickness requirements. Additionally, piping joining details are highlighted and the three types of flanges which are most commonly used in chemical tankers are presented.

Subsequently, an analysis of the cargo pumps used in chemical tankers takes place. More specifically, the analysis focuses on deepwell cargo tanks, as they are the most commonly used type of pumps in chemical tankers. The two types of deepwell pumps, the hydraulically driven ones and the electrically driven ones, are explained, together with their basic functions and operational requirements. Their structural components, such as the deck trunk, the intermediate and bottom supports, the section well, and the pipe stack are also presented, and some useful information about their characteristics are given.

Finally, all other cargo systems that are used on board a chemical tanker, such as tank cleaning systems, tank venting systems, cargo monitoring and control systems, and cargo environmental control systems, are mentioned, and their basic functions are explained.

7.2 Cargo piping

7.2.1 Cargo piping and manifolds arrangement

The main purpose of cargo pipes is to transfer the chemical cargoes from the cargo tanks to the cargo manifolds during the loading/discharging operations. As through the cargo pipes the cargo is transferred outside the area of cargo tanks, and passing through areas where human activity may take place, the proper design of cargo piping is essential in order to avoid exposition of crew members, or sensitive areas of the vessel, to the hazardous cargo.

The modern chemical tanker is based on the concept of the complete segregation of cargoes. For that reason each cargo tank piping system is independent from the vessel's other cargo tanks. This practically means that for each cargo tank, an independent cargo line exists, connecting the pump's discharge line to the respective cargo manifold, through which the cargo is discharged to shore. An additional benefit of this system is that many cargoes can be discharged/loaded simultaneously. When it comes to loading, some cargo systems load the cargo tank by passing the cargo back through the same cargo pipe to the pump outlet. Other systems however utilize a separate drop line that bypasses the pump and delivers the cargo directly to the tank bottom. In that case, the drop line must be connected to the cargo line running from the manifold to the cargo pump outlet. The drop line is beneficial, as it can be used together with the cargo pump to create a loop and recirculate the cargo within a single cargo tank. This could be very useful for cargoes containing large amounts of particulate matter that may settle to the bottom of the tank if the cargo remains stationary.[1]

However, this complete segregation of cargo lines is not applied to all chemical tankers. Cargo transfer systems that consist of a main piping system or several group main systems are also used. This group main system is a piping system generally used in conventional oil tankers and it is useful for chemical tankers if the ships are exclusive used or intended to load only a few non-reactive cargoes.[2] The two types of cargo piping systems are shown in Figures 7.2 and 7.3.

A fully segregated ship has a manifold line for each cargo tank and each manifold line is accessible from each side of the vessel. A ship with group piping systems though, is fitted with one or more large cargo lines or manifolds known as common lines or collecting manifolds. These lines are used to facilitate the loading and discharging of large parcels that are stowed in several cargo tanks. Each cargo tank can be connected to the common line and either load or discharge the cargo through the same large common line and manifold.

Figure 7.1 – Fully segregated ship manifolds

The center of the cargo manifold arrangement should be located at the mid-length of the ship, or as near as possible, but in no case should it be more than 3.0m forward or aft of the mid-length, as given by OCIMF[3]. For these purposes, the ship's length should be taken as the length overall. The centers of the manifold presentation flanges should be located at least 700mm above the horizontal projection of the top of the hose support at the ship's side, but not exceeding 2.1m. The working platform should be fitted to allow 900mm between the level of the platform and the centers of the presentation flanges. Additionally, the distance of the presentation flanges inboard from the ship's side should be 4.6m. The minimum spacing of the cargo manifolds as measured center to center along the line of presentation flanges, varies between 1.5m and 3m and depends on the tonnage of the vessel.

As stated in the IBC code[4], cargo lines shall not be installed under deck between the outboard side of the cargo-containment spaces and the skin of the ship unless specified clearances required for damage protection are fulfilled. Cargo piping located below the main deck may run from the tank it serves and penetrate tank bulkheads or boundaries common to longitudinally or transversally adjacent cargo tanks, ballast tanks, empty tanks, pump-rooms or cargo pump-rooms provided that inside the tank it serves it is fitted with a stop valve operable from the weather deck and provided cargo compatibility is assured in the event of piping failure. As an exception, where a cargo tank is adjacent to a cargo pump-room, the stop valve operable from the weather deck may be situated on the tank bulkhead on the cargo pump-room side, provided an additional valve is fitted between the bulkhead valve and the cargo pump. The above should also apply for cargo pipes which are installed within pipe tunnels.

Special attention should be given during the design of cargo pipes passing through bulkheads, as they shall be arranged in such a way that they preclude excessive stresses derived from the bulkhead's contribution in the vessel's strength. For the same reason, cargo pipes should not utilize flanges bolted through the bulkhead.

