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Structural design aspects of bulk carriers

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Abstract

Large and efficient bulk carriers, designed and built mainly in the 1960's and 1970's, are now reaching the end of their service life. The past few years have revealed several structural problems, which strongly affected the ships' safety. Although corrosion and bad maintenance was found to contribute mostly to the problems, the strength behaviour and design criteria have, nevertheless, to be reviewed taking into account the service experience observed. After describing different designs of bulk carriers and the governing structural design principles, the criteria and models for the strength assessment based on first engineering principles are summarised. Emphasis is placed on local strength analyses in order to cover fatigue aspects. Important will become also the strength analysis in flooded condition, considering extreme loads such as the pressure on bulkheads due to cargo and ingressed water. But rule developments related to such aspects are still under discussion. Finally, corrosion and wastage aspects are discussed which need to be considered more thoroughly as service experience has shown.

1 Introduction

Following the definition of the International Association of Classification Societies (IACS), the ship type notation "Bulk Carrier" shall be assigned to sea-going single deck ships of single or double skin construction with double bottom, hopper side tanks and topside and wing tanks (fitted below the upper deck) and intended for the carriage of dry cargoes in bulk, Figure 1.

These typical design features are almost independent from the size of the vessels and have been existing since the end of the last century when English colliers and ore carriers sailed between British and continental ports. The characteristics of such vessels are:

- quick loading and discharge of any type of bulk cargoes
- self-trimming of the cargo
- moderate speed
- strengthened for heavy cargo.

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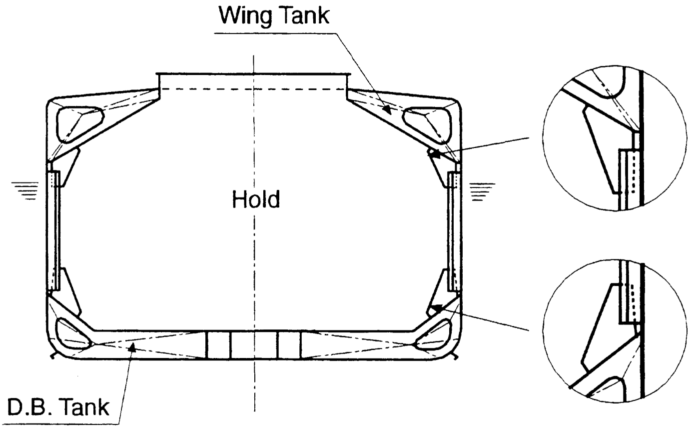

Fig. 1: Midship Section of a Bulk Carrier

It is a matter of fact that these vessels have mostly been sailing in tramp-shipping world-wide where high flexibility with regard to cargoes like coal, grain and concentrates is required. Due to the fact that ore has a high density, "Ore Carriers" as a special bulk carrier type are showing a different midship section. They are constructed with two longitudinal bulkheads, two wing tanks and a double bottom throughout the cargo region with the aim of carrying cargoes in the centre hold only, Figure 2.

In some cases it is intended to carry both oil and dry cargo in bulk, however not at the same time. These ships are to be considered as "Ore/Oil Carriers" and there are various different designs for the midship section, Figure 4. Ships that are suitable to carry oil, bulk cargo or ore in the same hold space are defined as OBO-Carriers (Oil Bulk Ore). Their midship section is almost identical to common bulk carriers with a double skin, Figure 3.

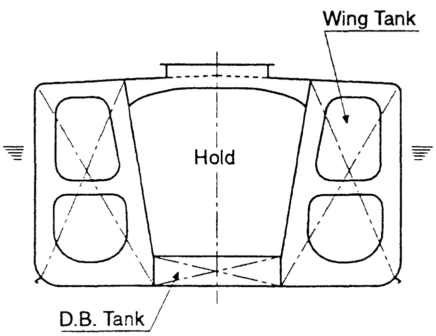

Fig. 2: Midship Section of an Ore Carrier

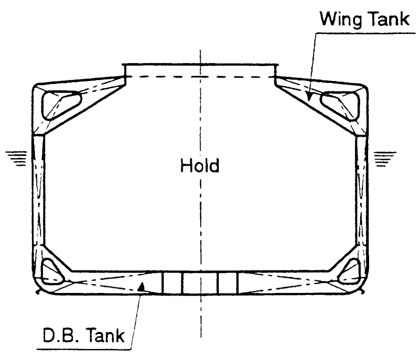

Fig. 3: Midship Section of OBO Carrier or Double Skin Bulk Carrier

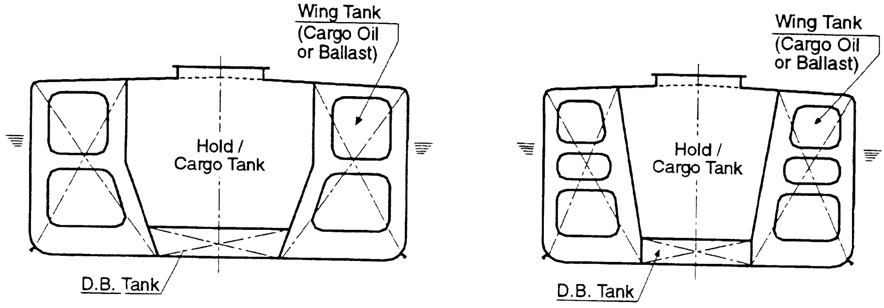

Fig. 4: Midship Section of "Ore/Oil Carriers"

