PROJECTION OF FRACTURES IN SHIPS FOR THE EVALUATION OF FATIGUE RESISTANT DESIGNS

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ABSTRACT

Cracks in ships have been of great concern to the maritime industry for a very long time. The problem is controlled by improving design, minimizing operating stresses and through regular inspections and repairs. The big trade-off which designers and owners have to face in the construction of a new ship is whether to invest in a fatigue resistant design, or to keep the construction cost low and incur the repair costs as cracks emerge later in the ship's life. This choice has to be made for hundreds of components throughout the ship's hull.

A procedure was developed to assess the cost effectiveness of fatigue design improvements in ships. It is based on comparing the additional cost of a proposed design (over the current design) with the present value of all the projected crack repair costs of the corresponding location. The present value of the repair costs has to be determined for the various locations in order to serve as a guideline when evaluating new fatigue resistant designs that promise to reduce the number of cracks and future repair costs. A general model was developed and then several assumptions were made to give a simplified version.

The assumptions and limitations of the model are discussed as well as the ways in which it should be used to address various problems and produce meaningful results. Suggestions are also made for avoiding problems in each stage. A large database of cracks is required to run the model and a location coding system in order to process and analyze it. The difficulties of collecting and processing the data are discussed as well as potential adjustments that have to be made to accommodate irregularities among ships and ship compartments.

A literature review was carried out of the various statistical surveys that have been conducted over the past 50 years relating to cracks and damages in ships. Differences in the results of surveys regarding the distribution of cracks lead to the conclusion that cracks follow different patterns than other damages and that the various kinds of ships exhibit different cracking behaviors. This emphasizes the importance of using a large data sample that is specific to a particular type of damage and ship type and size range when applying this proposed model and procedure.

Thesis Supervisor: Henry Marcus

Title: Professor of Marine Systems

Acknowledgments

First and foremost I would like to thank my supervisor Professor Henry S. Marcus for his valuable guidance and recommendations on my research. I would also like to thank all the principal members of classification societies, shipyards, and shipowners who gave me access to their unpublished research and literature on the subject for the purpose of preparing this project.

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Definitions

Capesize Bulk Carrier: Bulk Carrier ~ 175,000dwt

Handysize Bulk Carrier: Bulk Carrier ~ 20,000dwt

Handymax Bulker: Bulk Carrier ~ 45,000dwt

Kamsarmax: Bulk Carrier ~ 85,000dwt

Panamax Bulker: Bulk Carrier ~ 75,000dwt

Post-Panamax: Bulk Carrier ~ 95,000dwt

Supramax: Bulk Carrier ~ 55,000dwt

Abbreviations

AP: After Peak

bhd: Bulkhead

Cape: Capesize Bulk Carrier

CH: Cargo Hold

dwt: Deadweight

ER: Engine Room

FEA: Finite Element Analysis

FP: Fore Peak

IACS: International Association of Classification Societies

LOA: Overall Length

MV: Motor Vessel

OBO: Ore Bulk Oil

PMX: Panamax Bulk Carrier

PV: Present Value

S-Factor: Staging Factor

VLOC: Very Large Ore Carrier

Nomenclature

Parameters

CP: Cost Parameter for Ship

CT: Cost of time ($/day)

RC: Repair Cost

RT: Repair Time

$RT_{NoCracks}$: Repair time without cracks

Subscripts

i: Crack or Discount Rate

j: Ship Location with crack

k: Repair Process

s: Ship

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1. Introduction

Cracks have been of great concern for many decades to all parties involved in shipping. Owners are concerned with the safety of their ship and crew and of course repair costs. Charterers are concerned about cargo damage and delays. Maritime organizations and classification societies are concerned about the sea worthiness of ships, the safety of the crew and protection of the environment. Shipyards are also constantly trying to pin-point the problem in order to improve design and introduce new ships.

Cracks develop and propagate due to corrosion or fatigue and may ultimately lead to failure and sinking of the ship. Corrosion cracks manifest by the well-known mechanism of stress corrosion cracking. Furthermore, the structure is fatigued by the alternate loads due to sea waves, and during loading and unloading. There is practically no ship entirely free of cracks. The origin, type and size of cracks however may differ widely from one ship to another. Some cracks develop at an early stage for example due to bad design or bad construction, while others may develop later as a result of fatigue.

The problem of cracks is controlled by improving design, minimizing stresses during operation and through regular inspections and repairs. The big trade-off which designers and owners often face in the construction of a new ship is whether to invest in a fatigue resistant design, or to produce a lower cost structure and incur the repair costs as cracks emerge later in the ship's life. This kind of choice has to be made for hundreds of locations throughout the ship's hull

2. Objective and Outline

The aim of the present research is to develop a method of evaluating the cost effectiveness of proposed design modifications that promise to improve the fatigue resistance of a ship. The approach is to compare the additional cost of a proposed design with the present value of all the projected crack repair costs of the corresponding location. If the present value of the repair costs of the cracks that will be avoided with the new design exceeds the additional cost of implementing that design, then the design is cost effective.

The procedure consists of two parts. First, the projected cracks for a given location have to be estimated. Second, the repair costs of these cracks and its present value have to be determined. The procedure and model that will be developed to carry out the task will require several assumptions but will be applicable to any ship type and proposed design modification.

The application and calibration of the model however have to be for a specific ship type and will require the use of real data. The procedure involves examining the whole spectrum of cracks developed throughout the life of an average ship of the chosen type before evaluating the present value of the repair costs. A large database of cracks is required for that purpose. The data may come from survey reports of classification societies, shipyards and shipowners. A location coding system is then required to process and analyze the data before applying the model.

3. Previous Work On Cracks in Ships

Theoretical, analytical and numerical methods have been developed to assess the problem in many ways. Modeling of the marine environment however and accurately predicting the actual conditions and stresses are practically impossible. It is therefore essential to take direct measurements from ships and any conclusions derived as such will be much more reliable for the time being.

Extensive research of this sort has been carried out to cover the aspect of corrosion. Several databases of direct ultrasonic gauge readings have been collected and statistical studies have been performed. Similar studies on cracking however are very limited and most are quite old as can be seen in Table 1 which summarizes all such studies reported over the past 50 years.

DIRECT MEASUREMENT BASED SHIP CRACK LITERATURE 1958 – 2005			
Author	**Classification Society**	**Number of Ships/Type**	**Type of Data**
[GL 2005 Private Correspondence]	GL (72 of 145)	145 Bulk Carriers	783 Damages
[GL 2005 Private Correspondence]	GL	193 Tankers	1,201 Damages
[NK (b) Private Correspondence]	NK	124 (Tank, Ore C. & Bulkers)	643 Cracks

[DNV 2002 Private Correspondence]	DNV	-	221 Cracks / 304 Damages
[LR 1999 Private Correspondence]	LR	1,405 Bulkers	19,115 Damage Defects
[Bea et. al 1995]	-	10 Tankers	3600 cracks
[Yoneya et al 1993]	NK	18 VLCC	~180 cracks
[Ferguson et. al 1993]	LR	Bulk + OBO	Damages
[Exxon 1983 Private Correspondence]	-	>40 Exxon Tankers	Cracking/ Corrosion
[SSC 1980]	-	36	3,555 Cracking/Buckling
[Jordan et al 1978]	-	~50 (various)	6,856 damages
[Antoniou 1977]	-	233 Tankers	25,652 Cracks
[ABS 1976]	ABS	535 Bulk Carriers	104 Damages
[ABS 1976]	ABS	411 Tankers	413 Damages
[LR 1976]	LR	-	Cracks
[NK 1976]	NK	176 (Tank / Ore C./ Bulkers)	Cracks
[LR 1975]	LR	-	Defects
[ISSC 1973]	-	73	Cut-out Damages
[Yamaguchi 1968]	NK	97	Damages
[Vedeler, 1958]	DNV	-	Cracks
[NK (a)]	NK	-	Damages

Table 1: Crack and Damage Surveys

This is mainly due to the high confidentiality and difficulty of access to raw data which is never available to the public. As can be seen, most of the work has been carried out by classification societies who have access to the data of ships in the fleet under their classification. Many of them do not report details of their findings but only use them to develop their rules. Consequently, many of the surveys are not published and the number of ships and defects of the surveys are usually not made available. Some of the surveys only focus on a certain age group of vessels or only examine a particular area such as the After Peak [LR 1976]. Furthermore, very few surveys have been performed specifically on cracks. Most cover a wide range of damages or failures including dents, buckling, corrosion etc.

4. Bulk Carriers

Bulk carriers were introduced in the 1950s for the more efficient transportation of cargo in the form of bulk. They are divided into size-groups but the definitions have changed over time following technological developments and the shift to greater sizes in order to achieve economies of scale.

Traditionally they have been divided into three main categories. The smallest are the handy size ranging up to Handymax which are typically geared, the second main group are the Panamaxes which are the maximum size that can transit the Panama Canal, and finally the Capesizes which are larger and hence have to sail around the cape. Today the groups most commonly referred to, starting from smallest to largest are the Handy-size, Handymax, Supramax, Panamax, Kamsarmax, Post-Panamax and Capesize and VLOC (very large ore carrier).

The design of bulk carriers in general has remained more or less the same since they were introduced in the mid 1950's. What is even more interesting is that apart from scantlings and size, the cross section of a large Capesize bulk carrier (Cape) is almost identical to that of a Handy. The structural details in the cargo hold region of a typical bulk carrier are outlined in Fig 1 while Fig 2 provides an outline of the whole cargo hold configuration.