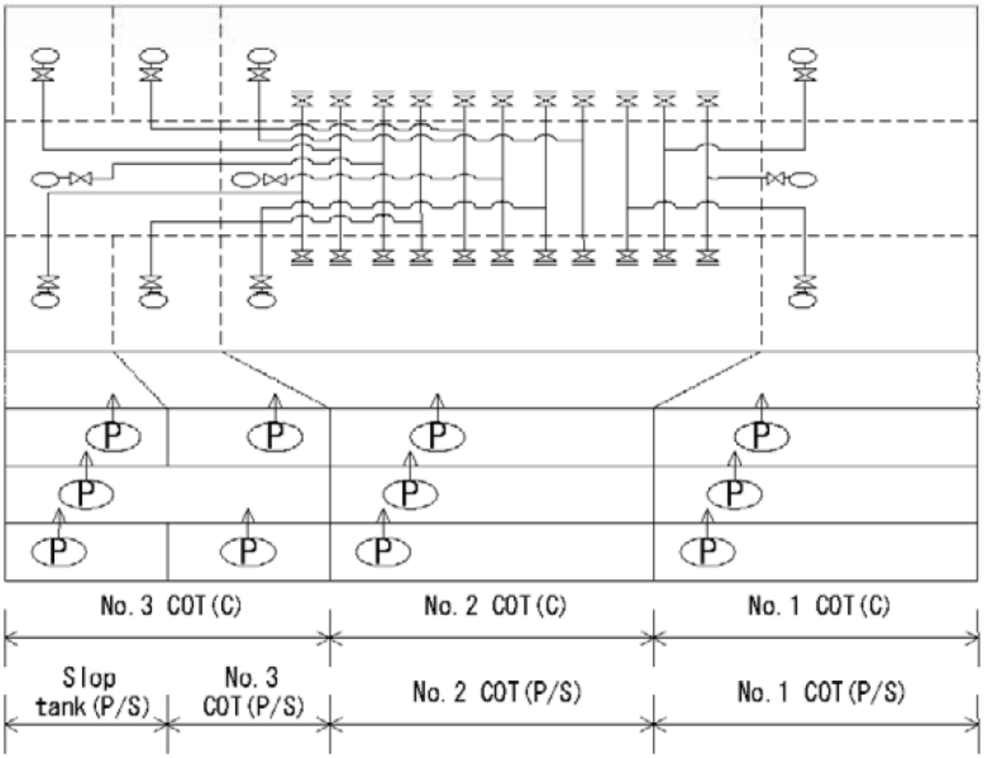


Figure 7.2 – One tank – one pump system

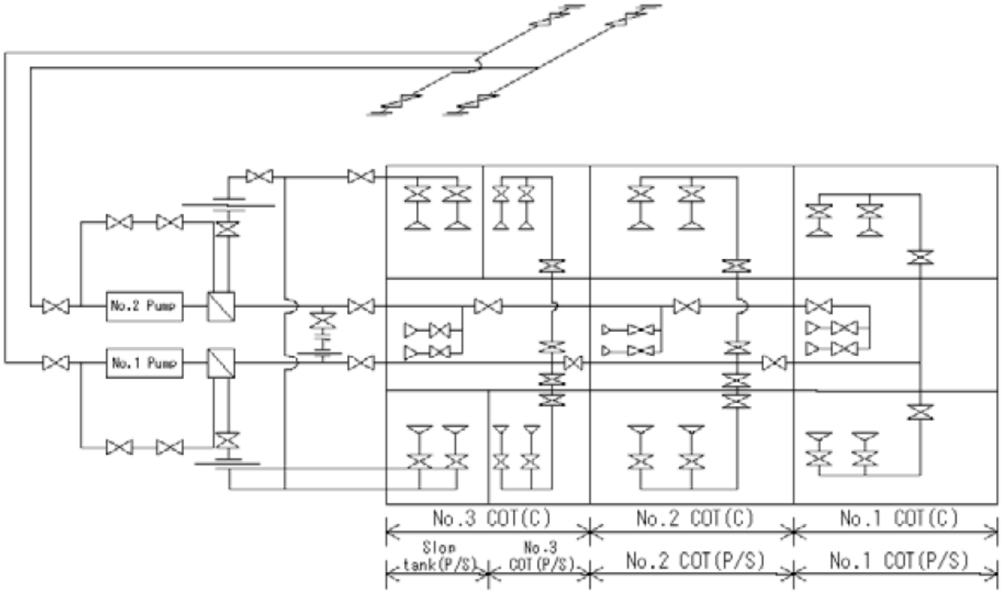


Figure 7.3 – Group main system

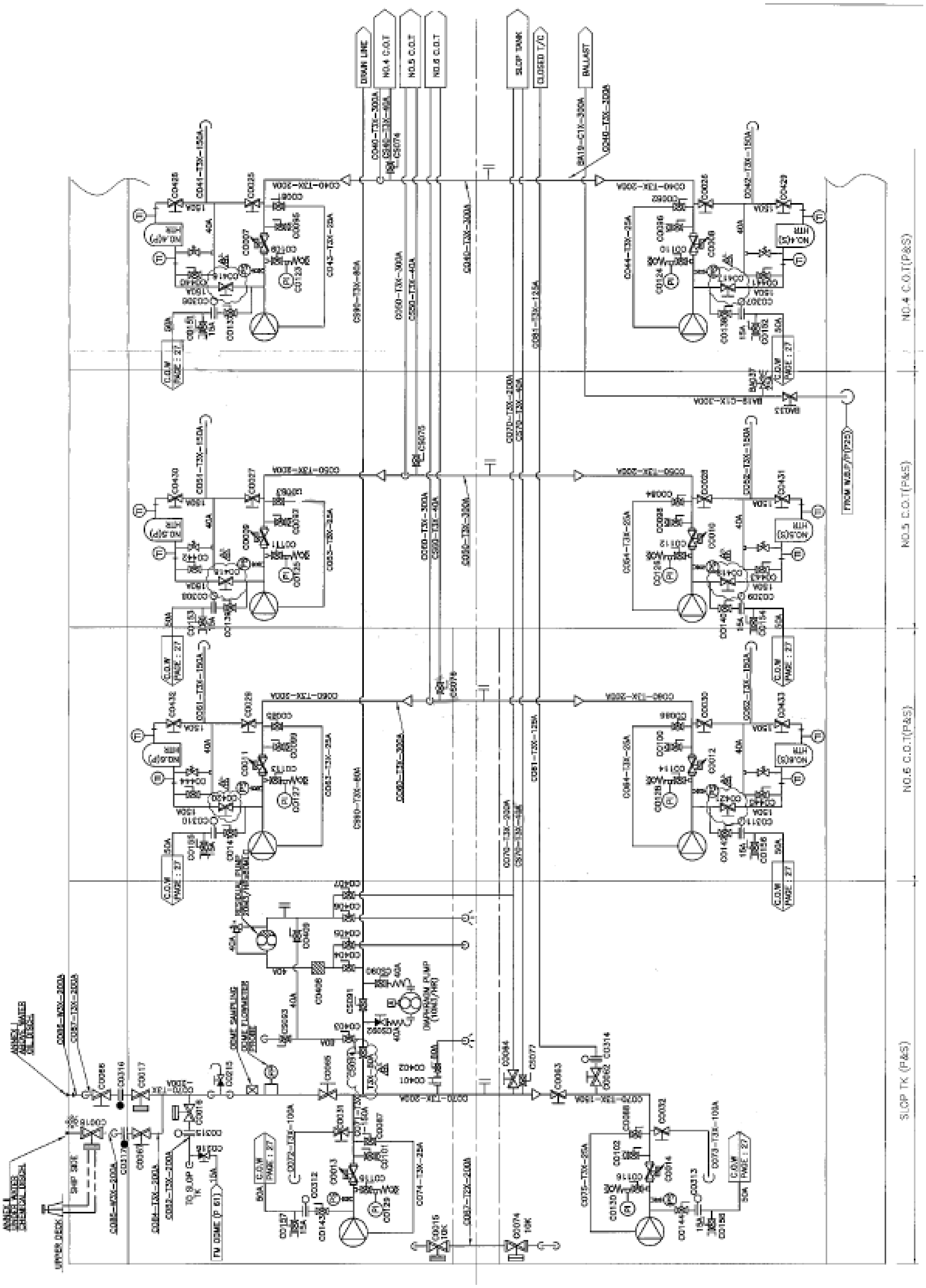


Figure 7.4 a – Hull piping diagram of a 50000 DWT Oil/Chemical tanker

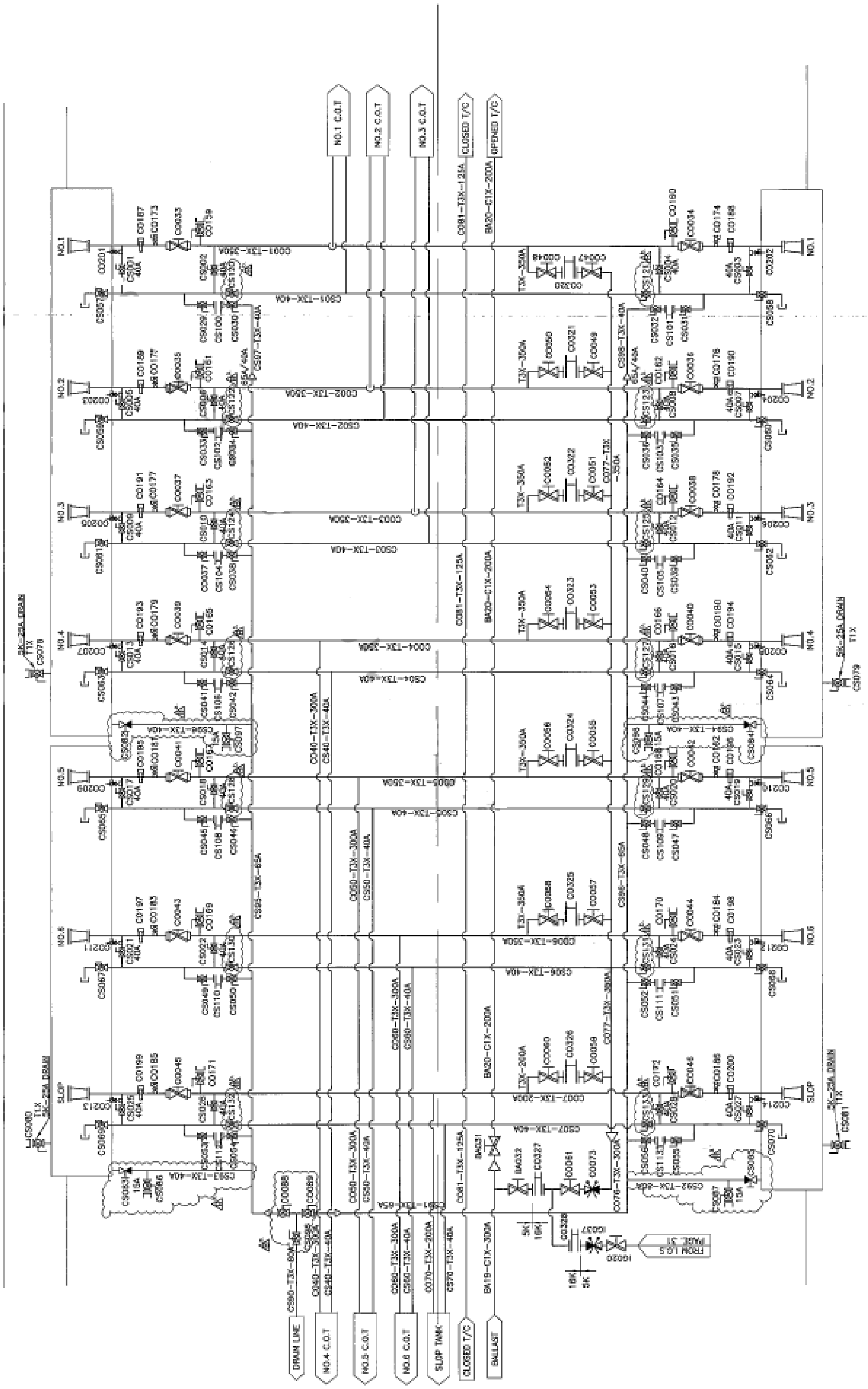


Figure 7.4 b – Hull piping diagram of a 50000 DWT Oil/Chemical tanker

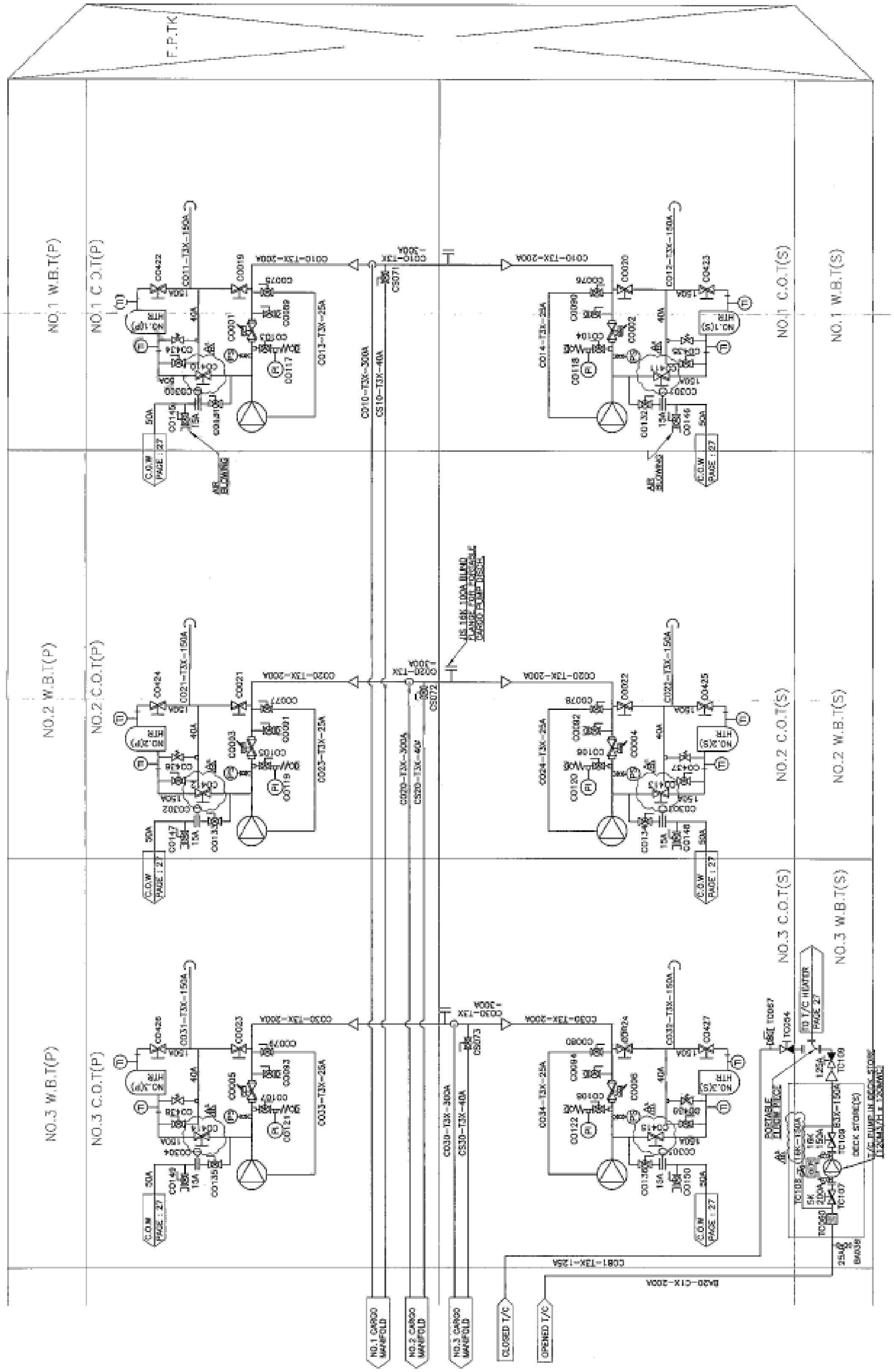


Figure 7.4 c – Hull piping diagram of a 50000 DWT Oil/Chemical tanker

7.2.2 Cargo piping scantlings and material

The wall thickness of the pipes is defined in the IBC Code as follows:

$$t = \frac{t_0 + b + c}{1 - \frac{a}{100}} \text{(mm)}$$

Where:

t_0 = theoretical thickness equal to:

$$t_0 = PD/(2Ke + P) \text{ (mm)}$$

With:

P = design pressure (MPa), equals to the maximum gauge pressure to which the system may be subjected in service, taking into account the highest set pressure on any relief valve on the system.

D = outside diameter

K = allowable stress, equals to the lower of the following values:

$$\frac{R_m}{A} \text{ or } \frac{R_e}{B}$$

Where:

Rm = specified minimum tensile strength at ambient temperature (N/mm^2)

Re = specified minimum yield stress at ambient temperature (N/mm^2). If the stress–strain curve does not show a defined yield stress, the 0.2% proof stress applies.

A and B shall have values of at least A = 2.7 and B = 1.8.

e = efficiency factor equal to 1.0 for seamless pipes and for longitudinally or spirally welded pipes, delivered by approved manufacturers of welded pipes, which are considered equivalent to seamless pipes when non-destructive testing on welds is carried out in accordance with recognized standards. In other cases, an efficiency factor of less than 1.0, in accordance with recognized standards, may be required depending on the manufacturing process.

b = allowance for bending (mm). The value of b shall be chosen so that the calculated stress in the bend, due to internal pressure only, does not exceed the allowable stress. Where such justification is not given, b shall be not less than:

$$b = \frac{Dt_0}{2.5r} \text{ (mm)}$$

With:

r = mean radius of the bend (mm)

c = corrosion allowance (mm). If corrosion or erosion is expected, the wall thickness of piping shall be increased over that required by the other design requirements

a = negative manufacturing tolerance for thickness (%).

The selection of the material for the cargo piping is not an issue for the designer. To protect against corrosion, all of the cargo pipes and manifolds are made of solid stainless steel. This is true both for mild steel – coated chemical tankers and stainless steel chemical tankers.[1]

7.2.3 Joining details

Pipes' connection and joints in chemical tankers are of great importance, due to potential leaks of hazardous cargo, and their design should follow the specific requirements stated in the IBC Code. These requirements are valid for the entire cargo piping system of the vessel, regardless if the pipes are inside or outside the tank region.

In general, all pipes in a chemical tanker are required to be joined by welding. This however does not apply for shutoff valves and expansion joints, as well as for exceptional cases that have been specifically approved.

The type of welded connection depends on the outside diameter of the connected pipes. Butt-welded joints with complete penetration at the root may be used in all applications, when slip-on welded joints with sleeves and related welding having dimensions in accordance with recognized standards shall only be used for pipes with an external diameter of 50 mm or less. However, slip-on welded joints should be avoided when crevice corrosion is expected to occur. Finally, screwed connections may be used, only for accessory and instrumentation lines with external diameters of 25mm or less.