At present, nearly 4.600 bulk carriers are sailing world-wide. Most of them are of classical design according to IACS-definition. It is therefore sensible to maintain the construction for this type of vessel. During past years, world-wide losses of bulk carriers had to be deplored. It is assumed that most of these casualties resulted from the ageing of the bulk carrier fleet. This paper presents a brief introduction into the state of the art of bulk carrier design focussing on the steel-structure of single skin and double skin bulk carriers. Furthermore, the effects of higher tensile steels and the related problems are discussed. This includes the presentation of different calculations of the strength of the entire hull based on a global finite element model, partial finite element models of the hold space as well as the calculation of the fatigue strength of structural details. Due to the fact that corrosion and wastage aspects are gaining importance, corresponding problems from the viewpoint of a classification society are presented.

The paper demonstrates that all questions concerning new buildings of bulk carriers as well as of ships in service can be answered professionally by Germanischer Lloyd, who is well prepared to meet the demands arising from bulk carrier problems.

2 Design Principles

2.1 General

As mentioned before, bulk carriers must be very flexible with regard to density of different cargoes. In case of coal or grain, with a relatively low density, the whole volume of the hold space is needed to bring ships on the maximum allowable draught. On the other side, in case of ore concentrate with quite a high density, a lower volume of the cargo will be required. It is therefore reasonable to fill only every second hold with cargo. This alternate loading concept offers several advantages, however also disadvantages.

Sailing with alternately loaded holds will result in a comfortable behaviour of the vessel in the seaway due to a moderate location of the centre of gravity of the cargo, which is less in case of filling all cargo holds. Discharging and cleaning the holds is obviously cheaper, if only some selected holds are in use. On the other hand, vessels intended for alternate loading have to be reinforced due to additional shear forces, in particular in the shell area in the vicinity of the transverse bulkheads between loaded and unloaded holds. This becomes more serious in case of flooded holds - which is under discussion within IACS.

2.2 Single Skin or Double Skin

The most important question today is how to design the vessel's shell - single or double skinned - and what type of structural design of the transverse bulkheads is the most reasonable one.

As mentioned before, the end connections of transverse frames of single skin type design are very vulnerable. Therefore the double skin design is preferable. It must be kept in mind that double skins are reducing the cargo hold volume because the distance between outer and inner skin must be wide enough to allow inspection (approx. 1000 mm). On the other hand, in case of double skin, the cargo holds are kept free from any arrangements like brackets or other similar structural elements.

A further advantage of the double skin design can be seen in better protection of the steel structure within the double skin space against tear and wear caused by loading and discharging procedures. However, the void space is recommended to be coated in order to prevent corrosion. From the structural point-of-view, double skin structures between upper and lower wingtanks yield to a more homogeneous distribution of the structural stiffness with regard to the transverse strength of the entire hull.

2.3 Transverse Bulkheads

Structural design of transverse bulkheads of bulk carriers is somehow different from the one applying to dry cargo vessels in general. This is due to condition that they have to resist against heavy bulk cargo pressure, which can be much higher than the water pressure usually taken into account. Another design principle to be considered is that no cargo residues should remain on the bulkhead structures after cargo discharge.

Figure 5 shows the different types of structural designs of bulkheads. The stiffened plane bulkhead design which is normally used in dry cargo vessels, is restricted to very small bulk carriers only. In case of bigger vessels the stiffeners become very heavy, even if supported by horizontal stringers, apart from the fact that these are disturbing the selftrimming discharge procedure because bulk cargo residues are unavoidable.

As can be seen from Figure 5a (stiffened plate design), the local plate bending stresses (σ_D) do not coincide with the maximum global stresses resulting from stiffener bending. However, in case of corrugated bulkheads the local plate bending stresses (σ_D) coincide with the maximum global bending stresses, just as in case of the double skin design.

Weight optimisation calculations have shown that the corrugated bulkhead design results in the optimum structure. However, the end connections are also critical here and require careful local design and fabrication.

3 Strength Analysis for Intact Condition

3.1 Scope of Strength Analyses

The complex structural configuration of the cargo holds of a bulk carrier requires careful structural analyses to avoid local overstressing. Normally, the following aspects are covered by special strength analyses:

- Global hull girder strength, with particular view to bending and shear stresses in the hull girder
- Strength of the double bottom grillage, particularly in case of heavy cargo and/or empty holds, considering supporting effects by the lower wing tanks and/or bulkhead stools
- Strength of the bulkheads, taking into account interaction effects especially with the bulkhead stools and double bottom
- Local strength of structural details considering stress concentrations and fatigue. Particular attention has to be paid to knuckles in the upper and lower wing tanks, connections between the stools and the bulkhead plating and/or inner bottom, end connections of side frames, hatch corners, terminations of coamings and transitions at the ends of the hold area [1].