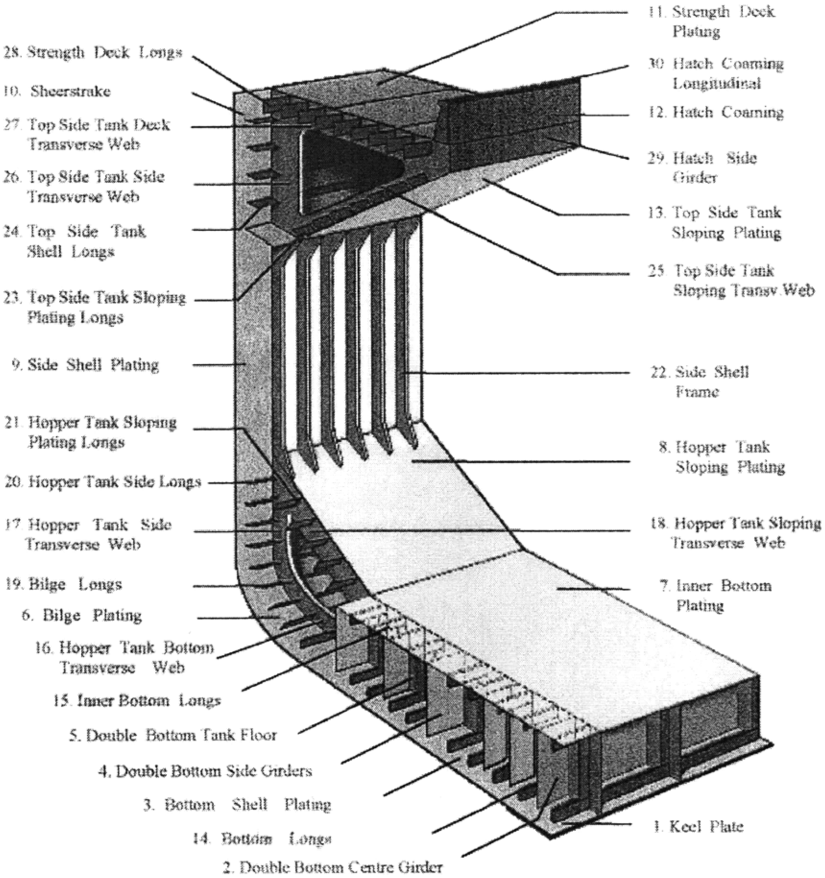


Fig 1: Bulk Carrier Mid-Ship section, Structural Items [Loukakis 2005]

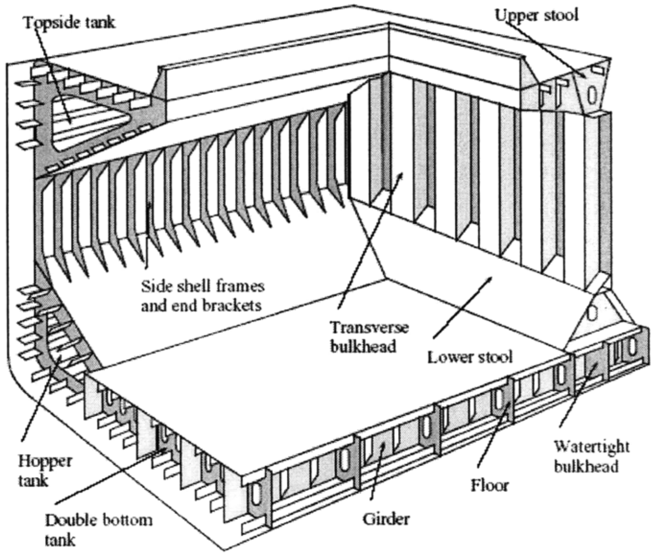


Fig. 2: Typical cargo hold configuration [IACS 2009]

About 10 ships and 50 lives are lost every year from bulk carrier losses alone since the beginning of the 1980s [Intercargo 2004, O' Mahony 2004, Macalister T. 2004, Intercargo 2002, Naval Architect 1996, Byrne et al 1998, Mortensen 1998]. Fig 3 shows the trend in bulk carrier losses and the resulting life losses since 1995.

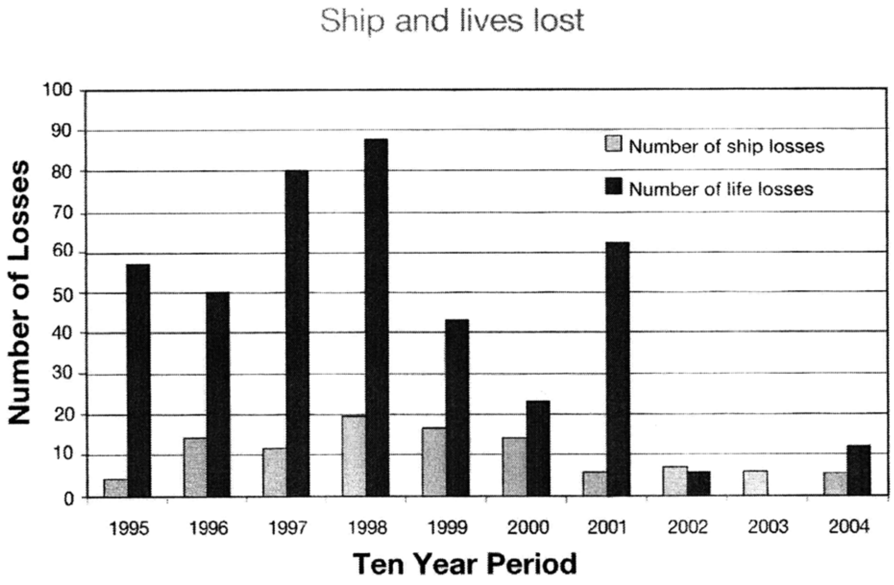


Fig. 3: Ship and Lives Lost due to Bulk Carrier Losses since 1995

[Intercargo 2004]

It is interesting to note that as suggested by ABS in an analysis of bulk carrier losses, these seem to follow the fluctuations in the freight market [ABS 1997]. The concept explaining this is that during a high freight market, repairs are likely to be postponed. Hence this emphasizes the influence of repairs and structural ability on ship casualties.

Capesize bulk carriers (capes) started with a deadweight of about 110,000 dwt in the 1960s and gradually progressed to the typical size of 172,000dwt. There are also a few specialized iron ore carriers (VLOCs) in excess of 300,000dwt. The world's largest ore carrier is Berge Stahl, built in 1986, shown in Fig 4 below. It measures 343m long and has a deadweight of 364, 767dwt.

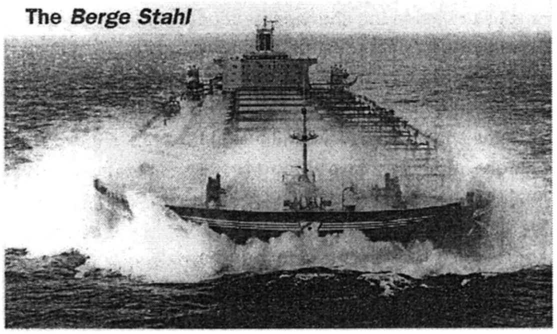


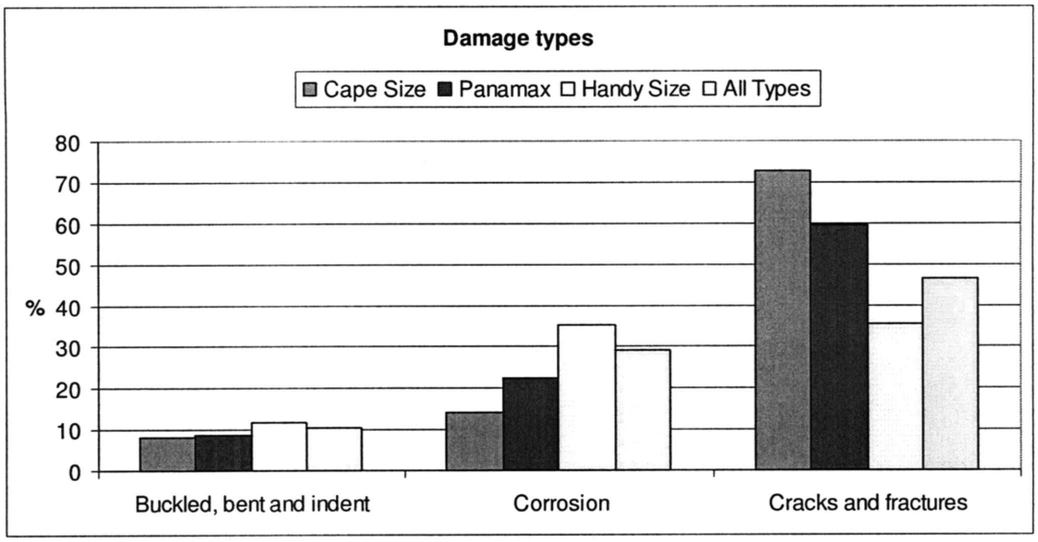
Fig 4: Berge Stahl - The World's Largest Dry Bulk Carrier

[Van Dyck 2004]

They are typically gearless with 9 cargo holds of approximately the same size, equal to about 25 metres deep. Their overall length (LOA) is typically 292 metres and the beam is about 50m. They are used mainly in the transport of high density cargos such as iron ore or coal within specific trade routes. Most common destinations include China, Australia, Holland, Brazil and South Africa. These ships today are designed for a fatigue life of about 30 years. Their trading life however is affected both by structural and economic factors and often exceed this. Life extension is worthwhile as long as returns over the projected remaining life of a ship outweigh the required costs.

Due to their large size and the consequent large bending moments and stresses, the problem of fractures is more severe than in smaller ships. This is illustrated in Fig

5 which compares the number of cracking and fatigue incidences between the various bulk carrier size groups.



Source: DNV damage

Fig. 5: Comparison of Cracks as a percentage of total damages between the three main Bulk Carrier Size Categories [DNV 2002 Private Correspondence]

5. Crack Growth and Monitoring

5.1 Cracking Mechanism

Cracks in ships generally develop and propagate due to corrosion or fatigue and may ultimately lead to failure and sinking of the ship. Corrosion cracks manifest by the well-known mechanism of stress corrosion cracking. Furthermore, the structure is fatigued by the alternate loads due to sea waves and during loading and unloading operations with rates of up to 18,000 tonnes per hour.

Cracks may initiate in gas cut notches, at geometrical discontinuities, in defects which are particularly common in welds, or in other high stress concentration sites which often arise due to poor design. Another cause of cracking is when steel plates during repairs are welded at a 90 degree angle to the direction is which they have been hardened. This is typical in large surface area regions such as deck plates, the tank top, the shell plate, hoppers, sloping plates, bulk heads etc.