Flanges should be of the welded-neck type, the slip-on type, or the socket-welded type. Socket-welded flanges however, should not be used in nominal size of more than 50mm. The three types of flanges are shown in Figure 7.5 - 7.7.[5]

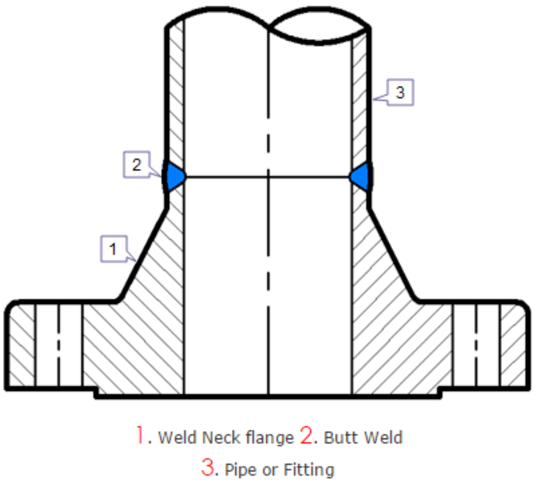


Figure 7.5 – Weld-neck flange

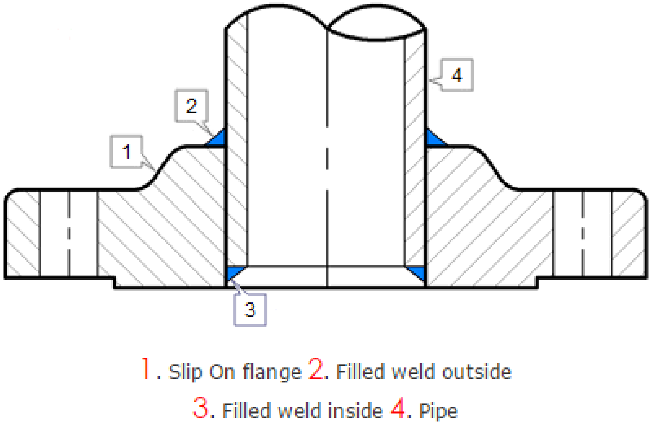


Figure 7.6 – Slip-on flange

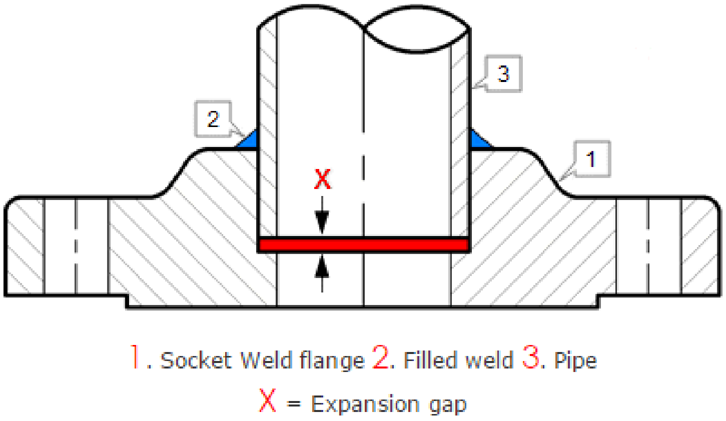


Figure 7.7 – Socket-weld flange

7.2.4 Test requirements

The satisfying and safe operation of the piping systems of a chemical tanker is very important. For that reason any defects of the system shall be spotted and rectified prior to the delivery of the vessel. In order of this to happen testing procedures of the piping systems have become mandatory.

As defined in the IBC Code, after assembly, each cargo piping system shall be subject to a hydrostatic test to at least 1.5 times the design pressure. When piping systems or parts of systems are completely manufactured and equipped with all fittings, the hydrostatic test may be conducted prior to installation aboard the ship. The same applies for joints welded on board and after on board piping modifications take place.

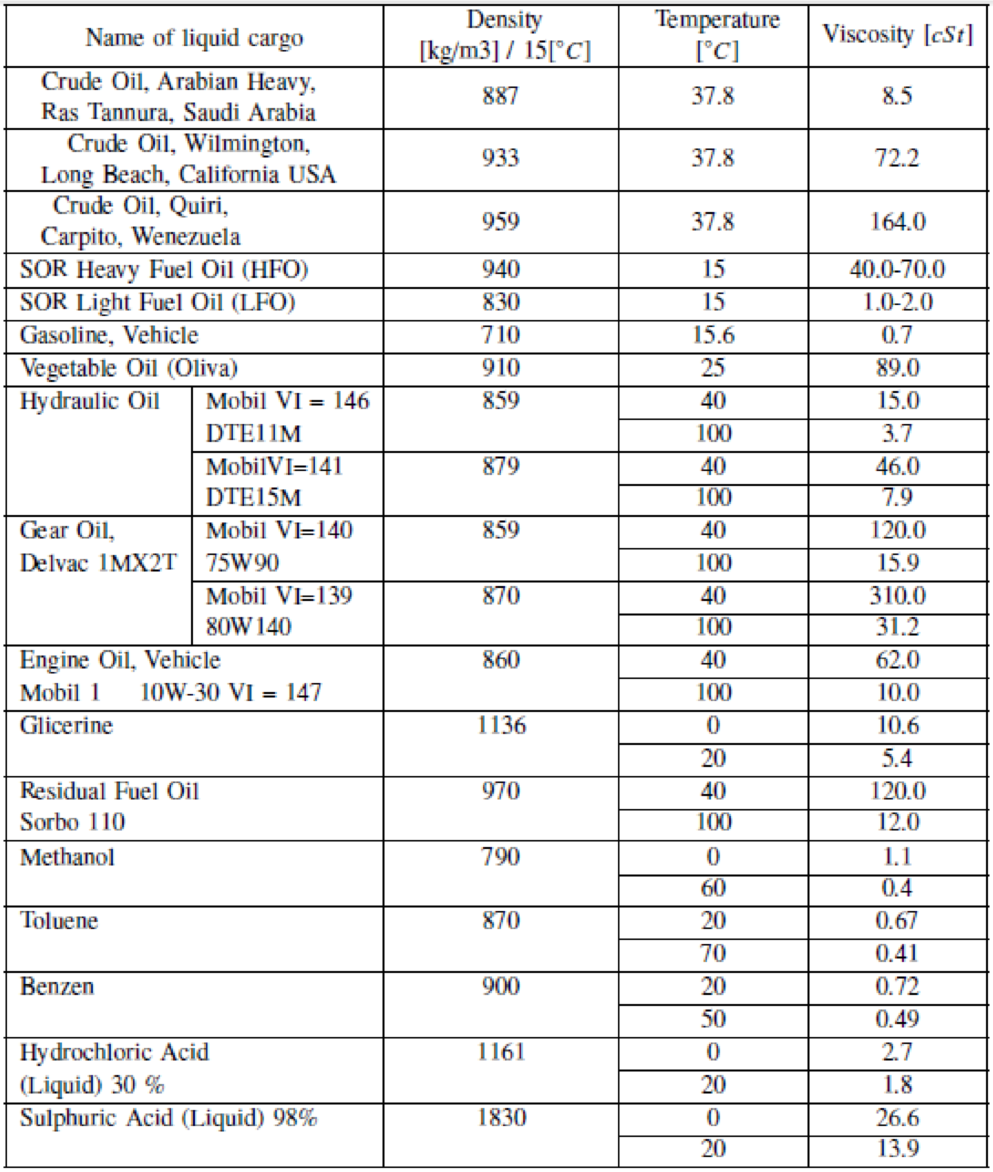
7.3 Cargo pumps

The modern chemical tanker is based on the concept of the complete segregation of cargoes. Each cargo tank is independent from the vessel's other cargo tanks. Additionally, each cargo tank is equipped with a separate cargo pump, designed for liquid cargo service. Such an idea of cargo system allows for simultaneous transport of diverse liquid cargoes during one sea voyage. It also allows for simultaneously loading – discharging operations in different tanks, and as a result reduced residence time in port.

As stated by Werner[6], at the heart of the complete segregation approach is the deepwell cargo pump. As its name suggests, a deepwell pump is submerged in the fluid that it is pumping, with its impeller placed in a well in the cargo tank bottom. Deepwell cargo pumps are of centrifugal type and are driven by either a hydraulic motor located in the tank with the impeller, or by an electric motor that drives a shaft that runs from the deck down to the impeller in the tank.

Hydraulically driven pumps of this type are more commonly used on chemical tankers than the electrically driven ones mostly for two reasons: because the electrical motors is preferred to be eliminated from the cargo tank region, and because hydraulic driven pumps offer variable speed control. Submerged hydraulic pumps are available with cargo flow rates ranging from 50 m^3/h to 2000 m^3/h and discharge heads in excess of 160 mlc.

One disadvantage of the deepwell cargo pumps is that they do not pump high viscosity cargoes well. As the density and kinematic viscosity of the carried liquid cargoes vary from cargo to cargo, some cargoes are easier to be pumped than others. In Figure 7.8, the values of density and viscosity for the most common type of cargoes are presented[7]. In order to encounter this issue, chemical tankers that frequently carry high viscosity cargoes, such as molasses, are typically outfitted with a deck-mounted booster pump to assist in the discharge process. These booster pumps are of the positive displacement type, with screw pumps being used most often.



Name of liquid cargo		Density [kg/m3] / 15[°C]	Temperature [°C]	Viscosity [cSt]
Crude Oil, Arabian Heavy, Ras Tannura, Saudi Arabia		887	37.8	8.5
Crude Oil, Wilmington, Long Beach, California USA		933	37.8	72.2
Crude Oil, Quiri, Carpito, Wenezuela		959	37.8	164.0
SOR Heavy Fuel Oil (HFO)		940	15	40.0-70.0
SOR Light Fuel Oil (LFO)		830	15	1.0-2.0
Gasoline, Vehicle		710	15.6	0.7
Vegetable Oil (Oliva)		910	25	89.0
Hydraulic Oil	Mobil VI = 146 DTE11M	859	40	15.0
			100	3.7
	MobilVI=141 DTE15M	879	40	46.0
			100	7.9
Gear Oil, Delvac 1MX2T	Mobil VI=140 75W90	859	40	120.0
			100	15.9
	Mobil VI=139 80W140	870	40	310.0
			100	31.2
Engine Oil, Vehicle Mobil 1 10W-30 VI = 147		860	40	62.0
			100	10.0
Glicerine		1136	0	10.6
			20	5.4
Residual Fuel Oil Sorbo 110		970	40	120.0
			100	12.0
Methanol		790	0	1.1
			60	0.4
Toluene		870	20	0.67
			70	0.41
Benzen		900	20	0.72
			50	0.49
Hydrochloric Acid (Liquid) 30 %		1161	0	2.7
			20	1.8
Sulphuric Acid (Liquid) 98%		1830	0	26.6
			20	13.9

Figure 7.8 – Density and kinematic viscosity coefficient of standard liquid cargoes on sea transport market

In the electrically driven deepwell pumps, the motion is transferred from the electric motor that is placed on deck to the impeller that is placed on the bottom of the tank, through a rotating driveshaft. The pump is designed in such a way, so that the driving shaft is separate from the liquid cargo. The pump stack consists of two pipes: one is for cargo discharge, and the other is an enclosure that contains the intermediate driving shaft, the shaft bearing and the lubricating oil. The separation of the shaft from the cargo gives the following advantages[8,9]:

- The intermediate shaft can be made from a heat treatable steel, which is ideal for this purpose. If the shaft was exposed to the cargo, it would be necessary to use a - not so suitable -more corrosion resistant material.
- Because the shaft is oil-lubricated, the pump bearings never runs ‘dry’ during stripping and tank cleaning operations, so there is no danger of explosion as a result of overheating of intermediate shaft bearings, and the service life of the shaft bearings is extended.
- Because the intermediate shaft and bearings are oil-lubricated, the pump can run at relatively high speeds. This results in a single stage deepwell pump.