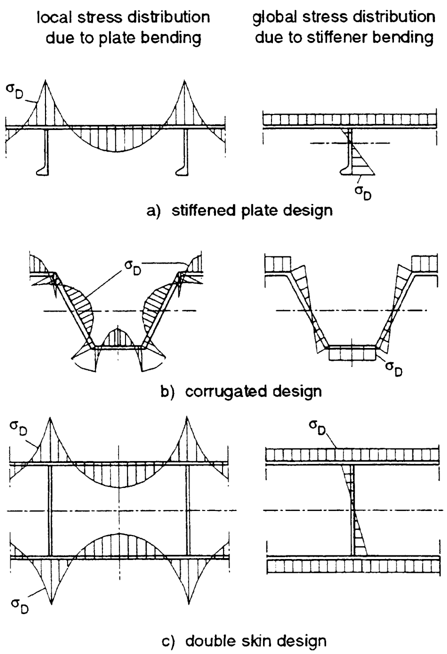

Fig. 5: Stress Distributions in Different Bulkhead Designs

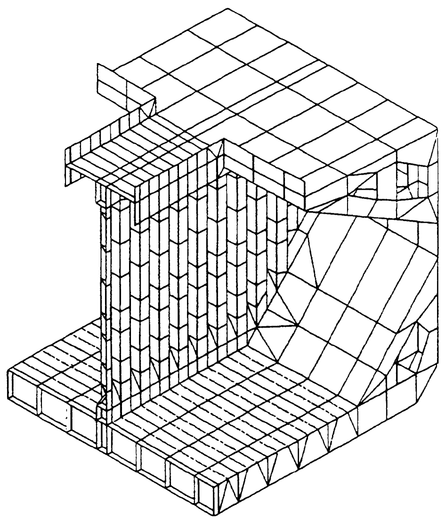

Fig. 6: Typical Hold Model of a Bulk Carrier

In recent years, the methods and tools for the analysis of ship structures have been further developed and refined. Today, direct dimensioning of structures based on first principles is introduced and computerised tools for the analysis are available. In the following, an overview about procedures of such a rational design and analysis will be described, taking the procedures used by Germanischer Lloyd as an example. Because direct dimensioning as well as fatigue strength requirements have been included in the GL-Rules already many years ago - the latter as early as in 1978 - the procedures, design loads and permissible stresses are based on a long experience.

3.2 Global Strength Analysis

In the early design stage, the sections of the hull girder are normally designed in the usual way based on beam analysis, taking into account local loads on plates and stiffeners as well as global loads on the hull girder. In the lower part of the hull, bending stresses of the grillage of the double bottom have to be included.

Today, grillage analyses using beam elements are frequently replaced by 3D finite element analyses, using membrane or plate elements for the inner and outer bottom, floors and girders and truss or beam elements for the longitudinals. This way, problems related to a beam model such as rigid ends or rotational stiffness of the lower wing tanks and bulkhead stools are dispensed with.

Usually, a partial model of the hull girder is set up, extending over one or two holds, see Figure 6. In this way, also bulkheads and side frames may be analysed in addition to the double bottom. Such a model offers the possibility to apply extreme loads according to the assumptions given in the Rules without major problems. Even alternate loading of the holds can be analysed together with maximum or minimum draft and dynamic pressure due to the waves. Reasonable boundary conditions can be defined at the ends because the hold and tank geometries are similar over a large portion of the ship's length.

Overall models of the hull girder have mainly been used in the past to investigate the structural behaviour of those ships which require particular attention to be paid to special structural aspects. Furthermore, a reliable prediction of deckhouse vibrations normally requires the analysis of an overall model of the hull girder.

Overall models of bulk carriers as exemplified in Figure 7 might be used in the future more frequently as a result from the further development of mesh generation techniques. Overall models generally allow more realistic load combinations to be analysed and all interaction effects between structural components to be correctly considered. Furthermore, critical areas at the ship's ends such as frames in the first hold or transitions between the engine room and the adjacent hold can be investigated as well. On the other hand it has to be admitted that it is sometimes difficult to apply extreme loads as specified in the Rules for specific components and simultaneously satisfy equilibrium conditions.

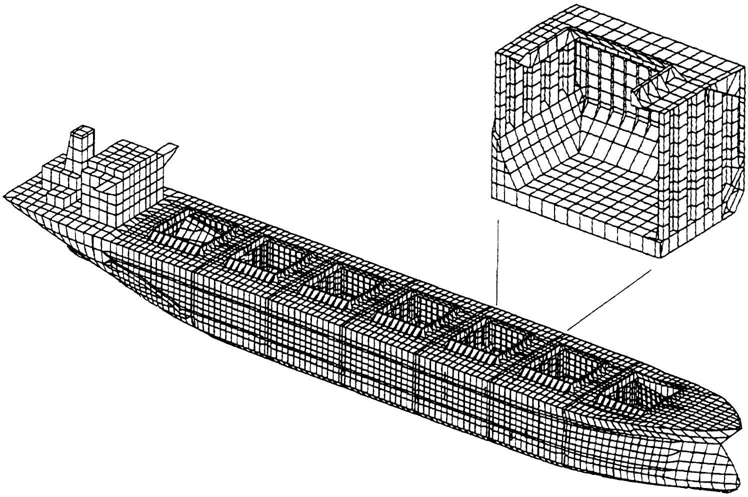

Fig. 7: Overall Model of a Bulk Carrier

In most cases, the deterministic approach is applied when analysing the global strength which means that a certain number of loading conditions and wave situations is selected representing the most unfavourable design conditions [2]. The model shown in Figure 7 has been set up to verify measurements of side pressure and related stresses which are currently performed. In addition, the model has been used to apply the so-called Integrated Fatigue Assessment procedure also on typical structures of a bulk carrier. Further details will be presented below.