Cracking can also occur through careless handling, for example by the impact of excavators during unloading or as iron ore strikes the tank top plate during loading. These and other factors may result in denting and the formation of high stress concentration sites which give rise to potential for cracking.

Cracks also tend to propagate along preferred paths such as along the grooves parallel to the welds because of the lower thickness of the material. The preferred path depends on the material, geometrical considerations such as the thickness and the mode of loading i.e. the direction of stresses relative to the crack.

5.2 Vulnerable Areas

The areas most vulnerable to cracks are known to be the side shell, bulk heads, longitudinal frames, hatch coamings connections to main deck, hatch covers, welds and other stress concentration sites. Fractures tend to initiate at the beginning or the end of the weld or a stiffener, at corners, intersections with other welds, at undercuts, or at the abrupt edges of bad quality welds. Fig 6 shows some typical defects which occur within the cargo hold region.

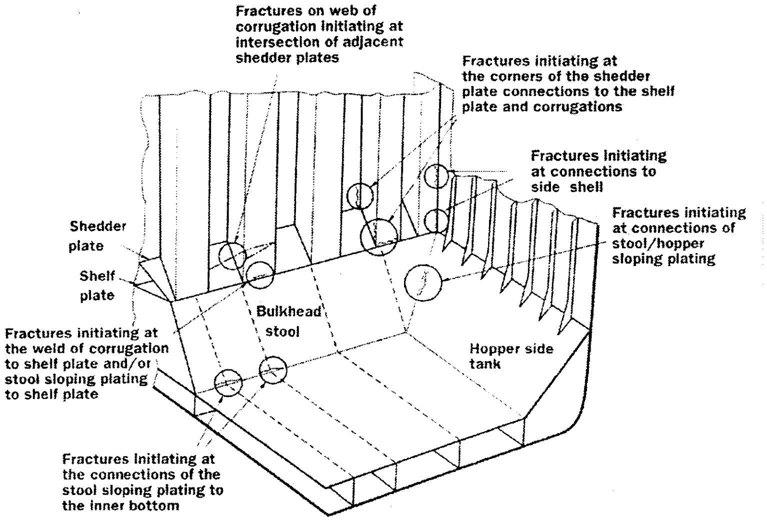


Fig 6: Typical Defects in Cargo Holds

[The Motor Ship 1994]

The main frames and end brackets are also very vulnerable to cracking. A few examples are illustrated in Fig 7.

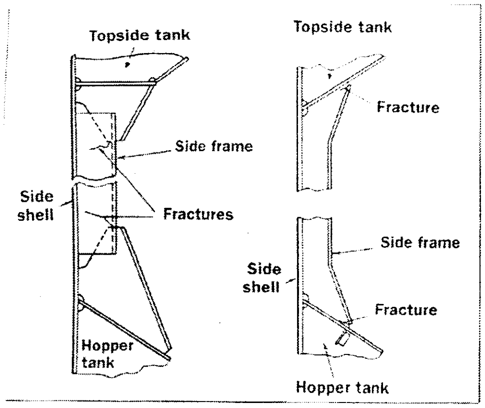


Fig 7: Potential Problem Areas in Main Frames [The Motor Ship 1994]

5.3 Inspection Planning

Inspections are carried out throughout the service life of ships by various maritime organizations including classification societies, the flag authority and the port state control when ships enter or leave ports.

Regular inspections are scheduled throughout the ship service life by classification societies. Their frequency and the items which are viewed each time vary with the type of survey and ship age. The IACS Classification societies carry out the hull surveys which are listed below according to the detail of inspection.

Special Survey: Carried out every 5 years and every time there is a change of classification society

Intermediate Survey: Carried out during the 2nd or 3rd year after each Special Survey

Annual Survey: Carried out every year and may coincide with an Intermediate or Special Survey

Occasional: Carried out randomly if there is a particular reason such as a damage or a request by the port state control

The scheduling of inspections as described above is based on the accumulated experience of maritime organizations over time, primarily regarding the plate thickness diminution.

5.4 Inspections

During hull inspections, 3 main factors are being searched. These are coating breakdown; corrosion or diminution; and damages such as buckling or cracks. Ultimately, all of these factors lead to cracking so their identification during inspection is of critical importance and of great relevance.

Regarding cracking, inspections should be based on experience of where cracks occur. These include a number of locations as discussed under section 5.2. Cracks are also likely to be found at the locations where coating breakdown or corrosion has been identified.

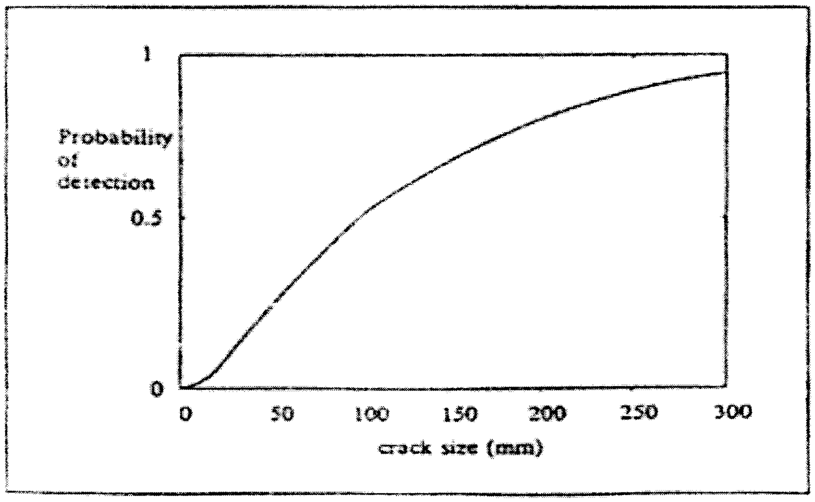


Fig 8: Probability of detection as a function of crack size [Barltrop 1992]

In many cases, cracks may not be evident during the time of inspection due to dirt, poor lighting, difficulty of access, or compression of the two surfaces. It is therefore important to first clean and then carefully inspect the critical areas. In some cases, the crack origin or tip may not be visible and the other side of the plate will have to be examined. A similar example is in the cracks of hatch coamings which can only be seen if one looks over the hatch opening if they have not yet propagated out to the deck.

It is consequently vital for an inspector to have a good understanding of the areas being inspected and also of the importance of cracks depending on both size location and origin. The chances of identifying cracks are then increased and dangerous cracks can be distinguished from other less critical defects.

When cracks are detected in the hull, the normal procedure is to replace the cracked plate with a new one. If this is not possible however, a temporary solution which is sometimes adopted is to drill a hole at the crack tip. This serves to eliminate the stress concentration and thus arrest the crack preventing further propagation. In areas where small cracks cannot be welded such as in the engine due to the use of cast iron rather than steel, cracks are often tied together using a method called "metalock".

There are several methods used to detect cracks. These are namely

- ***Visual*** – Easiest and most basic / surface cracks only
- ***Ultrasonic*** – Access to difficult regions / subsurface cracks / size and shape
- ***Magnetic Particle Inspection*** – Very easy / surface cracks only
- ***Dye Penetrant*** - Only large surface cracks on plane surfaces
- ***Radiographic (X-Ray)*** – Subsurface cracks / only size (a shadow)

6. Design

6.1 Fit for Purpose

Besides designing for maximum strength and survivability of a vessel, there are a series of other design considerations which must be taken into account for a design to be successful. First of all, there must be a clear understanding about the way a vessel is intended to be used in order to make the correct decisions in design.

It is a widely known fact that whilst all new ships should be safe in the most hostile wave environments, some designs will age better than others. Owners often intend to sell ships at the age of about ten years while others plan for a longer use. The commercial advantages which are offered by high tensile steel and the associated problems which develop as the ship ages are now understood. When designing for the short term therefore, it is common to use a greater percentage of HTS. If a ship is designed for a fatigue life of about 30 years which is typical for most cargo ships, it is important to have a clear understanding of the “correct” locations where HTS does not cause problems. A much smaller percentage overall is then normally used.

Another example is the design for alternate hold loading. This provides several advantages such as the ability to moderate the ship rolling motion by increasing the height of the centre of mass, or the fact that fewer holds require cleaning. Most important however is the time saved during cargo operations. This is achieved because fewer holds are unloaded each time while the bottom part of the holds is most time consuming. Alternate hold loading is thus preferable when loading high density cargos such as iron ore. As a consequence however, the stresses acting on the hull are amplified. As a result, special design is necessary to allow this type of loading, and strengthening of the required structural members. Fig 9 shows a finite element model of a hull section during alternate loading with the associated stresses.

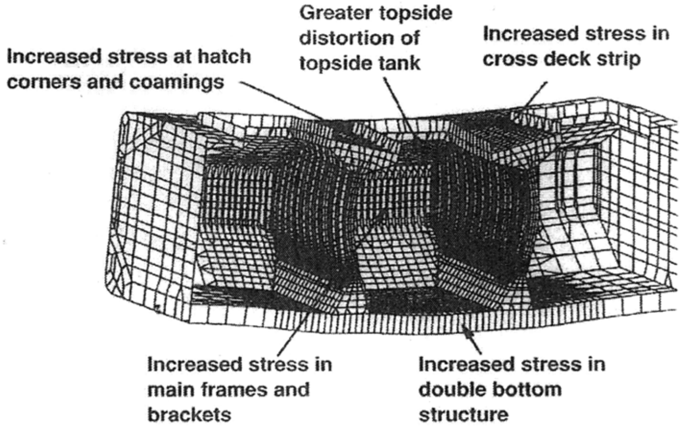


Fig 9: Hull Stresses under Alternate Loading condition

[MER 1997]

Regarding the aspect of correctly designing a vessel for its intended use, there are often problems associated with the required cost. It has been known that some ships were built to lower standards but were then used for a wider range of trades for which they were not suited. The way to overcome this is to produce a common minimum standard so that all ships are able to cope with all common cargos and with a common design life. According to Mr Bowring, most yards will always supply the bare minimum since most faults will not show within the 12 month guarantee period and there is almost no collection of data by the industry that would identify yards routinely building ships with faults [MER 2002]

There is no doubt that the ship design plays a major role in the problems developed by a ship throughout its service life. This is evident in sister ships which very often have the same weaknesses and develop the same problems even if owned and run by different operators in different trades. An important aspect of design however is its influence over other critical parameters. It is crucial through design to ensure conditions which promote easy, safe and effective running of the ship. This includes the aspects of operation, maintenance and inspection.