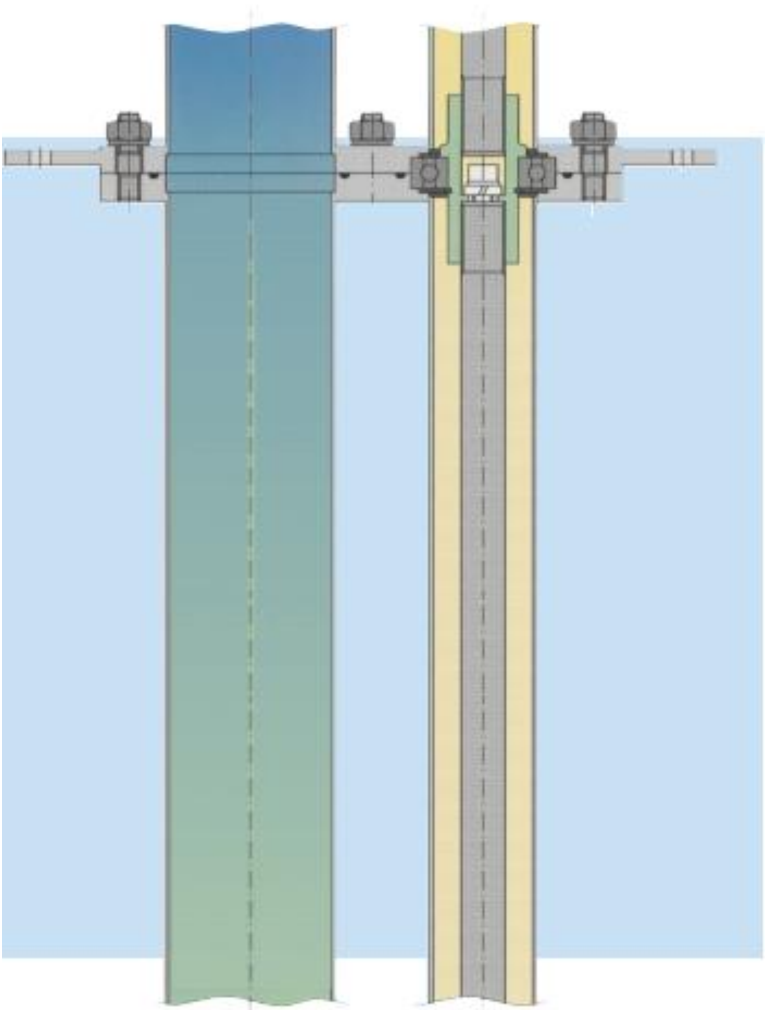


Figure 7.9 – Separation of the shaft in the electrical deepwell pump

Pumps with hydraulic drive are also of one stage. Their main elements are: the head of pump, the concentric hydraulic lines with cargo discharge pipe and the deck trunk with a hydraulic control block and connection ports to the cargo deck installation, and other (e.g. hydraulic) service installations. The structure of a pump with hydraulic drive is shown in Figure 7.10.

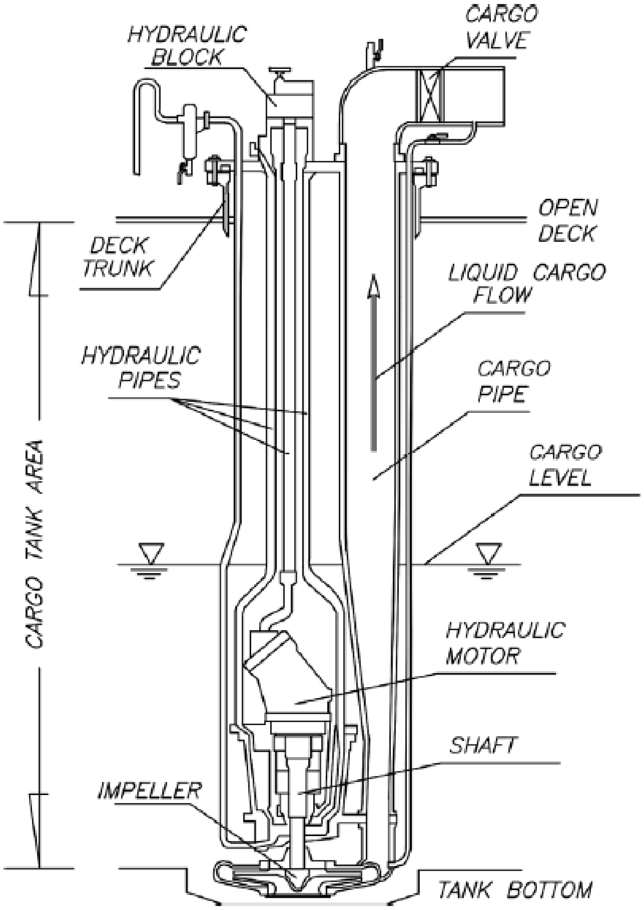


Figure 7.10 – Structure of hydraulic driven deepwell pump

In the head, situated in the lower part of the pump, there is an impeller driven by the hydraulic motor. The hydraulic motor is supplied by means of a concentric pipe system, in which hydraulic oil flows from the control block mounted on the deck trunk. The liquid cargo, pumped by the impeller, flows through the separate cargo pipe mounted in the pump structure to the deck trunk connection port.[10]

Power for the hydraulic pumps is provided by electrically driven hydraulic power packs that are typically located in an enclosed space aft or forward of the cargo area. It is preferred though to be located aft, so that is it closer to the machinery spaces. As hydraulic power packs tend to be very loud, with noise output in the higher frequency range, they should not be located very close to accommodation, and proper insulation should be provided. These power packs are made up of at least three electric motor / hydraulic pump combinations to provide redundancy in the system and efficiency at reduced loads. The hydraulic fluid is delivered from the power packs to the cargo pumps via high-pressure hydraulic piping. Once at the pump, the fluid enters a flow control valve, which determined how much hydraulic fluid is delivered to the hydraulic motor. After passing through the hydraulic motor, the hydraulic fluid returns to the power packs via lower pressure hydraulic lines.

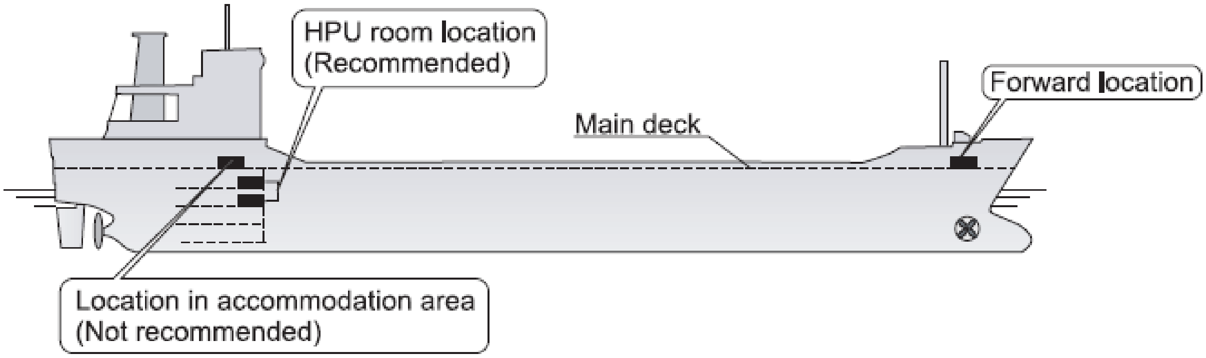


Figure 7.11 – Location of hydraulic power unit

As stated by DNV[11], hydraulically powered pumps, submerged in cargo tanks, shall be arranged with double barriers, preventing the hydraulic system serving the pumps from being directly exposed to the cargo. The double barrier shall be arranged for detection and drainage of possible cargo leakage.

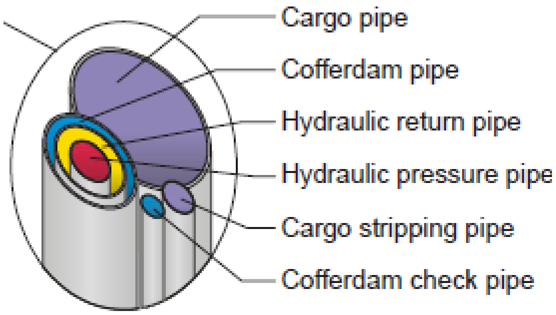


Figure 7.12 – Hydraulic pump pipe stack section

Submerged cargo pumps should be installed at the aft end or in the lowest part of each tank, located either to port or starboard, so that optimal tank emptying is feasible. The arrangement and installation of a cargo pump should be very precise, and for that reason the recommendations[12] from the manufacturers should be followed.

It is very likely, that during its service life a cargo pump will need to be removed and landed to shore for repairs. For that reason, appropriate precautions shall be taken in order to facilitate this removal. An obstruction-free zone on the deck, above the pump, makes it possible to lift the complete pump if necessary.

The cargo pump is supported by a deck trunk welded on the deck. A special gasket and a resilient bolt arrangement are required, in order to prevent noise and eliminate potential cargo leakage on the deck. The arrangement should also provide sufficient access to the pump for operation and maintenance. It is very important that the area close to the trunk is rigid enough to withstand the weight of the pump without any failure or deformations. For that reason, reinforcement of the area by the use of additional stiffeners may be required.

When the pump is long enough, additional support should be provided. This is obtained by brackets which are part of the ship's design and are attached to the bulkheads. During the design of these brackets, all forces that act in the tank area, such as sloshing, structural deflection etc., as well as the forces that are expected to be applied at the bracket by the pump, should be taken into account. When the pump is, under all circumstances, made of stainless steel, the intermediate supports may be of the same material as the cargo tank.

As corrugated bulkheads are the most commonly used bulkheads in chemical tankers, special attention should be given to the transverse position of the supporting brackets. In order of the supports not to affect or be affected by the geometry of the corrugations, the guidelines shown in Figure 7.13 should be followed.

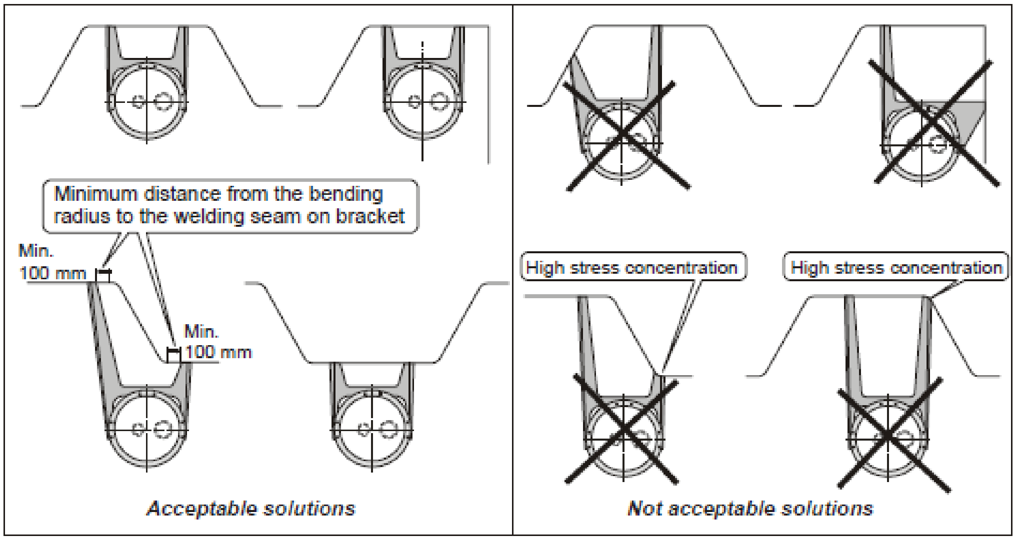


Figure 7.13 – Intermediate support transverse location

The vertical location of the brackets depends on the length of the pump. For very long pumps, applications with two supporting brackets may be required. To find the length of the pump and the location of the brackets, calculations as per Figure 7.14 need to be done.

Pump length:

$$L = TB + S - C$$

One intermediate support	
Height [mm]	Factor k_1
A1= k_1 x L	$0.35 \le k_1 \le 0.4$

Two intermediate supports	
Height [mm]	Factors k_2 k_3
A1= k_2 x L	$0.25 \le k_2 \le 0.3$
A2= k_3 x L	$0.55 \le k_3 \le 0.6$

L = Pump length [mm]
S = Gasket, approx. 2 mm.
C = Pump clearance, see dimensional drawing
P = Bottom support height [mm] (See dimensional drawing)
A1 = Intermediate support height [mm]
A2 = Intermediate support height [mm]
H = Deck trunk height [mm] *
TB = Height from bottom of suction well to top of deck trunk [mm]

* Standard deck trunk height, 500 mm. (High deck trunks complicates the cleaning work.)