3.3 Local Strength and Fatigue Analysis

As already mentioned, the assessment of the fatigue strength plays an important role today. The deterministic approach using selected load cases described in the previous chapter allows the fatigue strength to be assessed in a simplified way by determining the highest stress range from the results and assuming an appropriate stress spectrum. Figure 8 shows typical load situations producing extreme stress fluctuations in the transverse members of a bulk carier.

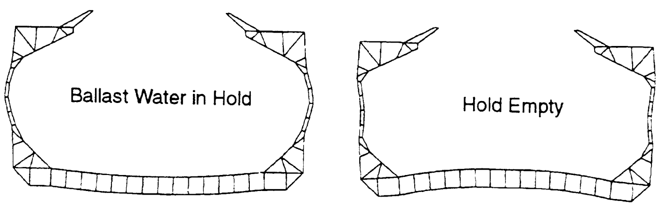

Fig. 8: Load Cases with High Stress Fluctuations in Side Frames

The above mentioned stress analyses using partial or overall models of the hull girder generally yield nominal stresses also if secondary stresses due to stiffener or plate bending are superimposed. These nominal stresses can be used directly for the fatigue strength assessment in most cases. The Rules of Germanischer Lloyd [3] favour a simplified check where the highest wave-induced stress $\Delta\sigma_{max}$ has to remain within the permissible stress range $\Delta\sigma_p$ which depends on the detail category $\Delta\sigma_R$ of the structural detail considered and some other factors:

$$\Delta\sigma_p = \Delta\sigma_R \cdot f_n \cdot f_m \cdot f_R \cdot f_w$$

The factor f_n considers the type of spectrum and the number of load cycles, f_m the effect of steel strength chosen (applicable only for base material), f_R the effect of mean stress (R-effect) and f_w the effect of a possible weld shape improvement. The simplicity of the approach is illustrated by examples of the fatigue strength assessment of various ship structural details in [4].

An effective corrosion protection is assumed in the approach which is, e. g., mandatory for ballast tanks adjacent to the shell. Due to the relatively conservative classification of details in the Rules as proposed by the International Institute of Welding, deterioration of the corrosion protection is included to a certain extent. On the other hand, inadequate corrosion protection during the whole lifetime can drastically reduce the fatigue strength. The change of the S-N curve due to corrosion as assumed in Rules for offshore installations is shown in Figure 9.

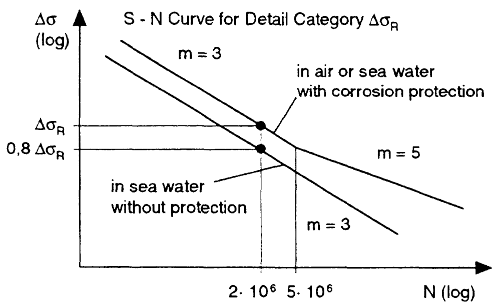

Fig. 9: Effect of Corrosion on the S-N Curve of Welded Details

Corrosion has to be expected especially in the hold area of bulk carriers where coatings can soon be destroyed by aggressive cargoes. Vulnerable are in particular the end connections of side frames. As a consequence of the failures observed, the required section modulus of side frames was recently increased in [3] by 20%. The related stress decrease is expected to compensate the negative corrosion effect on the fatigue behaviour shown in Figure 9. Further corrosion aspects will be discussed in Section 5.

Several bulk carrier inspections revealed that end connections have been frequently dented due to rough cargo handling [5]. Even small local dents may result in very serious local bending stresses in the brackets, reducing their supporting capacity due to local yielding.

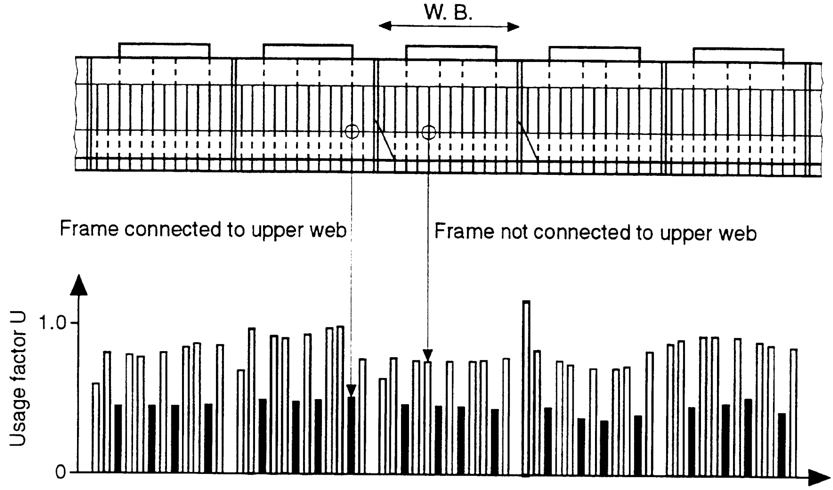

Fig. 10: Stress Range Usage Factors Computed for the Lower Brackets of Side Frames in a Bulk Carrier

The fatigue strength assessment of special geometrical configurations of structural details, such as knuckles or cut-outs, sometimes require the consideration of locally increased stresses, i.e. structural or notch stresses, which can also be assessed on the basis of the Rules mentioned. They may be computed using special finite element models containing the local geometry in more detail. The other, more economic way of determining locally increased stresses is the use of stress concentration factors which are currently evaluated for ship structural details to an increasing extent.