A typical example of designing for easy and effective operation is the design of large hatch openings. This may improve the process of cargo loading and unloading operations but may have significant implications regarding the torsional resistance of the hull [Plaza 1998]. It is thus very important to make the correct compromises in design.

Designing for a cheap construction is also important. It is often the case however that a lot of money can be saved in the subsequent maintenance throughout the ship service life, by taking the correct design decisions. An example is the use of full penetration welds in the cargo bulkheads. This may increase the fabrication costs for the building yards compared to the use of fillet welds, but it makes these critical components less vulnerable to corrosion.

Finally, ease of inspection is another very important factor which should be accounted for during design. A good example of failure in doing so is in the construction of joint bottom and top-side ballast tanks. This not only eliminates the option of ballasting the topside tanks when a leak develops in the double bottom tank, but it also makes inspection of the bottom tank impossible when the ship is in ballast. Another example where ease of inspection is limited by the design is in the case of the double hull. The following chapter provides a detailed analysis of the double hull design for its use in bulk carriers.

6.2 The Double Hull Bulk Carrier Debate

The first double hull ship was built by William Petty in 1662 [Wheater 2000]. Double hulls became mandatory for tankers over 5000dwt by the MARPOL Convention since the early 1990s in response to the *Exxon Valdez* disaster and phase out dates for the different types range until the later 2010s [Naval Architect 2003a, Naval Architect 2003b, GMOPIG (a), DF Dickins Associates Ltd. 1995]. In 2002, K-line (Wawasaki Kisen Kaisha) ordered the first ever double-hull capesize ships. The two 205,000dwt bulk carriers were ordered from Imabari Shipbuilding in Japan for delivery in 2005 [Flynn 2002].

The issue of double hull bulk carriers hit the headlines in the shipping industry a few years ago after the proposals of the IMO for its enforcement to newbuildings. Any modification as such, would have a great impact on ship construction and maintenance, which inevitably will reflect on the cost of freight. Consequently, an enormous amount of mental energy, as well as time and money, has been spent by both government and industry experts regarding this matter [De Bievre 2004a]. Fig 10 shows the modification in the cargo hold region in going from single to double hull.

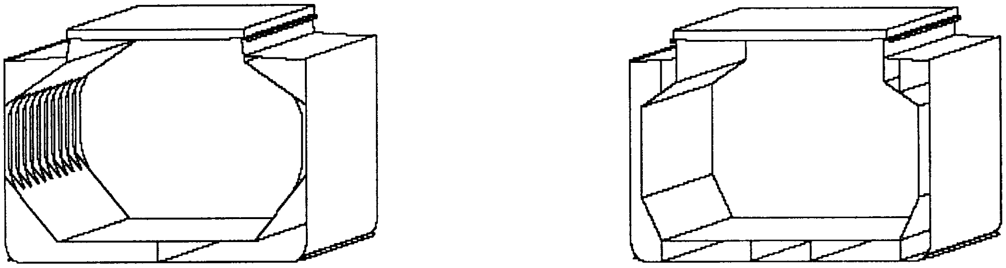


Fig 10: Single hull (left) compared to Double hull (right)

[Graig Shipping plc. & Carl Bro A/S]

The main reason which triggered research in this direction was the aspect of safety and protection of the environment [Lloyd's List 2004a]. IACS has also been considering the implementation of the double hull to other types such as containerships for the future [Landon 2004].

One of the strongest supporters of the double hull configuration was the ITF general secretary who characteristically accused the opposition of "favouring short term cost saving over sea farers lives". He also raised the question why the double hull was made compulsory for tankers and not bulk carriers claiming that "an oil spill costs an owner more than a dead crew" [O'Mahony 2004a].

Prevention of pollution is clearly not the case in bulk carriers. Bearing in mind that tankers are of different construction and operate under different conditions, it would be very unwise to make assumptions and directly compare the two. Capesize Bulk carriers carry non-polluting cargos such as coal and iron ore, so the only risk of pollution would be from bunkers. If this was the objective however, the double hull could simply be confined just to the fuel tanks as is now being considered independently [Lloyd's List 2005a]. It should be noted that even for tankers, the effectiveness of the double hull configuration has been disputed and is not clearly the ideal solution regarding safety and pollution prevention [Langdon 2004, Langdon, 2003, The Motor Ship 1991].

The concept behind the double hull configuration is that during a collision, the cargo holds remain isolated from seawater and flooding is thus confined to the void space which separates the two shells. This however only applies to low energy collisions (rarely the case of total loss) where the inner shell remains unaffected [Efthymiou 2004].

An advantage is that reduced hold width and the consequent reduction in free surface area of the holds would make the ship less prone to instability due to free surface effects in the case of partial flooding. Furthermore, the increased steel cross sectional area due to the secondary shell with longitudinal framing results in increased shearing strength and therefore reduces the probability of shear failure in the vertical direction.

Twice the number of hulls however does not necessarily mean twice the strength and the double hull is also faced with several disadvantages in the case of inner shell failure. Under that scenario for example, water is isolated from the void space at the other end of the hold, resulting in asymmetrical flooding and subsequent heeling of the ship to the side of the collision. Double hulls are also exempt from many regulations imposed to s-hulls by SOLAS-X11 [Corbett et al 2004a] including flood testing. As a consequence of this, some yards have found the overall cost of the double hull to be even lower than the s-hull and have been accused of providing ship owners with a cheap solution! [Corbett et al 2004a, Tradewinds (a)].

The small number of double hulls and the fact that they are all relatively new severely limits the validity of statistical data (comparing accidents) and makes the assessment of the proposed configuration a true challenge. It should also be noted that the double hull recommendation came from a study, which only considered pre-1998 bulk carriers [Bowring 2003]. Standards have greatly improved since then and continue to do so for newbuilding s-hulls which not only have to comply with tougher regulations [Corbett 2004a], but they are also scrutinized by surveyors in ports.

Instead, one can consider accidents of the past and assess whether a double hull would make a real difference. There are two very famous, tragic examples which suggest the opposite. These are the s-hull cape *MV Christopher* (Dec.2001) [Lloyd's

List 2004a], and the double hull ore bulk oil carrier (OBO) *MV Derbyshire* (Sept.1980). Both have been thoroughly investigated, they were both about 165,000dwt and both failed due to progressive flooding. In the case of *MV Christopher*, flooding started through the first hatch cover (forward) so obviously, a double hull would not have made a difference as it also didn't do so in the Derbyshire 21 years earlier [Woinin 2002, SSC]. Today, ships are designed using the principle of inherent redundancy to prevent this domino effect and all ships have to comply with the according regulations [Tradewinds (a), De Bievre 2004b].

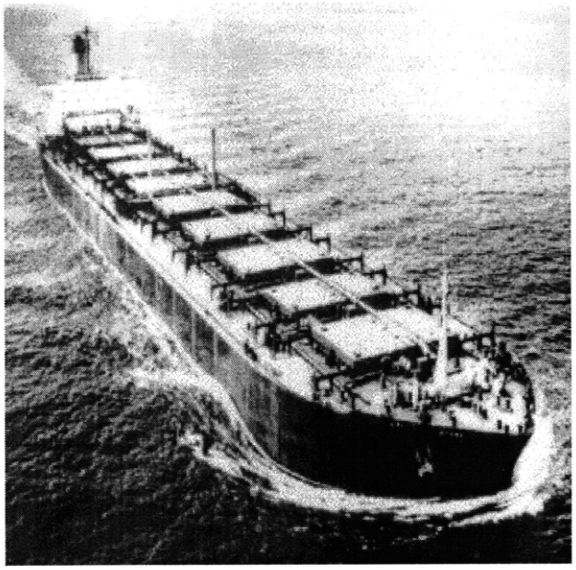


Fig 11: Double Hull Ore Bulk Oil Carrier *MV "Derbyshire"*

[SSC]

Fig 12: Capesize Bulk Carrier *MV Christopher*

[Corbett 2002]

Key factors on the double hull design are maintenance and inspection. Since the width of the space separating the two shells in double hulls is approximately 1m [Naval Architect 2003a], both are extremely difficult. Entry is via the top side ballast tanks and access is consequently prohibited when the ship is ballasted. This also provides a very good excuse to prevent inspection in general for prominent reasons. Potential corrosion in the double hull space due to the local break-down of coating is immense because of the frequent impact from grabs during discharge. As a result, existing double hull type vessels are typically scrapped 2 to 3 years earlier than comparable s-hulls [O'Mahony 2004b, Vassalos et al 2004]. Bearing in mind that new bulk carriers are designed for a 30 year fatigue life [Lloyd's List 2004b], the inability to properly maintain the double hull space may increase the chances of structural failure. Statistics also exist which show a far higher incidence of fatigue problems in double hulls [Vassalos et al 2004]. An example is shown in Fig 13.

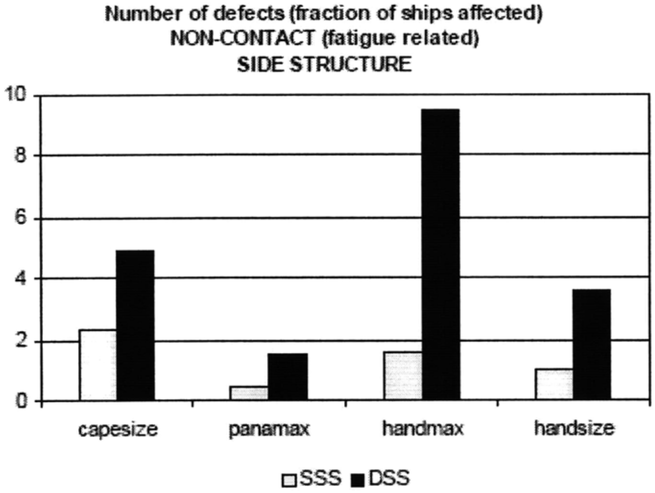


Fig 13: Fraction of ships affected between 1990-1999 by side structure fatigue

Comparing s-hulls (SSS) with double hulls (DSS) [Vassalos et al 2004]

There are also fears that the limited number of older double hulls to confirm their durability and the limited experience in their operation may also prove unsafe.