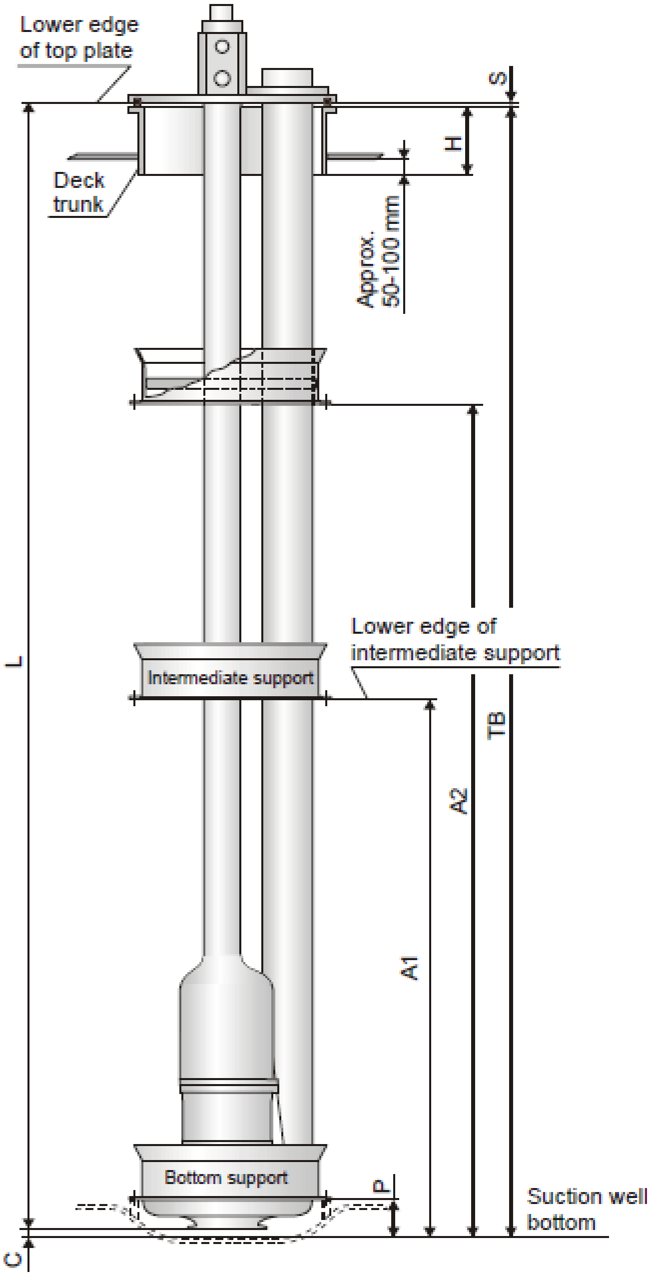


Figure 7.14 – Intermediate support vertical location

The bottom arrangement of the pump also plays a significant role in the pump's correct operation, and should be designed accordingly. The implementation of suction well at the tank bottom construction beneath the pump is important, as it offers optimal cargo pumping, stripping, and service access. It is important that the bottom arrangement is designed to ensure that all the cargo flows into the suction well at the end of discharging. The condition of trim/list of the vessel during discharging operation should also be taken into consideration during the design of the bottom arrangement. Additionally, the bottom arrangement must ensure necessary space for service of pump and removal of pump head.

The location of the brackets of bottom support and the minimum distance to heating coils, should be designed in such a way as not to affect the flow of the liquid cargo to the pump's suction (Figure 7.15). The purpose of the bottom supports is, primary to eliminate the free movement and vibration of the pump, and secondary to support the pumps weight. Two typical arrangements of bottom supports are shown in Figure 7.16.

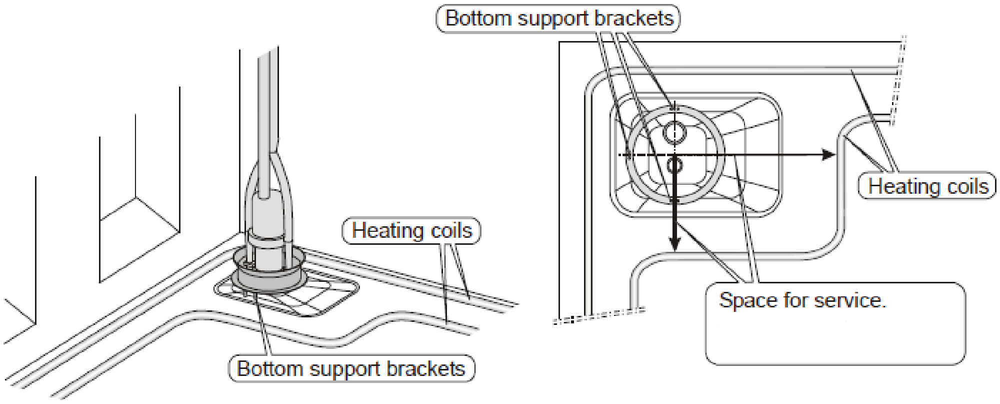


Figure 7.15 – Suction well arrangement

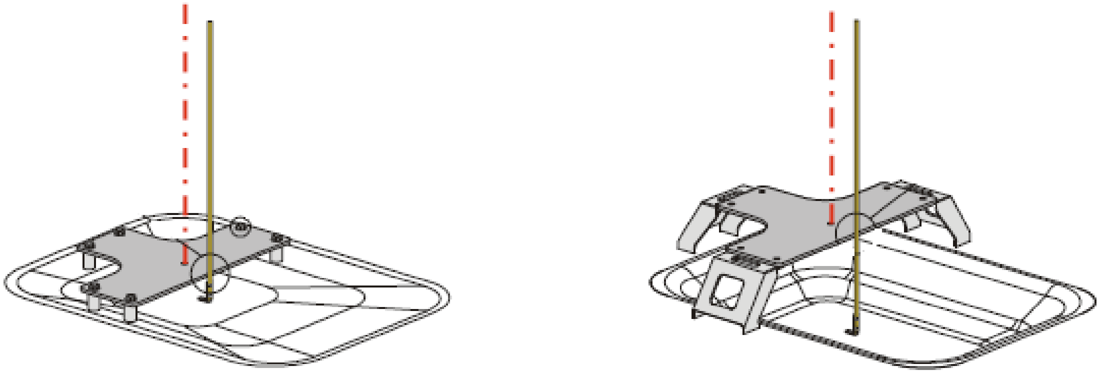


Figure 7.16 – Typical arrangements of bottom supports

The surface of the suction well is an area exposed to mechanical wear and corrosion to a greater extent than the other internal surfaces of the cargo tank. The reason is that during operation of the pump the relative motion between particles in the cargo tank and the tank surface will cause erosive wear. Additionally, residual water which usually accumulates at the bottom surface of the suction well, is likely to be acidic and induce corrosion.

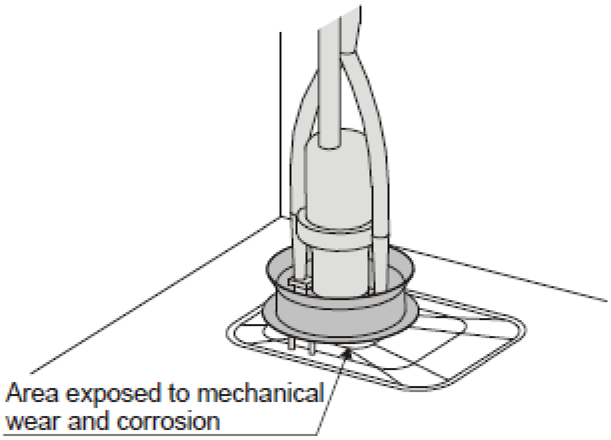


Figure 7.17 – Suction well

For that reason, special attention must be paid to the coating of the pump suction well. The selected coating must be resistant to mechanical (erosive and abrasive) wear. Additionally, the film thickness of the coating must be sufficient and discontinuities of the coating like pinholes must be avoided. For suction wells made of stainless steel, a sweep blasting of the suction well with a chloride free non-metallic abrasive could lead to optimal results.

Due to the importance of the coating in suction well to maintain its initial thickness and properties, inspection shall take place in regular intervals, so that the coating system is examined for discontinuities such as porosity. A low-voltage wet sponge tester is commonly used for this purpose. The film-thickness of the coating shall be also measured with a non-destructive dry-film thickness gauge.

7.4 Tank cleaning systems

As defined by MARPOL[13], ships carrying category A substances and high viscosity / solidifying B and C substances should be fitted with tank washing machines, in order to wash the surface of the tank structure and reduce cargo residues as much as possible. The machines should be of a rotary water jet type, operating at sufficiently high water pressure.

In the past chemical tankers and, to a certain extent, product tankers relied on sea water or fresh water cleaning using portable tank cleaning machines fixed to the end of flexible rubber hoses. Today, tank cleaning on such ships is carried out using fixed machines, operated from the cargo control room, an arrangement which is much less labor-intensive and ensures a fully enclosed procedure.[14]

Werner[15] explains how fixed tank cleaning machines perform the actual tank-cleaning by spraying the tank-cleaning media at high velocity from spinning nozzles on the machine's cleaning head. The number of fixed machines per tank varies, as the number installed in a particular tank is determined by the tank's size, shape, and structural arrangement. The number of machines installed in a tank must be sufficient to ensure that the combined spray patterns reach all areas of the cargo tank structure. A typical tank cleaning machine, while in operation, is shown in Figure 7.18.

Figure 7.18 – Tank cleaning machine

Some fixed tank machines are set at a fixed distance below the underside of the deck, while others can telescope and automatically extend and retract in the tank while the cleaning head turns and the nozzles spin.

The tank cleaning machines are connected to tank cleaning pumps and tank cleaning heaters. The pumps supply fresh water or sea water to the tank cleaning machine, while the heaters raise the temperature of the water that will be used in order to facilitate the cleaning procedure. The temperature at which the water should be heated is defined by MARPOL and depends on the cargo.

Fixed tank cleaning machines – as well as portable, whenever they are used – must be always constructed of stainless steel to prevent them from being corroded by hot seawater, aggressive cargo residues, and cleaning solvents.

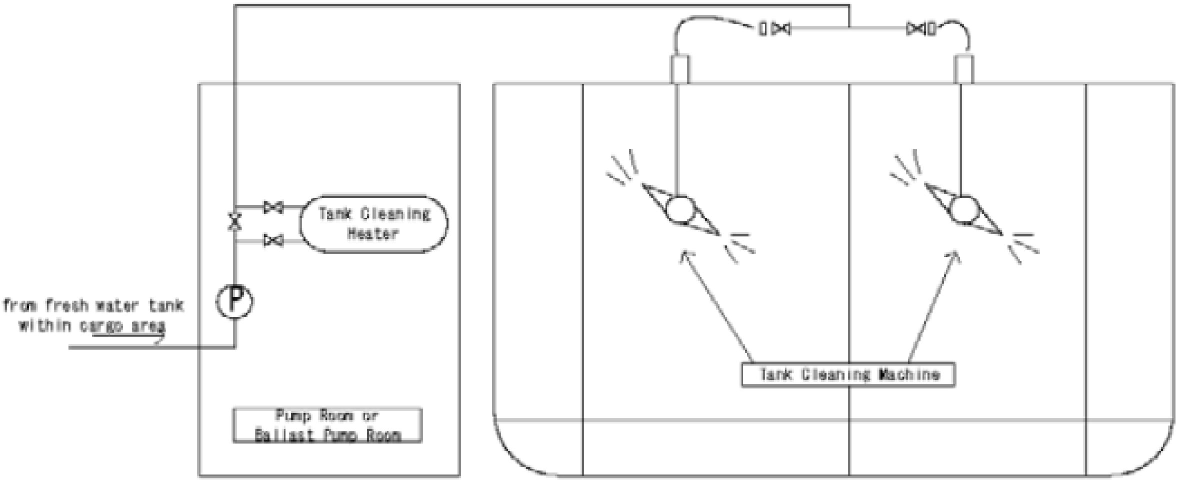


Figure 7.19 – Pre-wash arrangement

7.5 Cargo tank venting systems

As defined in the IBC Code[16], all cargo tanks of a chemical tanker shall be provided with a venting system appropriate to the cargo being carried. These systems shall be independent of the air pipes and venting systems of all other compartments of the ship. Tank venting systems shall be designed so as to minimize the possibility of cargo vapour accumulating about the decks, entering accommodation, service and machinery spaces and control stations and, in the case of flammable vapors, entering or collecting in spaces or areas containing sources of ignition. Additionally, tank venting systems shall be arranged to prevent entrance of water into the cargo tanks and, at the same time, vent outlets shall direct the vapour discharge upwards in the form of unimpeded jets.