A more thorough fatigue analysis, based on the spectral method, which allows prediction of the long-term spectrum of stress ranges in various structural members, requires consideration of a large number of load cases. First results of such an analysis, which considers relevant non-linearities occurring especially at the ship's sides, have been published in [6].

Results obtained for the side frames of a bulk carrier are shown in Figure 10. The usage factors refer to stresses and not to fatigue lives because this gives the designer a better idea about necessary or possible modifications. Remarkable are pronounced differences in the usage factors of frames which are connected and not connected to webs in the upper wing tank. The latter are more highly stressed.

4 Strength Analysis for Flooded Condition

4.1 General

In order to cope with the problem of bulk carrier losses, IACS - the International Association of Classification Societies - has proposed that consideration should be given to the strength of bulk carriers in flooded condition. Relevant unified requirements (UR) have been elaborated and are still under development, i. e. UR-S17 for the longitudinal strength in flooded condition, UR-S18 for vertically corrugated transverse watertight bulkheads and UR-S20 for the double bottom. The intention is to apply these requirements to all new single side skin bulk carriers of 150 m in length and above, which are contracted for construction after 1st July, 1998. In addition similar standards with respect to bulkheads and double bottom have been elaborated for existing ships of the same identity.

Contrary to the damage stability calculation according to IMO-Regulations, where an exchange between cargo and ingressed water is assumed, flooded condition in this context means that each cargo hold is assumed to be separately flooded by an opening in the side shell. This opening is not defined in size and location but allows the ingress of water until the equilibrium waterline is reached. Thus, in this scenario the strength check has to be done in addition to the strength in the intact still water loading conditions defined in the loading manual, but it has to be well understood as a "case of emergency".

4.2 Longitudinal Strength

Depending on the number of cargo holds as many loading cases in stillwater condition have to be calculated with regard to their bending moment and shear force distribution along the ship's length, each single cargo hold assumed to be flooded up to the equilibrium waterline.

The most severe basic service loading condition is, in general, the alternate hold condition as shown in Figure 11 for an example. The vessel has 7 holds and the holds with odd numbers are loaded with cargo while the others are empty. This is the typical arrangement when shipping heavy bulk cargo. Figure 11 shows the bending moment and shear force distribution over the ship's length. In addition the permissible values at each section in stillwater condition are given, which have to be approved by the classification society. As far as the shear forces are concerned, they are corrected according to the direct load transmission by the longitudinal structure at the transverse bulkheads (see continuous line).

Figure 12 shows the bending moment and shear force distribution where the foremost hold is flooded according to the scenario described above. One can see that the shear force at the aft bulkhead of hold 1 is increased and the value is higher than the permissible one. Also the bending moments change their values and are locally higher than the permissible ones.

Using the same procedure for hold No. 2 and for each subsequent hold, an envelope curve of loads can be evaluated, which is the basis for structural strengthening due to longitudinal bending and shear in flooded condition.

While the stress check in the intact condition is carried out with the maximum stillwater bending moment and the design wave bending moment, the

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check in flooded condition is performed using only 80 % of the Rule wave bending moment. The same procedure is used with regard to shear forces.

If one assumes that in the "intact" condition the stillwater loads are as high as the wave loads, the strength has to be increased for the flooded condition, if the stillwater loads in flooded conditions increase by more than 20 %. This value is a good approximation.