Having discussed the safety issue concerning the double hull, it should be noted that there are other more effective and efficient ways of improvement. Examples include the forecastle and wave breaker which became compulsory for capes after the *MV Christopher* incident, stronger hatch covers, improved scantling design, enhanced surveys and stronger bulkheads etc. As BV committees commented, “Single skin design bulk carriers could become much safer if the additional steel requirements for the double-side skin design were to be strategically distributed in the scantling” [Corbett et al 2004b].

Besides safety issues however, there are many operational advantages of the double hull design. Chris Williams, director at Graig comments “We designed the Diamond double hull bulker from the shipowner’s point of view. We came up with the design before the whole double-hull thing became a debate" [Corbett et al 2004a]. Contrary to the s-hull, frames are placed on the outer shell, which leaves the cargo hold with a smooth surface free of discontinuities. This allows quicker dispatch at ports, less stevedore damage, effective cleaning of holds without the obstacles presented by frames, and easier maintenance and inspection [Lloyd's List 2004a, Jones 2002, Fricke et al 1998, Jang et al 1998].

Terminal time is of major importance to ships and shippers and is probably the greatest advantage of the double hull. This is achieved due to less obstruction to bulldozers during discharge; avoidance of cargo getting lodged between frames; easier cleaning without the need for entry of shore workers to holds to remove residual cargo (also a great health and safety issue); and easier inspection without the need of a cherry picker which can be a major problem to find and load on large gearless ships. Terminal operators claim that double hulls have a 10% faster discharge rate for coal and that the mechanical damages per ton discharged is 6 times lower than in s-hulls [Naval Architect 2003a]. [Vassalos et al 2004] suggests a 6.5% reduced time in port overall for a cape by employing a double hull.

Maintenance within the hold is also made easier. Welded frames are difficult to maintain and are very vulnerable to grooving corrosion especially when exposed to corrosive cargos such as Australian coal. Sand blasting is much easier on the double hull whose design also provides large areas of smooth surfaces for the rust-bust machine to work on. In the case of damage to the side of the hold however, repair works are very difficult since both sides need to be accessed.

A big concern in double hulls is the use of the space between the two shells. The double side spaces could be used for ballasting as in the handymax type "Diamond" [Lloyd's List 2005b]. The gain in ballast volume could possibly allow the elimination of the topside tanks, which will regain part of the lost cargo volume. The same may apply to hopper tanks though hoppers are also convenient to guide the cargo towards the centre of the hold. On the other hand, ballast is very corrosive and as discussed earlier, ballast tanks are the most corrosion prone region of the ship's hull. According to Alan Gavin, principal surveyor for Lloyd's Register, "...Because of the narrow width of the wing space and the cellular construction, atmospheric corrosion within the upper spaces will be more significant," [The Motor Ship 1993].

Noting the difficulty of maintenance and inspection discussed earlier, it would seem much safer for the area to be used as void space which would provide much higher corrosion resistance. Additionally, some yards are also very concerned that ballast would give rise to excessive bending moments in the flooded condition [Naval Architect 2003a].

A disadvantage of the double hull design is the additional steel as part of the hull. Several yards and classification societies suggest that the lightship of a double hull will be in the region of 3-5% higher than of an equivalent s-hull [O'Mahony 2004b, DNV 1997]. This makes the ship more expensive to built, increases consumption (due to deeper draughts) and leads to loss of deadweight. ABS has calculated the additional steel cost in the double hull capesize bulk carrier to be about $484,000 while savings due to reduced maintenance and cleaning amount to approximately $9,700 per year [ABS]. More detailed calculations by [Vassalos et al 2004] which include steel, coating and construction costs as well as running costs such as increased fuel consumption, increased maintenance and repair costs and loss of earnings due to reduced deadweight and volumetric capacity, add up to $4,869,264 for a cape. The benefits to the ship owner, port and stevedores due to reduced time in port as well as increased scrapping value in the same analysis add up to $556,414.

There are experts however who suggest that the structural weight could be reduced reasonably in comparison to the existing double hull designs" [Jang et. al 2002].

More important than the loss of deadweight is the loss of grain capacity (cubic meters of cargo hold space). This may not be such a great issue for high-density cargos like iron ore but will be of major importance in the trade of lower density cargos such as coal. Ways, which have been considered to reduce the loss in freight earning capacity (both weight and volume), include the use of high tensile steel and the reduced double bottom depth respectively, but this may have a negative effect on the strength of the hull girder [Naval Architect 2003a]. There is extensive research going on to perfect a steel/concrete sandwich double skin using a special lightweight 900 kg/m3 concrete aggregate as shown in Fig 14.

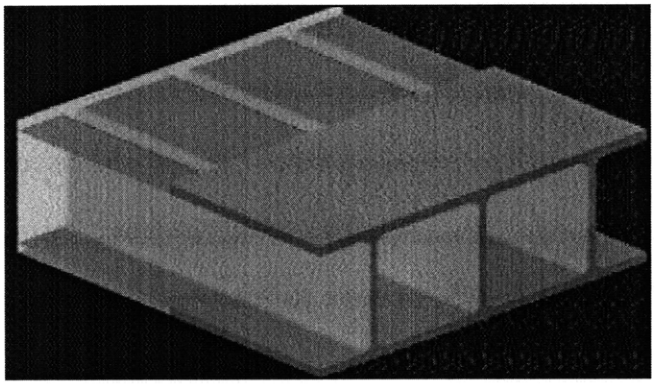


Fig 14: Steel Concrete Sandwich double hull structure [Naval Architect 2003b]

This will be stiffer and hence will allow narrower double hull and d-bottom spaces to be occupied saving more cargo space. There are fears however that it will be more uneconomic if regulations are imposed on the minimum width of the double hull space [Naval Architect 2003b].

As a conclusion, excluding safety issues, it should be left to the market and owners' discretion to judge which is the most competitive design and this is not the purpose of legislation. As Arthur Bowring states "*Commercial considerations should be left to market forces, not to regulation*" [Bowring 2003]. It is therefore natural that the proposal was voted against by 32:22 [O'Mahony 2004a, Corbett et al 2004b]. Nevertheless, there have been proponents of the double hull who have been pushing for it to be mandatory, mainly for commercial reasons. An example includes Luis Dreyfus, an owner of double hull bulk carriers who a year later issued a plea for the adoption of double hulls as the standard for large bulk carriers. He was arguing that this would get rid of the 15%-20% of the world fleet which are substandard and whose owners would have difficulty finding the resources to convert them to double hulls [Spurrier 2005].

There are several owners who seem to prefer the double hull design, for example Transmed [Lloyd's List 2004a], Angelicoussis [Lloyd's List 2004b], K-Line and Dreyfus [Corbett et al 2004a]. Many including Transmed seem unaffected by the IMO decision to reverse its previous decision for compulsory double hull design as they have continued to order double hull capesize bulk carriers [Lloyd's List 2004a, Corbett et al 2004a].

Both the s-hull and the double hull designs have advantages and disadvantages and it will be interesting to see which is going to be most widely adopted in the future.

6.3 Designing against Cracks

Cracking is generally associated with corrosion as a result of rough treatment in a rough environment and with the neglect of fatigue and stress concentrations in the design and fabrication. According to Lloyd's Register, one of the main factors which can contribute to structural failure and loss of bulk carriers is the design of details such as the main frame bracket toes [MER 1997].

Many studies on fatigue strength assessment of ships have been carried out and the analysis procedure of fatigue and fatigue design criteria have been established [Capanoglou 1993]. Design has a great influence on the cracks which a ship will develop during its service life. A typical example where this is evident is in European ships whose construction is significantly more stiff and heavy than Asian ones and hence they often have cracking problems.

One of the most important precautions which have to be taken during the design stage is to avoid high stress concentrations. These can result for a variety of reasons such as geometrical discontinuities, corners, sharp edges, holes, connections, welds, changes in thickness, hard spots etc. A hard spot is defined as a point of high rigidity in a more flexible structure i.e. when there is an abrupt change in rigidity [LR 2004a]. According to Lloyd's register, a hard spot occurs when the distance between the end of a bracket and the next supporting floor or stiffener exceeds 80cm [LR 2004b].

Another way by which design can reduce the probability of cracks is by reducing the applied stress in a critical region through enhancement. A remarkable difference in the applied stress range can be achieved by the attachment of transverse frames in the topside tanks. Cracks can also occur due to the misalignment of connected units as a consequence of the resulting bending moment and high stress concentration. A typical example of this would be the misalignment of two brackets which are attached on either side of a plate. This is illustrated in Fig 15 below.

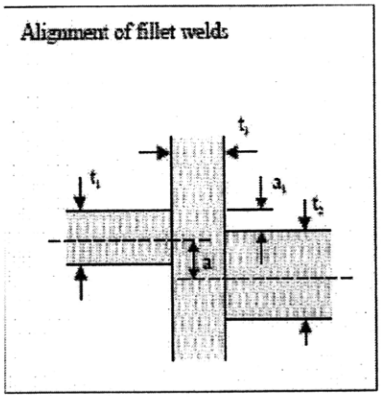


Fig 15: Resulting moments and stress concentrations due to the misalignment connections across a plate

Besides trying to minimize the development of cracks during design, it is also very important to consider the implications and to ensure an acceptable outcome after they develop. There is an effort to design ships with crack arrest sites which serve to stop cracks from propagating to large lengths. This however is often expensive and does not allow construction using large continuous sections. Another example where fatigue prone design is tolerated is the scallops. These are a recognized high stress concentration site but are essential for the assembly of blocks during fabrication.

6.4 Methods used in Design

Classification rules for ship scantlings are generally derived from experienced based criteria which include many semi-empirical formulae. These formulae based rules however are a significant development from the pure deterministic table rules of the 1950s [BMT CORTEC LTD 1993]. Ship designs in the past were solely based on static principles which were modified by empirical factors to account for the actual dynamic conditions [MER 1993].