The cargo tank venting system of a chemical tanker must be designed in such a way, so that it prevents the development of high pressures or a vacuum in the in a cargo tank during loading, discharging, or sailing. There are two types of cargo tank venting systems; the open tank venting systems and the controlled tank venting systems, as described by class NK.[17]

Open tank venting offers no restriction – except for friction loses and flame screens, if fitted – to the free flow of cargo vapors to and from the cargo tanks during normal operation, and should only be used for cargoes having a flash point above 60°C and not offering a significant inhalation health hazard. An open venting may consist of individual vents from each tank, or such individual vents may be combined into a common header or headers, with due regard to cargo segregation. However, under no circumstances should shut off valves be fitted neither to the individual vents nor to the header.

Controlled tank venting is a venting type in which pressure/vacuum valves are fitted to each tank to limit the pressure or vacuum in the tank. Controlled venting systems are used for cargoes other than those for which open venting system is permitted. They may consist of individual vents from each tank or such individual vents on the pressure side only as may be combined into a common header or headers with due regard to cargo segregation. In no case should shut off valves be fitted neither above nor below pressure/vacuum valves. Provision however may be made for bypassing a pressure/vacuum valve under certain operating conditions, provided that flame arrester is fitted and that there is suitable indication to show whether or not the valve is bypassed. The vent piping and pressure/vacuum valves should be made of corrosion resistant materials such as stainless steel in order to prevent damage from cargo vapors.

A typical operation of a pressure/vacuum valve is shown in Figure 7.20. As the pressure in the storage tank increases, the vacuum pallet is held shut. When the set pressure is reached, the pressure pallet lifts and relieves tank pressure to the atmosphere (or to a header if it is a pipe away valve) (Figure 7.20 a). On the other hand. As a vacuum is drawn in the storage tank (for example, when fluid is being pumped out), the pressure pallet is held shut. When the vacuum setting is reached, the vacuum pallet lifts and air is drawn into the tank from the atmosphere (Figure 7.20 b).[18]

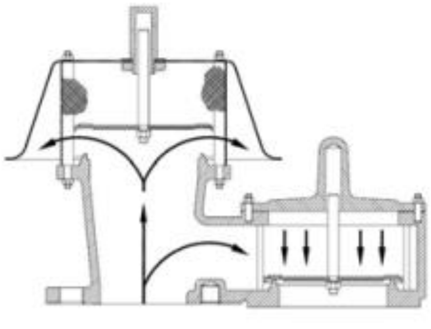


Figure 7.20 a – Pressure relief

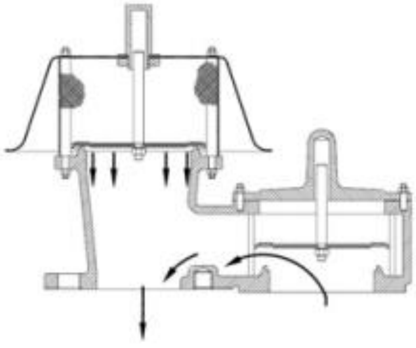


Figure 7.20 b – Vacuum relief

Class NK provides also guidelines regarding the vent outlets arrangement of a controlled tank venting system. The vertical position of the outlets should be at a height of not less than 6m above the weather deck or above a raised walkway. If high velocity venting valve of an approved type directing the vapor/air mixture upward in an unimpeded jet with an exit velocity of at least 30 m/s is fitted, the vent outlet height may be reduced to 3m above the deck or a raided walkway (Figure 7.21).

The horizontal position of the outlets should be at a distance of at least 10 m measured horizontally from the nearest air intake or opening to accommodation, service and machinery spaces and ignition sources. In case of carriage of toxic products, the distance is increased to 15m.

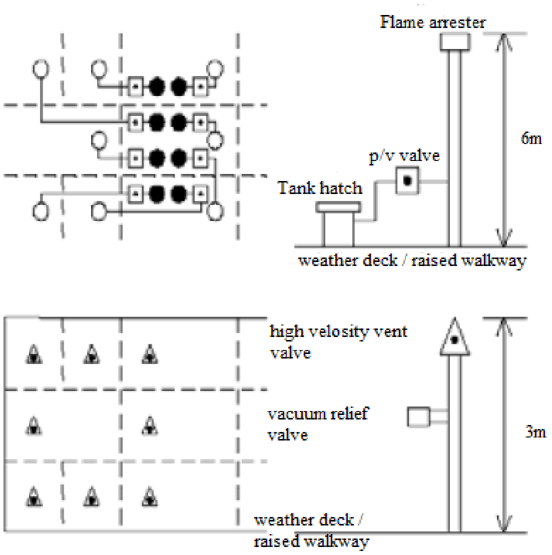


Figure 7.21 – Controlled venting system outlets

Figure 7.22 – Controlled tank venting system

Figure 7.23 – Vacuum valve

Figure 7.25 – High velocity valve

The IBC Code also requires that a vapor return system is used when highly toxic cargoes are being loaded, to prevent the toxic vapors from being discharged from the inside of the tank to the atmosphere. A vapor return system is designed in such a way, so that during the loading of the cargo, the vapor mix that is formed inside the tank is not released into the atmosphere, but is guided through a collection line to the vapor recovery facilities of the port. There, the toxic vapor is chemically treated before released in the air. Vapor return systems work together with the venting systems, not in place of them.

Chemical tankers are also fitted with tank ventilation systems. These systems are used to gas-free the cargo tank after a cargo has been discharged and dry cargo tanks after they have been washed. Tank ventilation can be performed using portable tank fans or a fixed tank ventilation system.

7.6 Cargo monitoring and control systems

The importance of proper cargo monitoring to the operational safety and environmental protection is highlighted by Werner[19]. The type of a cargo monitoring system that is required on a particular chemical tanker is based on the cargoes that it will carry. More hazardous cargoes require more advanced monitoring systems, when requirements for less hazardous cargoes are not that strict.

For more hazardous cargoes, it is required that the contents of the tanks are not been released at any point. For that reason, a closed gauging device, such as float-type systems and tank radar, should be implemented. The information from this system are sent directly to the cargo control room.

Additionally, cargo samples must be taken at regular intervals. For less hazardous cargoes this is happening through open cargo hatches. However, for more hazardous cargoes this is not permitted, so closed sampling systems must be installed on all vessels carrying hazardous cargos, or cargoes laded under nitrogen blanket.

Finally, careful temperature monitoring is very important for most of the cargoes carried by a chemical tanker. Closed temperature measuring systems and temperature alarms are required for ships carrying the most hazardous cargoes, as they can become extremely dangerous if the temperature is permitted increase above certain limits. For other products, careful control of their temperature is crucial in order to preserve their quality.

7.7 Cargo environmental control systems

Due to the sensitive and hazardous nature of chemical products, the maintenance of cargo environments is very important both for safety and cargo care. Therefore, chemical tankers should be equipped with cargo systems which moderate the cargo environment accordingly, such as temperature control systems and inert gas systems.

7.7.1 Inert gas systems

Chemical tankers do not use combustion gases to inert cargo tanks and void spaces, as their constituents may react with or contaminate the chemical cargoes. Nitrogen gas is used instead to inert the cargo tanks. After the loading of the cargo, the tank and associated piping systems are filled up with nitrogen, so that the cargo is blanketed by a nitrogen layer. This layer shall be maintained for the whole length of the voyage.

There are two different nitrogen systems that can be used on chemical tankers. The simpler of the two is a nitrogen bottle system that uses bottled nitrogen gas stored in the cargo area. The bottles are connected through pipes to a manifold, and nitrogen gas is released inside the required tank to maintain the blanket. This system provides only a small amount of gas, therefore it is only used to maintain the nitrogen blanket and not in order to create it. The initial filling of the tank in that case is been made from a shore source.

The alternative approach, which is most commonly used, is to outfit the vessel with a nitrogen generator and a nitrogen accumulator. In this case, a nitrogen generator produces nitrogen gas from compressed air. The purity of the generated gas can be a priori selected depending on the transferred cargo. The greater the purity, the better the quality of the inner gas. This type of inert systems can provide a greater quantity of nitrogen, enough to meet the demand without a shore-side source.

The IBC Code provides three more types of control for cargo tanks, that may be used for specific cargoes:

- Padding: by filling the cargo tank and associated piping systems with a liquid, gas or vapour which separates the cargo from the air, and maintaining that condition.
- Drying: by filling the cargo tank and associated piping systems with moisture-free gas or vapour with a dew point of -40^{o}C or below at atmospheric pressure, and maintaining that condition.
- Ventilation: forced or natural.

7.7.2 Cargo temperature control

As defined in the IBC Code, some products require heating or cooling media to be provided inside the cargo tank they will be carried. Regarding heating of the cargo, there are two common methods used on chemical tankers.

The first involves the implementation of heating coils at the bottom of the cargo tank and is the most commonly used system. Steam or thermal oil, which are introduced through pipe line from above the upper deck, are circulated through the heating coils and raise the temperature of the cargo. The heating systems should be provided with valves to isolate the system from each tank and to allow manual regulation of flow. It should also have means of measuring the cargo temperature. While the heating system is not in use, the heating coil is usually filled with compressed air in order to keep inside pressure higher than cargo tank pressure.

Thermal oil may not be used to heat a cargo that will be directly used in a food product. To select the proper heating medium the vessel's planned trading pattern must be taken into account. Some vessels are fitted with a certain number of tanks heated by thermal oil and the rest heated by steam or hot water.

Where the heating system heats toxic cargoes, installation of sampling equipment is required, to check a sample of steam/thermal oil for the presence of cargo. If non-toxic cargoes are loaded in other tanks, heating system should be separated.

Finally, materials used in the construction of temperature-control systems shall be suitable for use with the product intended to be carried.

Figure 7.26 – Heating coils in chemical tanker

The second heating system, involves using the cargo pump to circulate the cargo through a deck mounted heat exchanger. In order of this to happen, a separate drop line should be utilized, that will be connected, via the heat exchanger, to the cargo pump line, as shown in Figure 7.27.

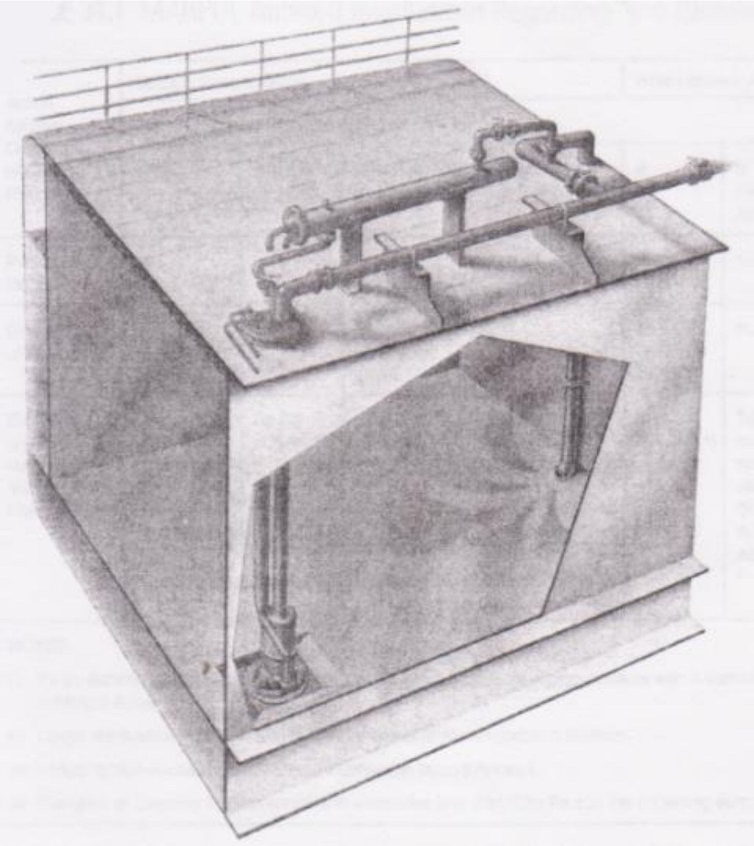


Figure 7.27 – Deck mounted heat exchanger

Cooling systems in chemical tankers are required less often than heating ones. Only a small variety of cargoes require cooling systems to be implemented in the cargo tank during their carriage. These cargoes typically have high vapor pressures at ambient temperatures and must be maintained at a lower temperature to limit cargo evaporation and development of high internal pressures within the cargo tanks.