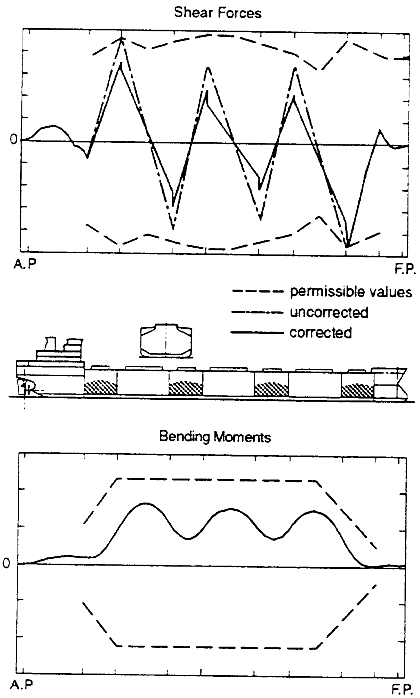

Fig. 11: Alternate Loading, Intact Condition

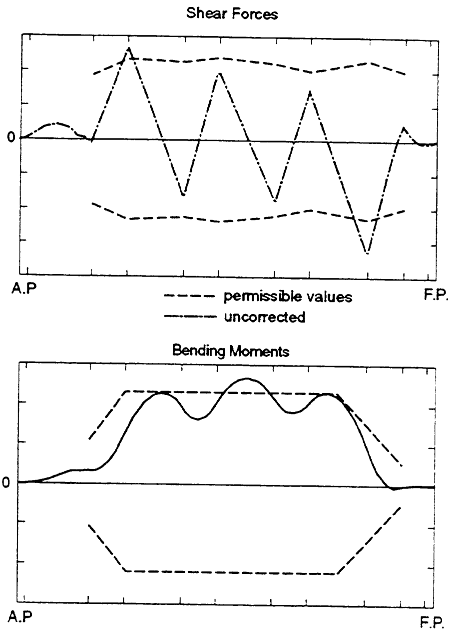

Fig. 12: Alternate Loading, One Hold Flooded

Germanischer Lloyd investigated several bulk carriers according to the procedure described. These were 9 vessels with 9 holds, 8 vessels with 7 holds and 6 vessels with 5 holds. Figure 13 shows the required thickness increase of the side shell for the shear forces in the flooded condition. The line named „GL-proposal" has been evaluated by data of only two ships.

Of course, the data of these 25 vessels are not sufficient for a statistical verification. But nevertheless they show the trend where to reinforce the hull structure for the emergency case "flooding", which hopefully will never happen.

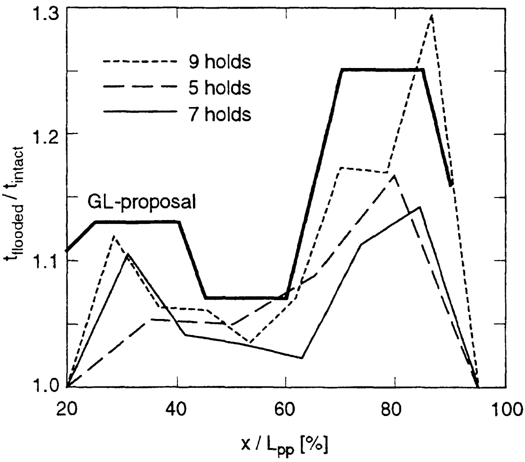

Fig. 13: Relative Thickness Increase of Side Shell in Flooded Condition, Lumped Values

4.3 Vertically Corrugated Transverse Watertight Bulkheads

While in the aforesaid consequences of a failure of the first barrier namely the side shell has been addressed, the transverse bulkheads as the second barrier are now discussed. The most severe combinations of cargo and flooding loads are to be used for the determination of scantlings of each bulkhead depending on the specified loading conditions defined by the designer:

- homogeneous loading conditions;
- non-homogeneous loading conditions;
- packed cargo conditions (such as steel mill products).

The flooding head h_f which is defined in Figure 14, differs from that of UR S17 (longitudinal strength) because UR S18 is not related to the equilibrium waterline but to fixed values d_f as specified below:

a) in general:
- D for the foremost vertically corrugated transverse bulkhead
- 0,9 D for the other bulkheads

b) for ships less than 50.000 tdw with B freeboard:
- 0,95 D for the foremost vertically corrugated transverse bulkhead
- 0,85 D for the other bulkheads

Top of ore means the horizontal line after levelling the piled up ore. This assumed line is the basis for the calculation of the horizontal pressure loads shown also in Figure 14.

The strength criteria to determine the scantlings (section modulus and local plate thickness of corrugation) have been evaluated on the basis of extensive calculations, carried out by different classification societies to unify as many global and local structural details as possible.

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Figure 15 illustrates stress results in the corrugation at centreline for a ship in service in case of flooding the hold which is partly filled with cargo, using the FE-model in Fig. 6, for different assumed plate thicknesses.