It is necessary during design to have a very clear understanding of the loads to which the hull may be subjected during its service life. As [Saunders 1965] said, "It is necessary to coordinate what seas look like to seafarers with what naval architects imagine them to be". Waves of significant heights "Hs" in the range 13 to 15 meters can be expected in severe storms of Beaufort 10+, and consequently waves of up to 26 to 30m may be encountered [Faulkner et al 1996]. The stresses and bending moments which will result on the hull may depend on numerous parameters and are by no means straight forward.

In general, loads from the sea are transmitted from the shell plate to the secondary members (stiffeners), from there to the primary members (large webs), and finally to the hull girder. Loads are transmitted along this path by shear and bending via welded connections. These connections form the topic of detail design. It is the design and the type of detail particularly at these locations that is fundamental to the structural safety of the ship, because small cracks from these welds can propagate due to the applied stresses to cause significant damage.

Our understanding of the loads acting on the hull has improved significantly over the past few years and this has had an impact on the way ships are designed. It used to be assumed that the major loads acting on the hull were carried by the main deck on the two sides of ship. As a result, the cross deck plates between the hatch openings were made thinner. After several studies however, we have come to realize that this is not the case and higher loads and stresses often act on this area. This may be due to torsional effects which are imposed by twisting and compression as a result of heavy cargos in adjacent holds [The Motor Ship 1994]. Furthermore, the cross deck structure may be subjected to side loads during bad weather conditions. As a result, thickness requirements for the cross deck plates have increased significantly in order to accommodate the loads.

The increasing use of finite element analysis (F.E.A.) over the past 30 years has also enhanced our understanding of the stresses to which the various structural components are subjected during different situations. Fig 16 shows a finite element model of a cargo hold.

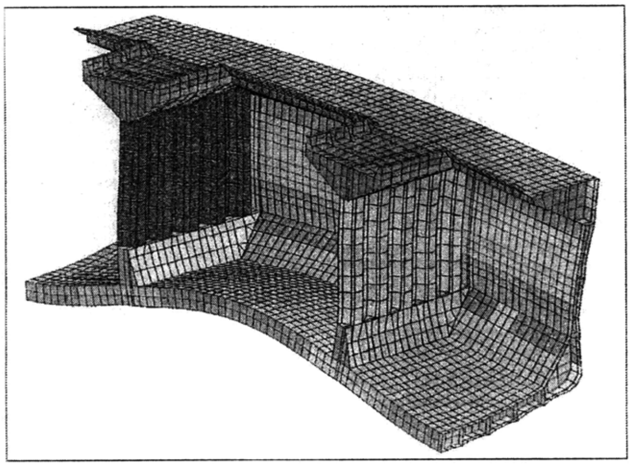


Fig 16: F.E. model of a D.Hull BC. Cargo Hold under Alternate Loading (deformations magnified) [Shipping World & Shipbuilder 1997]

The detailed stress results thus obtained from the F.E.A. can be evaluated to assess the fatigue strength at more specific locations with greater accuracy. This consequently results in a better allocation of scantlings while excessive conservativeness in the areas where there is lack of understanding can be avoided.

The methods currently used for estimating fatigue life are quite inaccurate while there is limited use of fracture mechanics. There is thus a potential for great improvements to be seen in the future. A better understanding of the stresses acting throughout the hull however will lead to better designs of higher fatigue strength and a reduction in fatigue related problems.

7. Data Requirements

7.1 Database

In order to perform the required analysis, the data required should consist of ship age at the time of the survey; number, size and location of cracks; and the types of repairs carried out. Data regarding cracks in its raw state is highly confidential and thus access to it is of great difficulty. As [Adam et al 1991] quotes about defects information in the Lloyd's Register database, *"No identifiable information is released to third parties without the owner's consent. In most cases we can present the data statistically to preserve its anonymity"*. Furthermore, the size of the database in such statistical surveys is crucial to the validity of the results, and therefore all possible sources have to be exploited.

Potential sources include IACS classification societies, ship owning companies and shipyards. Ship names would have to remain confidential for the classification society to have the legal right to release any data unless they have permission from the shipowner. In its raw state, the data is in the form of survey reports, some of which are well over 150 pages long. The relevant hull related survey reports of classification societies have to be searched in detail and all cracks, locations, crack sizes and repair procedures have to be recorded.

Classification societies however don't have the same procedures in terms of reporting and this may also vary between surveyors. It is often the case that if a repair is made, the cracks are not reported. This is often the case when a large plate has to be replaced due to corrosion wastage, in which case the surveyor may not bother to find all the cracks in the plate and report them. It is also often the case that the owners find cracks and repair them without having to report them to the classification society. In order to get a complete set of data therefore, it would be good if the records of classification societies, shipowners and shipyards are combined for each repair.

Before carrying out the analysis, a large sample size is required in terms of ships, cracks and total crack length. It is also very important that there is a good age distribution of the ships in the database. An adequate number of ships is required for each age in order to get a representative average crack distribution throughout the ship's life. This may potentially be a problem as many of the repairs may be clustered around the ages when dry dockings are due. This would leaving gaps in between with limited data for certain ages.

7.2 Location Coding System

In order to perform the analysis and present the results, a system of coding has to be devised whereby each location is asserted by a particular code. The coding system will then require many modifications to accommodate irregularities as more data is processed. Bearing in mind that any such modifications lead to a huge amount of subsequent work in regrouping the data particularly during later stages, such a system has to be very detailed and accurate from the beginning.

The coding can be done using a three dimensional coordinate system with the x-axis starting from the forward perpendicular towards the stern (measured in stations), the y-axis starting at the centerline going starboard, and the z-axis starting at the keel going up as is customary in naval architecture. A potential problem is that ships may vary in their dimensions so the same coordinates may correspond to different locations or components on different ships.

Alternatively, the ship can be divided into compartments along the length going forwards, and height zones. Then the various compartments can then be subdivided using codes for each component. This may be more convenient because transverse bulkheads are commonly used dividing the ship along the length. These may or may not correspond to the stations used in the coordinate system. Fig 17 shows the cross section of a bulk carrier ship along with the various components that will have to be coded.

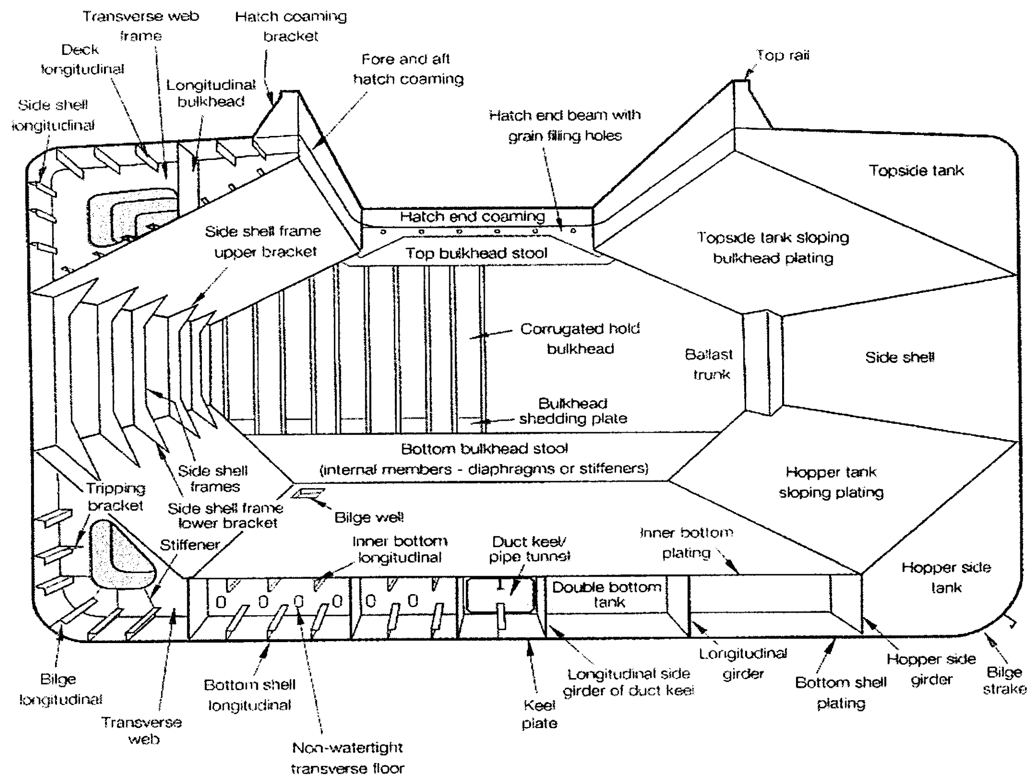


Fig 17: Structural Configuration of a Typical Capesize Bulk Carrier

[MER 2002]

It is clear from the picture that with a number of compartments along the length, the number of locations would be in the hundreds. Extra care in designing the coding system at the beginning can save many days worth of additional work to fix it after it proves inadequate. Even with a carefully devised system however, one always needs to make certain adjustments or decisions on how to deal with unexpected data.

There are two key issues that will have to be dealt with no matter what kind of ship is chosen. These are double counting and accounting for structural differences. Double counting can be a problem when dealing with cracks on the bulkheads that are adjacent to two compartments, and also when dealing with ships of the same type but with a different number of compartments (e.g. one less cargo hold). Adjustments have to be made to accommodate structural differences both between compartments particularly at the fore and aft ends of the ship, but also between ships which may have design differences such as a double hull.

7.3 Crack Distribution

The crack distribution will have to be generated before applying the model in order to check the data. Crack distribution along the length and along the height should resemble the stress distribution. Stresses due to bending moments are higher on the upper deck and keel so a larger number of cracks should be expected at the upper and lower ends with fewer cracks in between where the neutral axis lies. Similarly, a higher number of cracks would be expected in the middle along the length since that area experiences greater deflections due to bending. There are other factors however which may cause differences depending on the ship type and operation.