A typical cargo cooling system is shown in Figure 7.28. As these systems are used occasionally, the in-tank cooling lines are usually possible to be removed from the tank when they are not in use. [16,17,19]

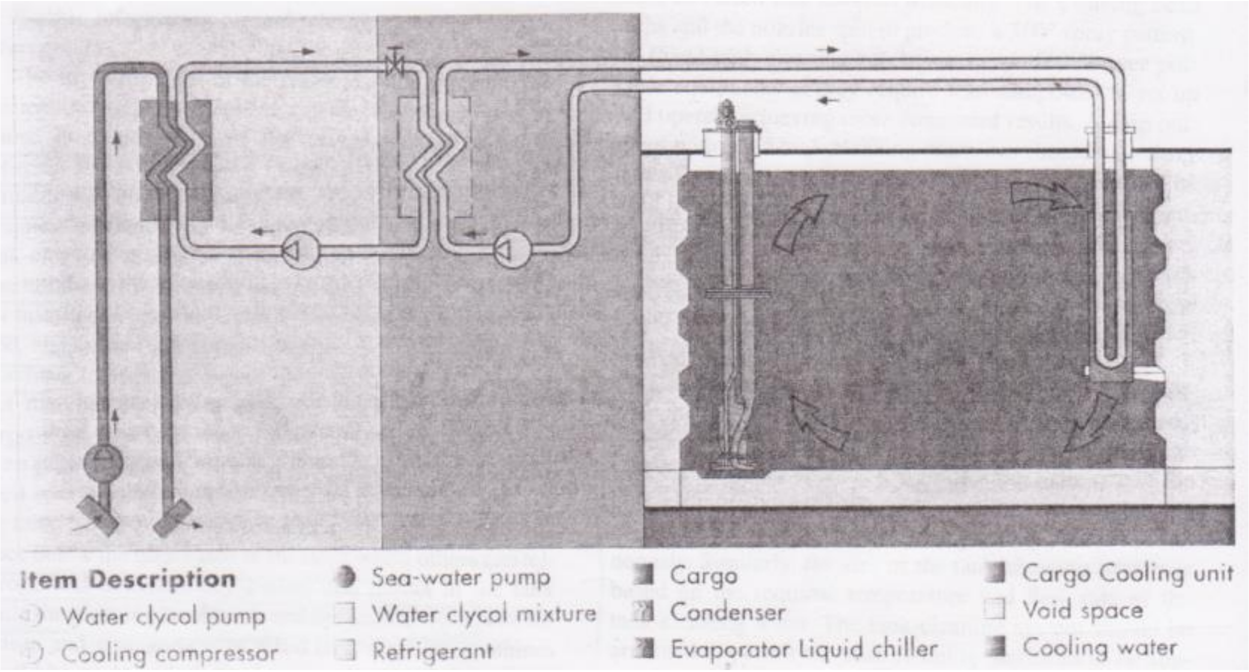


Figure 7.28 – Cargo cooling system

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Chapter 8

Alternative Designs

8.1 Introduction

Due to the nature of the cargoes they carry, which may be extremely hazardous and require special care during their transportation, modern chemical tankers are characterized by increased technological sophistication. They are complex and expensive ships, and a lot of experience and know-how has been gathered over recent decades and used for their further technological development. This have led the present generation of double hull chemical tankers, equipped with several cargo systems, to be regarded as state-of-the-art vessels in matters of design and safety.

Therefore, future design philosophy is more focused on how to further improve the current design, rather than to develop new alternative design models. Improved coatings for cargo tanks, advanced steels for cargo tanks manufacturing, and several improvements of the cargo systems are some of the areas of development.

As described in *Shipping Innovation*[1], the design of chemical tankers in the future, will be influenced by the following two factors: Elimination of pollution from slops, by trying to reduce the amount of water used for the washing of cargo tanks via innovative tank design, and obtainment of high quality standards equal to those used in the food industry. It is also highlighted, that a general revolution that takes place in the design principles of all kind of vessels, which focuses more on the engineering part rather than on the rules-based part of the design, will also affect the design of chemical tankers in the future.

In this chapter, two already existing designs; the combination of duplex stainless steel and clad stainless steel for the construction of cargo tanks, and the development of a 75,000 DWT chemical tanker, are presented. In addition, an alternative design of a chemical tanker with cylindrical tanks which has not yet though been applied, is reviewed.

8.2 Duplex/clad stainless steel combination in cargo tanks

In November 2014, the world's first chemical tanker to use a combination of duplex stainless steel and stainless clad steel in the construction of its cargo tanks was delivered. The vessel, named Sunrise Hope, is a 12,500 DWT chemical tanker equipped with 14 cargo tanks, all of which employ duplex stainless steel technology.

This was the first time that a combination of both duplex and stainless clad steels have been used in the construction of a chemical tanker's cargo tanks. Lean duplex stainless steel, which contains lower nickel compared to duplex stainless steel that is used in most of the cases, was used for the construction of the bulkheads inside the cargo tanks, while the bulkheads adjacent to the cargo tanks were constructed using stainless clad steel, in which stainless steel and carbon manganese steels have been compression bonded together into a single plate. The ballast tanks were also constructed from stainless clad steel.[2]

The duplex/clad stainless steel combination in cargo tanks may become a common practice in the future, as it combines the advanced strength and corrosive resistance characteristics of duplex stainless steel, with the most economical clad stainless steel, reducing in that way the cost of the construction to the minimum.

8.3 The 75,000 DWT chemical tanker

The number of the liquid chemical cargoes has increased enormously since the early days, when the tanker market was expressing only for carriage of petroleum products. However, the chemical tanker market has lost acceleration in last few years, and – as a result of the global economic crisis - demand has failed to comply with supply, leading to lower freight rates and a slowdown in the order of new chemical tankers. Due to this decline of the fleet growth and the shrinking of the tonnage growth though, the market gives positive forecast for its short and near future.[3] As a result, new chemical tankers have been ordered, as the shipowners try to increase their chemical fleet capacity. In this respect, the size and capacity of new built chemical tankers is increasing, resulting to the construction of the first 75,000 DWT chemical tanker delivered in 2013.

The vessel, named Bow Pioneer, designed with two longitudinal corrugated bulkheads with lower stools and transverse corrugated bulkheads with lower stools, which form 10 sets (Port, Starboard and Center) of cargo tanks, and 11 water ballast tanks consisting of four pairs of wing and double bottom tanks, one U-type tank and two water ballast heeling tanks.

The ship is equipped with a cargo handling system for the loading, storage and discharging of the intended cargos of IBC ship type 2 & 3 with typical cargoes such as Methanol, Vegetable Oils, MEG (Mono Ethylene Glycol), EDC (Ethylene DiChloride), MTBE (Methyl Tert-Butyl Ether), Xylene, Toluene, Cyclohexane, etc., as well as refined petroleum products (products with flash point below 60 deg-C).

The ship is constructed with a continuous upper deck with forecastle, a raked stem with a bulbous bow, and a transom stern with open water type stern frame. A raised catwalk is arranged from the front of the accommodation to manifold platform area and to forecastle deck on the upper deck. Double side and double bottom are provided in cargo area and the volume of each cargo tank does not exceed 3,000 cu. m.

The cargo tanks, as well as the slop tanks, are coated with inorganic zinc silicate coating, and all cargo piping and related cargo systems are made of stainless steel. Complete segregation of tanks is applied, resulting to 31 cargo manifolds, which are arranged on the port and starboard sides with two tiers at the middle length of the ship.[4]

Bow Pioneer is the largest chemical tanker yet constructed. However, as the use of chemical products is spreading across the world, and the demand for their transportation is increasing, even bigger chemical tankers is likely to be constructed in the future.

The case of Bow Pioneer indicates that despite the increase in the size and the capacity of chemical tankers, their structural configuration and basic structural arrangements remain unaffected.

Figure 8.1 – Bow Pioneer, 75,000 DWT chemical tanker

8.4 The cylindrical chemical tanker

One of the major problems of the seaborne chemical trade is the fact that the time that chemical tankers spend in port is very long in relation to the time they spend at sea. A major chemical tanker owner and operator, faces a port time of around 40 percent. This causes a tremendous loss of charter revenues; therefore many efforts have been made for this problem to be reduced.

One of the potential reasons behind the large port time is the current design of the chemical tankers, based on the integral rectangular tanks, often with stiffeners inside, corrugated bulkheads and heating coils, which incommode the discharging and washing procedures of the tank.

Therefore, efforts have been made to redesign and innovate the chemical tanker in a fundamental way. One of these efforts, as described by Wijnolst and Wergeland[5], is focused on the design of chemical tanker with stainless steel cylinder type tanks. These tanks are easy to manufacture under factory conditions and through their ideal form can withstand enormous pressures and are easy to clean, because the heating coils are placed outside the tank and no internal stiffeners are used.

This alternative design concerns the naval society for the last two decades, however not such a vessel has been constructed yet. Many studies have been made though, revealing some positive conclusions. For that reason it is possible that the cylindrical chemical tanker will become reality in the near future.

A case-study that took place in the early 1990s described the design of a 44,300 cbm cylindrical chemical tanker, compared to a standard chemical tanker design of the same capacity. The main particulars of the two vessels are shown in Figure 8.2.

Dimensions	Standard design	Cylinder tanker
Deadweight (tons)	35,400	35,497
Tank capacity (cbm)	38,021	44,300
Length over all (m)	182.3	218.5
Length between pp (m)	176.1	209.5
Breadth (m)	32.0	32.24
Depth (m)	14.0	21.5
Draught (m)	10.6	10.7
Lightship weight (tons)	12,600	18,043
Displacement (tons)	48,00	53,500
Block coefficient	0.78	0.722
Service speed (knots)	13.5	17.75

Figure 8.2 – Main particulars of a standard design and a cylindrical tanker design

The cylindrical tanker consists of 43 cylindrical tanks and 10 small slop tanks, with a total volume of 44,300 cbm as shown in Figure 8.3. For a draught of 10.6 meters, equal to the draught of the equivalent standard chemical tanker, the displacement of the cylindrical tanker is 53,497 tons, and its deadweight is 35,497 tons. However, the draught of the cylindrical tanker can be increased to 11.6 meters due to its large volume and high freeboard. This leads to an increased cargo capacity of 38,292 tons.

In addition, because of the form of the tanks, the block coefficient of the vessel is reduced from 0.78 to 0.722, and the length of the ship is increased, resulting to a speed of 17.5 knots, which is at least 2.5 knots faster than the standard design.