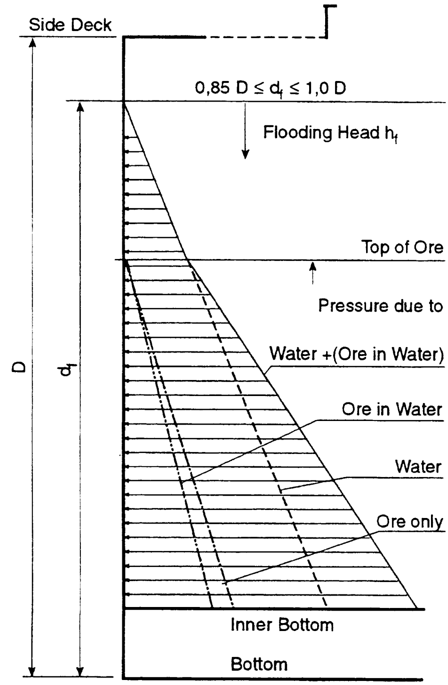


Fig. 14: Horizontal Pressure Load on Transverse Bulkhead, Flooded Condition

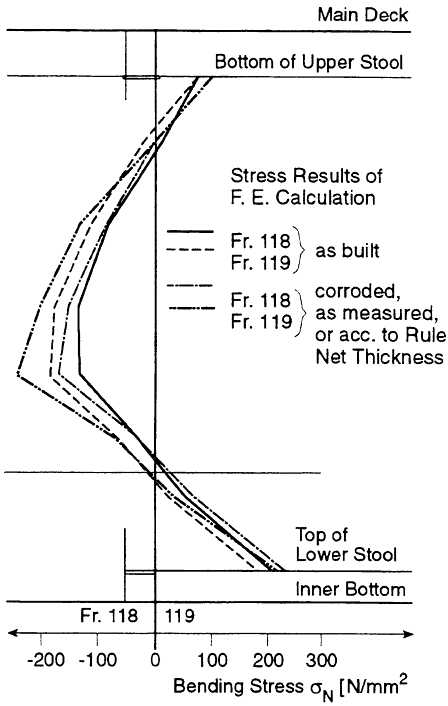


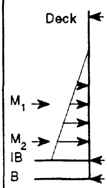
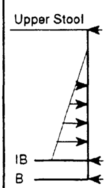
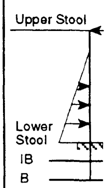
Fig. 15: Stress Distribution Along Corrugation at Centreline, Flooded Condition

Table 1 compares with each other the bending moments at half the corrugation length and at the top of lower stool derived from the FE-calculation and from three different beam models. Beam No. 1 model is used by Germanischer Lloyd for estimate purposes.

As the flooded condition is understood as a case of emergency the strength requirements compared to those of the service conditions according to the loading manual have been reduced.

Results of non-linear FE-calculations led to a strength assessment taking into account the reserve of strength beyond the elastic limit. Details will be defined in the unified requirement S18.

Table 1: Comparison of Bending Moments acc. to Different Calculation Methods

Calculation Procedure	F. E. M.	beam 1	beam 2	beam 3
				
M_1 [kNm] Half the Corrug. Length	1642	2025	1987	1348
M_2 [kNm] Top of Lower Stool	3282	3370	2919	4251

4.4 Shear Strength of Double Bottom

For existing and for new bulk carriers of single side skin construction the allowable hold loading in the flooded conditions has to be evaluated on the basis of the flooding head h_f mentioned in 4.3 for the bulkhead strength assessment. In no case the allowable hold loading in flooding condition is to be taken greater than the design hold loading in intact condition, documented in the loading manual. The vertical loads considered as acting on the double bottom are those given by the external sea pressure and the combination of the cargo loads with those induced by the flooding of the hold which the double bottom belongs to. The respective shear capacity is taken as the sum of the shear strength at each end of all floors and girders considering existing openings for pipes etc.

In the future not only a shear strength check of the double bottom will be required, but also the interaction between local and global loads will have to be considered.

5 Corrosion and Wastage Aspects

5.1 Corrosion and Wastage of Bulk Carrier Structures

Corrosion and wastage problems in bulk carriers have been underestimated in the past. Many bulk carrier losses within the last two decades have their reason in loss of strength due to severe corrosion and wastage. In bulk carriers we have to consider the following effects:

- corrosion by sea water, mainly in the wing and double bottom tanks,
- corrosion by aggressive cargoes, such as coal in cargo holds,

– wastage due to rough service conditions during cargo loading and discharging operations.

The corrosion problem in the ballast tanks has been recognised by the classification societies by introducing the IACS-Unified Requirement Z 8, which requires since 1990 all salt water ballast tanks of newbuild bulk carriers having boundaries formed by the hull envelope to be protectively coated by epoxy or equivalent. Since 1992 IACS requires by the Unified Requirement Z 9 for all newbuild bulk carriers that those surfaces of the side shell and transverse bulkheads, which may be exposed to cargoes, are to be protectively coated. These surfaces include the bottom stool 300 mm from its top and those parts of the upper and lower wing tanks, which are within 300 mm beyond of toes of the frame brackets (see Figure 16). With these measures the classification societies intend to reduce corrosion effects caused by ballast water and cargoes. Some coal cargoes with high sulphur content may be highly aggressive. The condensing moisture at the side shell and the sulphur of the cargo may form sulphuric acid, a highly aggressive medium causing severe corrosion specifically to side shell structures.

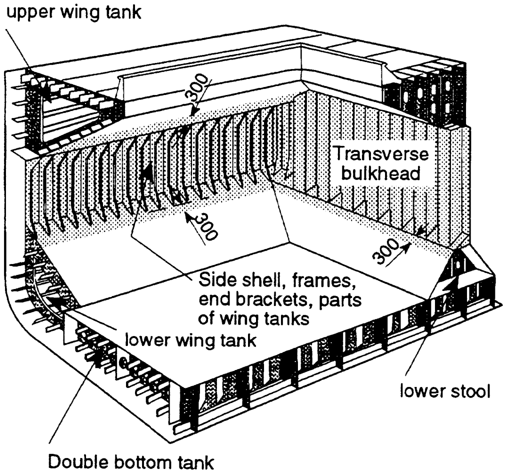


Fig. 16: Spaces and Areas of a Bulk Carrier to be Protectively Coated

From the view point of corrosion aspects it should be avoided to apply stiffeners with relative small web thicknesses to the plating. Frequently one sees for instance a shell thickness of, say 18 mm, with frames attached thereto having a web thickness of say 9 mm. In case of aggressive cargoes the stiffeners' webs may relatively quickly loose their strength due to heavy corrosion, whereas the shell thickness is still within the allowable margins. In such cases the stiffening effect of the stiffeners is lost and the shell is subjected to high membrane stresses which may in turn cause failure of side shell itself. This may explain typical side shell failures observed in bulk carriers. It is therefore important that in areas subject to corrosion, the web thickness of the stiffening elements must be adequate to that of the stiffened plating.