Table 2 shows the results obtained by Lloyd's Register in a damage survey (including cracks) on Bulk Carriers and OBOs of 65'000 DWT and over. These results seem to be slightly skewed towards the right showing a maximum of hull damages in the forward mid section of the ship.

Hull Damages Distribution in Bulk & OBO Carriers of 65 000 DWT +					
Region	AP+ER	MID-AFT	MID	FWD-MID	AP
% Damages	9.01	17.11	27.93	32.74	13.21

Table 2: Lloyd's Register Hull Damage Survey Results for PMX + size ships

[Ferguson et al 1993]

Cross checking can also be made in greater detail to account for the distribution of the cracks in the specific locations within the compartments. This can be done by comparing the results with those of similar studies of the past. Table 3 provides a comparison of a few examples.

LOCATION	DNV (Capes – %Damages)	LR (Bulkers – %Damages)	ABS (Bulkers – %Damages)
DECK	16	21	36.5
D.B.T. & HOPPER	19	16	33.7
T.S. TANK	13	36	-
SIDE	15	27	29.8
BULKHEAD	12	-	-
OTHER	25	-	-

Table 3: Comparison of Previous Findings on Damage Defect Distribution

[DNV 2002 Private Correspondence, LR 1999 Private Correspondence, ABS 1976]

Even when comparing the results of studies focusing on similar types of damages and similar kinds of ships and ship sizes, there are significant differences due to the methods used, the range of damages considered, the size of the database, the rigor involved in the process etc. Furthermore, cracks have a significantly different distribution to other types of damages while the ship type and size also has an effect. This emphasizes the importance of highly focused surveys concerning a specific type of damage and vessel.

7.4 The Impact of Design

The repair procedure is often decided depending on the origin of the crack and the design of its location. The repair of cracks due to corrosion is often carried out by simply replacing the part with an insert. Cracks due to high stresses where there is no corrosion are often repaired by replaced the stress-cracked plate with one of increased thickness. This for example is typical on the deck at the corners of the accommodation or the hatch coamings of bulk carriers. On the other hand, design changes may also be required to avoid re-emergence of cracks. Some times, there are also various grades in the design upgrade and one may have to upgrade an already previously upgraded design if cracks persist.

One should note that cracks can also often be avoided in the first place by using a thicker plate or a more crack resistant design when the ship is built. One can pay an additional price in the design and construction phase or start with a more economical ship and carry out the repairs and modifications as necessary when the cracks emerge. There are many typical examples of this tradeoff.

One example includes tripping brackets which connect web frames to the longitudinals. Cracks often initiate at their corners due to the "hard spot" and propagate through the face plate of the longitudinal and through it towards the outer shell. A solution is to increase the radius of curvature at the point of crack initiation. If this is not adequate one can increase the face plate thickness or replace the bracket with a more curved one to weaken the hard spot and provide a more even distribution of stresses along it. Ultimately, if the problem is not solved, a secondary tripping bracket can be placed on the other side of the web frame as shown in Fig 18

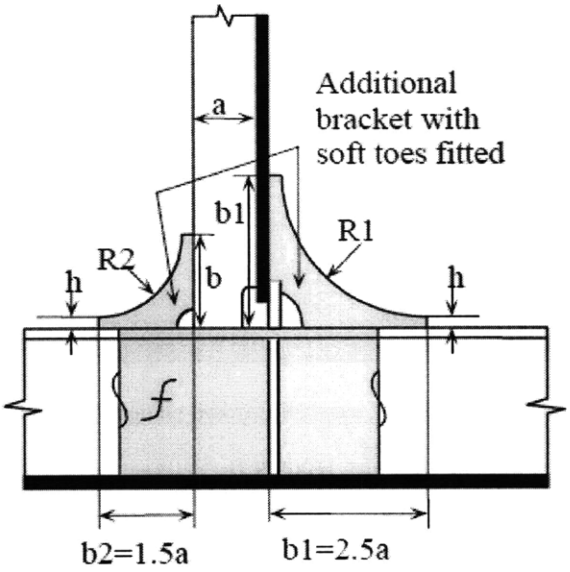


Fig 18: Tripping Bracket Modifications along with the Principal Dimensions [IACS 2004]

Tripping brackets are also used to prevent large deflections that cause cracks in frames for example. Fig 19 shows frames without tripping brackets that have deformed under large global deflection and Fig 20 shows tripping brackets between frames which counteract the problem

Fig 19: Deformation of Side Shell Frames Under Global Deflection

[IACS 2004]

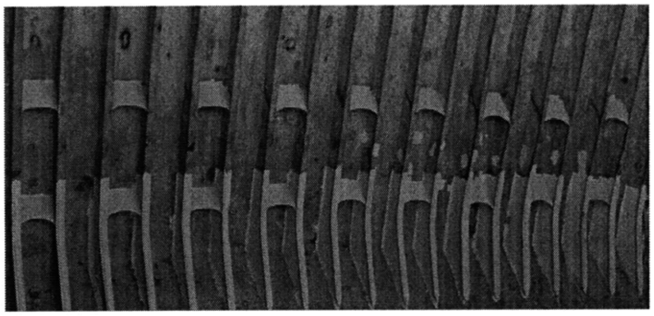


Fig 20: Tripping brackets between side Shell frames

[LR 2005]

In most cases, cracks develop due to design flaws which are known already from the design stage. Construction costs however very often outweigh the benefits and a sacrifice is made. As a result, design changes have to be made once cracking appears in order to solve the problem permanently. The purpose of this work is to assist in the choice of investing in a better design during the construction phase by comparing the additional construction cost with the cost saved from repairs of cracks throughout the ship's life at that location.

One of the most typical examples is that of the scallops. These are there for no other reason other than the fact that they are needed for the assembly of the blocks in construction. The associated problems regarding cracks in scallops as shown in Fig 21 are well understood.

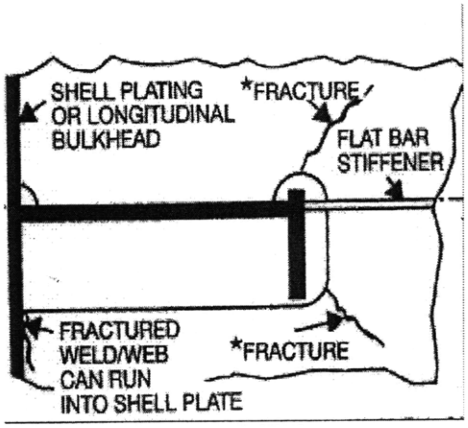


Fig 21: Associated cracking problems with scallops

Scallops can be enhanced by a doubler or a collar plate which helps prevent cracks from developing at the scallop corner. Including this to all the scallops at the construction stage however is too expensive and thus they are designed knowing that the area will develop say 50 cracks over a course of 30 years. Consequently, these solutions serve as modifications after the problem starts off. Fig 22 shows typical scallop modifications.

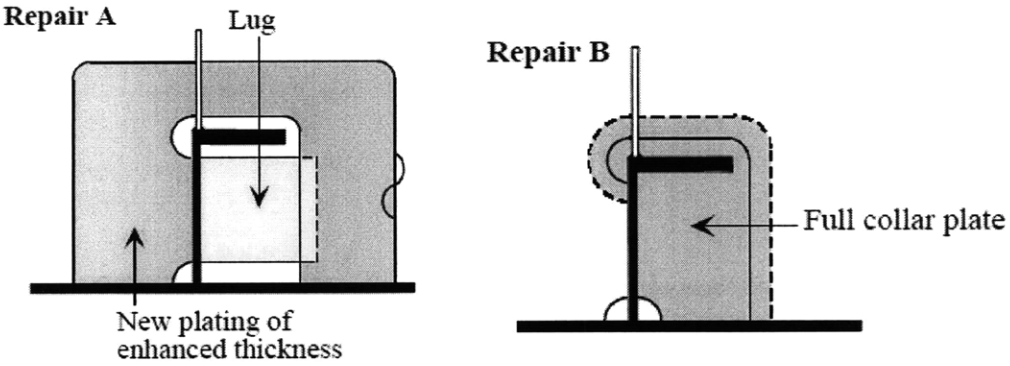


Fig 22: Scallop Modifications [IACS 2004]

Design consequently plays a major role in the number and locations of cracks which are going to appear in a ship's life. The effects of design are witnessed during the very early stages where cracks due to design faults may appear but also during the later life as some designs age better than others.

Sister ships and ships from particular building shipyards or countries very often share the same problems and weaknesses. Romanian ships are commonly viewed as inferior and are valued significantly lower in the market. Japanese ships are considered to be of the highest quality and are generally the most expensive but develop many cracks which are associated with the extensive use of high tensile steel particularly as ships age. There are also many Korean ships and these are generally of good quality but these are being overtaken in terms of global numbers as shipbuilding capacity in China is increasing radically. The quality of Chinese ships is improving quickly overall but it seems to vary significantly between the numerous shipyards.