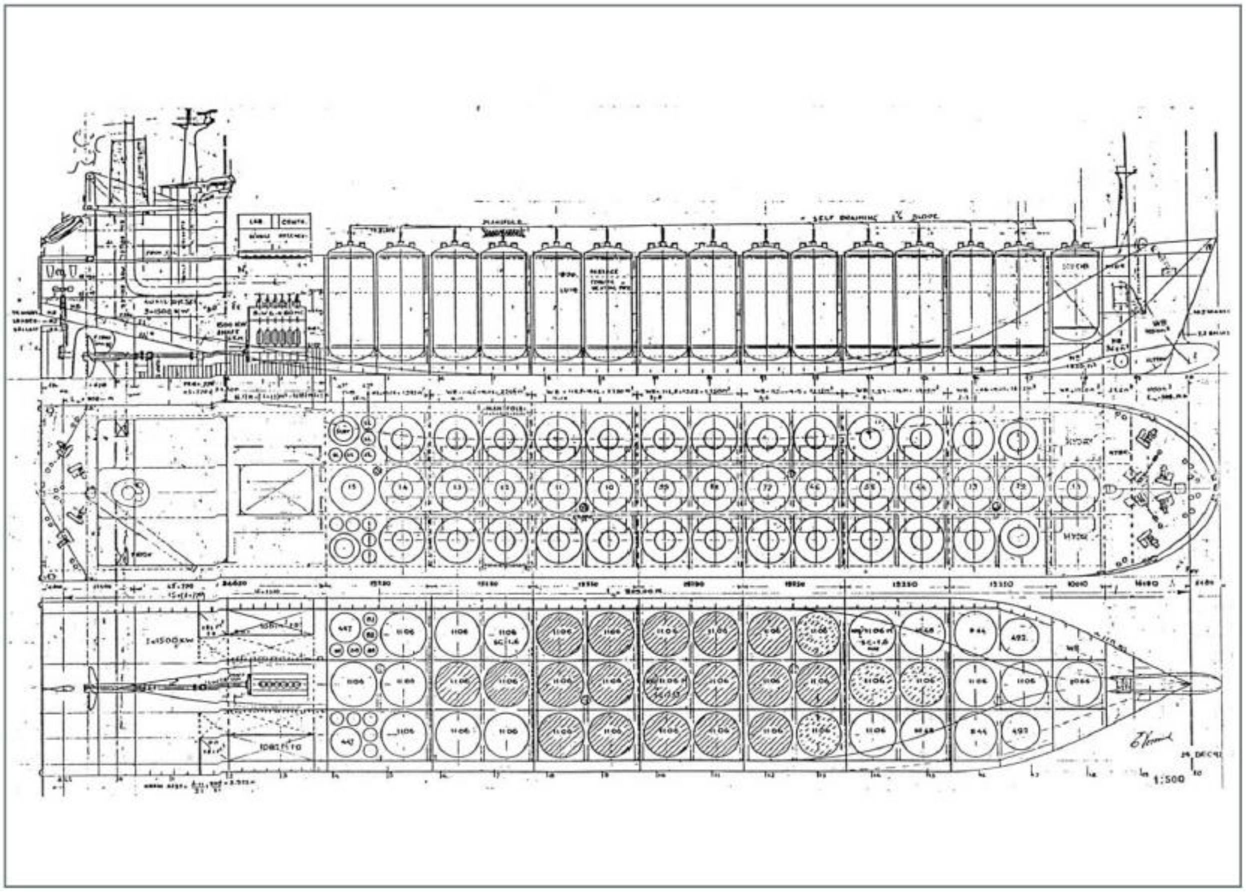

Figure 8.3 – Cylindrical chemical tanker design

A cross section of the cylindrical tanker is shown in Figure 8.4. The width of each tank is 8.5 meters and the height 20 meters. The capacity per tank is approximately 1,100 cbm. As the tanks are extremely protected, all tanks should be allowed by I.M.O. to carry type I cargoes. An advantage of the completely independent cylinder tanks is that the problem of cargo incompatibility is fully eliminated.

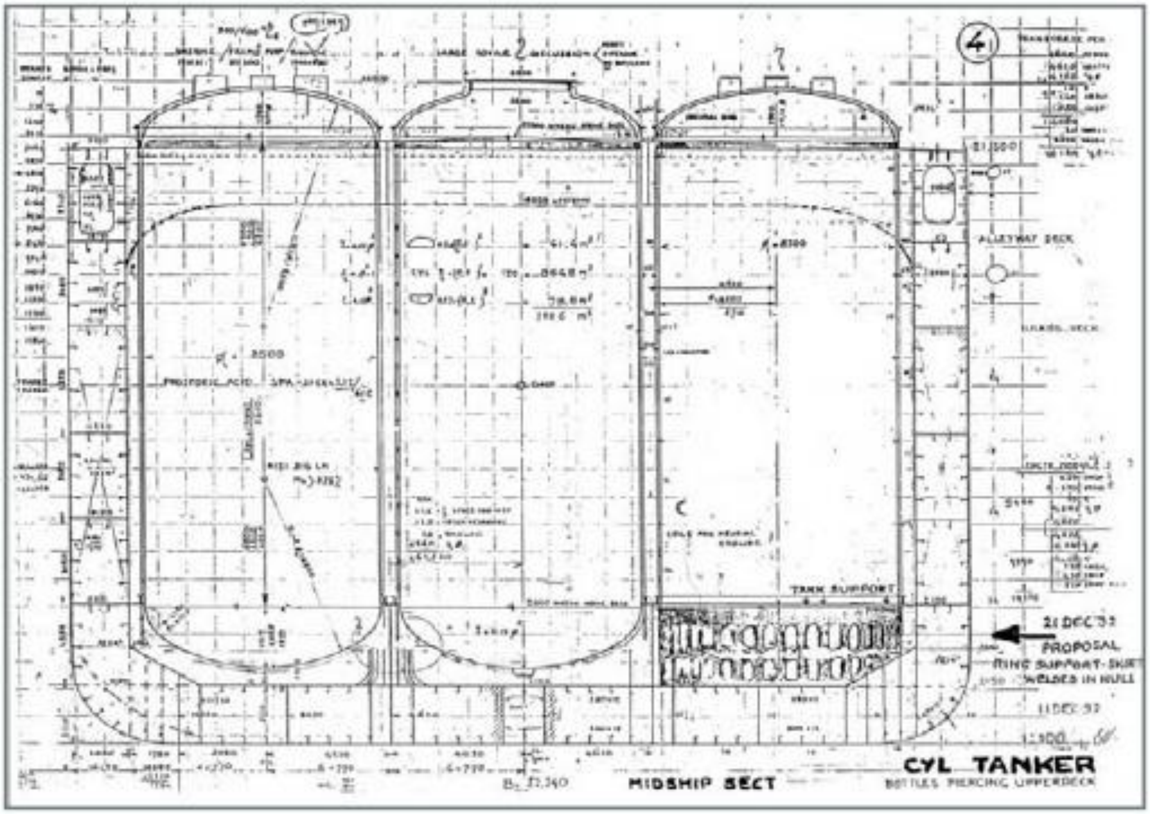

Figure 8.4 – Cross section of the cylinder chemical tanker

All tanks are from stainless steel and are easy to clean, because of their ideal cylinder form, their small diameter (large impact of water jet), and the absence of cargo coils within the tanks. The cylindrical form of the vertically placed tanks allows the installation of automated washing machines in the tanks. According to calculations of a specialist in tank wash installations, the tank can be cleaned in less than 15 minutes (pre-wash), which represents a time saving of 75% compared to a conventional, integral tank of similar capacity. In addition, it is estimated that a reduction of 75 percent of the water use can also be achieved.

The lower slops production saves time in port for washing and reduces the cost of delivery of slops to shore reception facilities. Loading and discharging operations are also accelerated by the shape of the tanks. The cylindrical tanks can be filled at any rate, as the relatively small diameter of the tanks limits the free surface effect, creating again more flexibility. In addition, the fact that the cylinder tanks have practically all the same capacity, in combination with the absence of compatibility problems, makes commercial and operational planning of cargoes easy and fast.

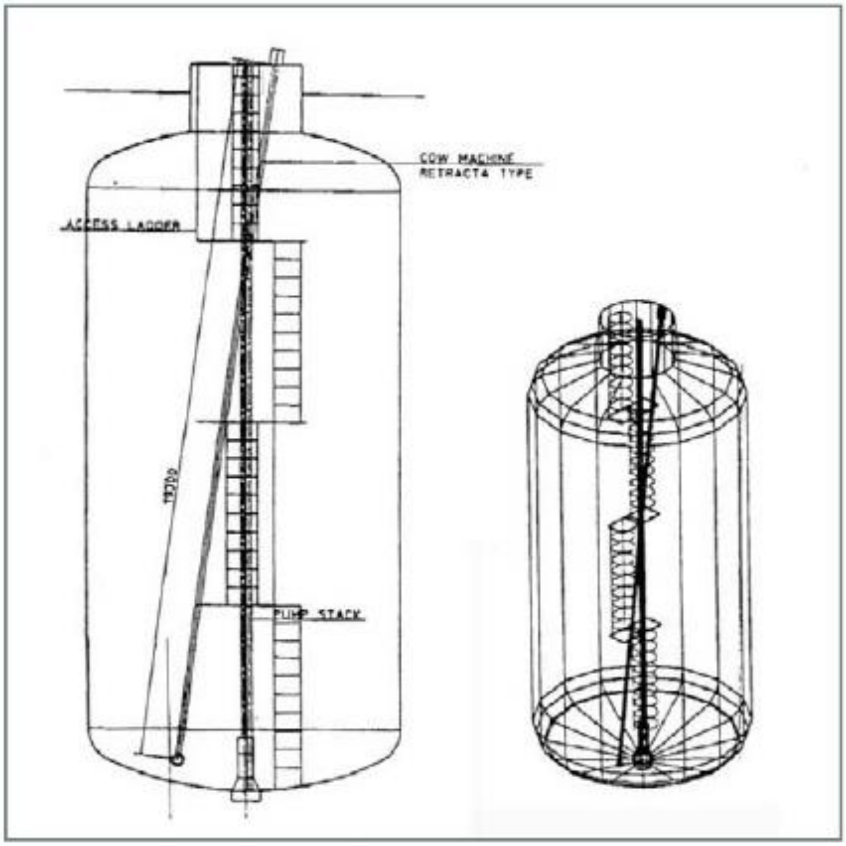

Figure 8.5 – The inside of a vertical cylindrical tank

All the tanks of a cylindrical chemical tanker are made of stainless steel and are independent. In the standard design, the ratio of tank surface to tank capacity is 0.8 m^2/m^3, when in the independent cylinder chemical tanker this ratio is reduced to 0.6 m^2/m^3. This is a 25 percent reduction in tank surface for the same capacity, which reduces the amount of stainless steel and leads to a more cost-effective design.

On the other hand, the fact that the independent tanks do not form part of the double hull structure increases the lightship weight of the cylinder tanker. It is estimated that the extra steel weight increases the building cost up to 5 percent. It should be borne in mind though, that the tanks in the standard design are not all made of stainless steel, but are partly coated, in particular the wing tanks. Therefore the quality of the designs is not really comparable.

The stainless steel cylinder tanks are built under factory conditions to the highest quality standards, independent of the workmanship at the yard and the weather conditions. As the steel hull and the stainless steel tanks are built in parallel, the construction period is reduced by 3 to 4 months. The fact that the hull is relative simple to build, resembling to a double-hull oil tanker or an open containership, and the absence of difficult stainless steel work at the yard, also contribute to the reduction of the construction period.

A significant advantage of the cylindrical chemical tanker is the fact that the stainless steel tanks can be taken out of the hull at the end of the commercial life of the tanker and even be reused in a new tanker. In that way, the residual value of the stainless steel weight, which is normally lost when scrapping standard chemical tankers, will increase with the value of the stainless steel weight of the tanks. Consequently, the annual depreciation can be reduced.

The cylindrical tanker is suitable for the carriage of a wide variety of cargoes. The fact that it has a triple barrier (double hull and tank shell) makes it suitable for the carriage of IMO type I products in all its tanks. In addition, the cylindrical tanks can be designed to transport super-phosphoric acid (specific weight 2.15). They can therefore also become pressure vessels, and transport certain chemical gases, in combination with cooling of the tanks. Some tanks in the ship can also be designed to transport high heat products, while others may transport refrigerated cargoes at little extra cost.

It becomes clear that a cylindrical chemical tanker may be a very advantageous option for the transportation of chemical products in the future, as it combines fast harbor operations, capability of carriage of almost all chemical products with complete segregation of cargoes, and very good quality, as the cargo tanks are made inclusively of stainless steel. In financial terms, the cylindrical chemical tanker has a slightly increased construction and operational cost, which is though offset by the option to take out and reuse the cylindrical tanks, and the increased deadweight respectively.

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