The classification societies require therefore since 1992 by the Unified Requirement S 12 that the web thickness of frames in bulk carriers shall not be less than a specified minimum thickness ranging normally from 11,5 - 13 mm, irrespective whether mild or higher tensile steel is used. The thickness of the lower frame brackets is required to be at least 2 mm thicker than the above minimum web thickness for frames.

The above strengthenings are also important from the wastage point of view. As mentioned above, bulk carrier hold structures are exposed to severe treatment during cargo operation causing physical damages. Heavy grabs may be moved against frames and brackets and cargo residues are removed from the structures by special movable „hammering equipment“. Another case is worth to be reported, where, as a consequence of loading and discharging big logs, severe deformations of the side framing and framing brackets were observed. Consequently, the framing system lost its ability to sufficiently stiffen the side shell, which in turn failed for the reasons explained above, causing hold space flooding.

From the corrosion and wastage point of view also some aspects concerning the use of higher tensile steel should be considered. The corrosion rates are also influenced by the stress levels, which may cause higher corrosion rates for higher tensile steels. Therefore, hold structures exposed to corrosive cargoes should be made of mild steel, wherever possible. The application of higher tensile steel in bulk carriers should be limited to longitudinal hull structural elements within the upper and lower hull flange.

One design aspect of the inner bottom is its stressing by heavy grabs during cargo discharge. These grabs, having a net weight of some 15 t, are frequently moved onto the inner bottom in the final phase of the discharging process causing thereby severe impact forces. These impact forces can best be absorbed by a „flexible“ inner bottom construction. According to GL's experience a relatively thick inner bottom in combination with a relative large stiffener/girder spacing of say not less than 800 mm has a much better chance to survive these impact forces than a relatively thin inner bottom thickness in combination with a small stiffener/girder spacing of say 400 - 600 mm.

5.2 Corrosion Additions, Residual Strength of Corroded Structures

The GL rule corrosion addition t_k is defined such that it results in a relatively large percentage addition for small thicknesses t' and a relatively small percentage addition for large thicknesses t', because a mean corrosion rate of say 0,2 mm per year means abt. 3 % thickness reduction for a 6 mm thick plate, but only 0,8 % thickness reduction for a 25 mm thick plate.

The corrosion addition t_k ranges therefore generally between ≈ 10 - 25 % of the original thickness. For plates designed for local pressures, the absolute corrosion addition t_k expressed in terms of millimetres is the same for mild steel and higher tensile steel, because the Rule thickness depends inter alia on the square root of the material factor k. Relative to the thickness, the corrosion addition t_k is larger in case of higher tensile steel compared to that for mild steel. This is intended to cover the above mentioned somewhat higher corrosion rates of higher tensile steels.

The strength concept of the GL Rules is based on the condition that steel renewal will be required when the average thickness reduction equals the corrosion allowance t_k, i.e. when the net thickness $t' = t - t_k$ is reached. The maximum permissible local thickness reduction is about 20 percent. This means that the GL rules consider also the structural strength in the corroded condition.

For the longitudinal strength standard in the corroded condition it is required that the hull girder moduli are not reduced by more than 10 % due to corrosion. This means a maximum increase in hull girder bending stress of 10 %, i. e. from 175 to abt. 193 N/mm^2, or a safety factor of abt. 1,2 against yielding in the corroded condition. It can be shown that in case of a 20 % thickness reduction the safety factor against plastic failure of a bottom plate panel and of a bottom longitudinal subjected to both hull girder and local bending is still in the range of 1,2 [7].

The Rule requirements for the proof of buckling strength are also based on the „net thickness“-concept by using the thickness $t' = t - t_k$ for the buckling analysis. For the net thickness the safety factor against buckling must be equal or greater than 1,0, having in mind that steel renewal becomes necessary when the original thickness is reduced by the corrosion addition t_k. This concept also implies that the post buckling behaviour provides an additional strength reserve.

6 Concluding Remarks

Severe problems with the ageing world bulk carrier fleet during the past few years demanded a review of the strength behaviour and design criteria. The methods and procedures available for the overall and local strength analysis - as shown in the paper - allow a rational assessment of the structural integrity based on first engineering principles. This includes aspects such as fatigue strength and detrimental effects of corrosive environment on crack initiation.

A new aspect will be the requirement of strength analyses in flooded condition. The current status has been discussed in the paper, final decisions will be taken by the relevant IACS governing bodies.

It has to be emphasised that even a bulk carrier of an excellent structural design will have problems during the service life if it is not properly maintained. Corrosion and wastage aspects are therefore, most important for the structural integrity. Design requirements with respect to fatigue, corrosion additions and protective coatings can contribute to reduce the problems, proper maintenance and efficient inspections are essential to control them.

Germanischer Lloyd is fully aware of its responsibility for sound design requirements and adequate rule development for safe and efficient bulk carriers, as well as for careful plan approvals including all necessary strength analyses and for careful surveys during construction and service time. Based on the good experience in the past with a large number of bulk carriers in class, the prospects for new generations of bulk carriers are considered as good as far as strength requirements are met and maintenance is taken care of.

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