8. Model Construction, Calibration and Use

8.1 Developing the Model

Crack repair costs can involve several components depending on the location and size of the crack. Some of these cost components including staging and steelwork are specific to each crack whereas others such as cleaning, venting and testing are specific to the location. For example, the repair cost of 3 cracks far apart in one ballast tank will involve the staging and steelwork cost for each individual crack, plus the cleaning, venting and testing of the ballast tank. Introducing some nomenclature:

Parameters

CP: Cost Parameter for Ship

CT: Cost of time ($/day)

RC: Repair Cost

RT: Repair Time

$RT_{NoCracks}$: Repair time without cracks

Subscripts

i: Crack

j: Ship Location with crack

k: Repair Process

s: Ship

Crack-Specific Costs

k=1: Staging

k=2: Steelwork

Location-Specific Costs

k=3: Cleaning

k=4: Venting

k=5: Testing

k=6: Gas Free

In order to capture all these crack repair costs throughout the hull, a summation has to be carried out over the total number of cracks and another summation over the total number of locations that involve one or more cracks. A high component of the crack cost may be associated with the repair time besides the cost of the repair itself. This may be particularly important in the case of large bulk carriers or tankers which at time are earning hundreds of thousands of dollars per day. The following model accounts for these effects.

$$CP = RC + (RT - RT_{NoCracks}) * CT$$

$$RC = \sum_{i} \sum_{k=1}^{k=2} RC_{ik} + \sum_{j} \sum_{k=3}^{k=6} RC_{jk}$$

$$RT = \sum_{i} \sum_{k=1}^{k=2} RT_{ik} + \sum_{j} \sum_{k=3}^{k=6} RT_{jk}$$

This captures both the repair costs and the cost of time lost during repairs. For most types of ships however, in the great majority of cases, the additional time due to cracks will probably be equal to zero. This is because the crack repairs are usually carried out in conjunction with other repairs such as sandblasting, replacement of corroded steel, coating etc. Since, all this additional timely work has to be carried out as part of the dry docking or special survey regardless of the presence of cracks, one cannot attribute the time spent to the shipyard and the consequent loss of hire to the cracks. In other words, since $(RT - RT_{NoCracks}) \approx 0$ most of the time, the total cost associated with cracks can be approximated as follows:

$$RC = \sum_{i}\sum_{k=1}^{2} RC_{ik} + \sum_{j}\sum_{k=3}^{6} RC_{jk}$$

Furthermore, the cost to gas free a fuel tank can probably be neglected because it is very rarely incurred since the locations in which it is required show extremely low cracking frequency. This essentially makes k=6 redundant. By eliminating this, the final simplified crack repair cost for a given ship “s” is given as follows:

$$RC_s = \sum_{i}\sum_{k=1}^{2} RC_{ik} + \sum_{j}\sum_{k=3}^{5} RC_{jk}$$

8.2 Model Assumptions

The major assumptions involved in this model are summarized below:

1. The cost of time is neglected since cracks are usually not the determining factor.
2. Cost to Gas Free is neglected because it is very rarely incurred because the locations in which it is required show extremely low cracking frequency.
3. Cost of ultrasonic measurements are neglected since only a few measurements are usually taken and they are relatively cheap.
4. The final cleaning cost (required before painting) is included in the cost of steel. This is done on the whole area to be coated – not just for cracks.
5. Coating is also neglected since a very small area is required for cracks. For example if $40m^2$ of coating is required for the cracks of a whole ship repair, that corresponds to about 12 liters of paint or about $100 which is negligible. The coating is carried out by the repair yard if the crack is in a highly corroded area and by the crew if otherwise.
6. It is assumed that in order to ballast the top side tanks of a ship, it is not required to first ballast the double bottom and the lower wing tanks. This may not be true for all in service, but since ships today are built that way and since this model is intended for future predictions (a ship that will be designed and built), that makes this assumption necessary.

8.3 Model Calibration

8.3.1 Basis for Calibration

In order to calibrate the model, the actual costs for each of the items have to be determined. The actual numbers used in this case are based on what Chinese Shipyards were charging on average in September 2008. Chinese shipyards were chosen because that is where the great majority of big ship repairs are carried out. Different numbers can be used depending on where the ship will be operating and where it will carry out its repairs.

8.3.2 Staging Cost (k=1)

Staging and de-staging is required in order to provide access to the location of the crack for its repair. There is a charge per m^3 that includes both staging and de-staging. In some circumstances, when a crack is very high (e.g. in the upper part of a cargo hold) it is more appropriate to construct a hanging staging which provides access through the hatch opening. This saves a great deal of volume but the cost per m^3 is much higher. Shipyards also charge a different price on normal staging depending on the location (e.g. higher for staging inside ballast tanks). Table 4 below provides a summary of the staging costs for closed and open spaces.

Staging Costs Charged At Each Location		
Region	Stage/De-staging	Hanging Staging
	$/m3	$/m3
Ballast Spaces	4	**12**
Open Spaces	3.5	**12**

Table 4: Staging Costs per m^3

The average staging cost required per crack depending on its location must be determined. The average dimensions of each location are known since the model is applied on a certain ship type and size range. The amount of staging in m^3 that would be required to repair a crack can therefore be deduced. Since however the same amount of staging could be used to repair more than one crack when cracks are close together, an adjustment or a "staging factor" must be applied in order to avoid double counting. This factor will depend on the frequency and proximity of the cracks in each location and may be determined or approximated based on the crack distribution of the database. The staging cost of each crack can therefore be determined using the amount of staging required to access the crack depending on its location, the relevant staging factor and the corresponding price per m^3.

8.3.3 Steelwork (k=2)

The base price charged by the Chinese yards considered in Sept 2008 ranged between from 2.8 to 3 $/kg. This varies depending on parameters such as the size of the repair or the relationship with the client and it was more often close to $2.8/kg. $2.8/kg is therefore assumed in the following calculations.

On top of the base price, yards charge a premium for 4 things as follows. An additional 20% for high tensile steel, 20% for a bend, 30% for a corner or stiffener, and 20% if it is in a closed space (e.g. ballast tank). They therefore come up with a $/kg value based on the above and charge accordingly. They also charge a minimum of 15kg per piece. This gives 16 different combinations giving 16 different prices of steel depending on the requirements. Table 5 below provides a list of those categories and uses the above information to determine a $/kg amount for various category of crack repairs.

Steel $/kg Calculation

Region Type	HTS (20%)	Bent (20%)	Angle-bar / Stiffener (corner) or Holland Profile (30%)	Closed Space (20%)	**$/kg**
A					**2.8**
B	YES				**3.36**
C		YES			**3.36**
D			YES		**3.64**
E				YES	**3.36**
F	YES	YES			**3.92**
G	YES		YES		**4.20**
H	YES			YES	**3.92**
I		YES	YES		**4.20**
J		YES		YES	**3.92**
K			YES	YES	**4.20**
L	YES	YES	YES		**4.76**

M	YES	YES		YES	**4.48**
N	YES		YES	YES	**4.76**
O		YES	YES	YES	**4.76**
P	YES	YES	YES	YES	**5.32**

Table 5: Steelwork cost in $/kg for each location

Using the typical dimensions of the component that has to be replaced in each location when repairing a crack, the amount of steel in kg can be calculated. By combining this with the corresponding price per kg based on the requirements, the $/crack amount can be determined for each location.

8.3.4 Compartment-Specific Components (k = 3, 4 & 5)

When considering compartment specific components, it is important to be careful to avoid potential errors with the coding system. If for example cargo hold or cargo tank bulkheads are used to define the compartments along the ship length, these may not coincide with the bulkheads of other compartments such as ballast tanks. It is typical in bulk carriers for ballast tanks to span two cargo holds along the length. Extra care must therefore be taken in this part to avoid confusion and potential mistakes.

The cost that shipyards typically charge is summarized in Table 6. They charge a total dollar amount for cleaning and testing whereas they charge a per day amount for venting. Venting is usually required for two days in a typical repair.

COMPARTMENT COSTS	
CLEAN	1 $/m^3
TEST	1.2 $/m^3
VENT	50 $/tank/day

Table 6: Compartment Costs

The typical size of each tank must be considered based on the chosen ship type. Again care must be taken to include both and avoid confusion between port and starboard side compartments.

The testing procedure (k=5) after the repair involves pressurizing the compartment and checking for leaks. This however is not always necessary and it is only carried out if a crack is beyond a critical length. Critical crack lengths for testing each location are therefore required in order to decide whether to include this cost. An IF function can be used when going through the summation throughout the hull in order to determine whether to step up the total cost by the necessary amount. The argument of the IF function would involve the number of cracks being greater than zero for the case of cleaning (k=3) and venting (k=4), while it is the largest crack being larger than the critical length for the Testing component (k=5). The amount added to the summation if the IF function is satisfied, can be calculated using the relevant prices and compartment sizes.

9. The Form, Uses and Limitations of Results

By applying the above model on a large database of ships of a specific type and size range a wide range of results can be produced in order to assess the cost effectiveness of design modifications. The average crack repair cost as a function of ship age can first be determined. That is the average cost to repair all cracks during a repair as a function of ship age. It should be noted however that these only represent a fraction of the total repair cost which would include other components such as corroded steel renewals.

The average repair cost can be decomposed into the various repair processes (k=1 to k=5) for each individual year. This may be used when deciding which repair yards to go to depending on the ship's age. In a more refined analysis, one may then choose to apply the corresponding price-parameters to each ship depending on its age.

The average repair cost can also be decomposed into the various locations of the ship or the compartments along its length for each individual year throughout its life. This would provide a picture of what an owner should expect to spend and where throughout a ship's life on average.

To get the above results, one can calculate the percentage accounted by a location or repair process for every ship, and then plot the mean of the percentages for each age. Alternatively, the total amount spent in each location or repair process for all ships of a given age can be plotted as a percentage of the total amount spent on those ships. The second method would give a more accurate picture of what one should expect for a typical ship because the results of the first method would be distorted by insignificant repairs.

In order to evaluate proposed design modifications or improvements, one needs to know the present value of the repair costs that will be avoided. Shipping companies often use a discount rate of about 10% (always higher than the bank interest rate). Certain shipping companies often require a 15% return on investments but today interest rates are significantly lower than what they have been in the previous couple of years. Either way, the present value of crack repairs for each location on the ship can be determined using the chosen discount rate.

This in effect limits what an owner should consider investing against cracks in the design stage. Owners who use a lower discount rate, meaning that they value money today compared to later less than other owners, can afford to pay more against cracks in the design stage in order to save on later repairs.

The break down of the present value into the various regions of the ship allows choices about specific design modifications to be made. If for example, the present value of the crack repairs in a certain location amounts to -$0.5M and a new design promises to eliminate all the cracks in that same location throughout the ship's life, one should theoretically invest in it as long as it costs less than $0.5M above the current design.

The major limitation of the model is that it only accounts for the repair costs of the cracks and not the safety aspect. An additional cost that has to be considered is the expected cost of failure due to the cracks. This would require a reliability analysis to determine the probability of failure of the whole ship due to a crack, as well as an estimation of the associated costs. Those might involve the whole ship, cargo and possibly the crew if the ship sinks, or they might involve off-hire and high repair costs in the event of an emergency repair. This is an important limitation because there are cases when the expected failure cost heavily outweighs the present value of the repair costs, so neglecting this may lead to non-optimal decisions when deciding not to invest in a more expensive design. This essentially means that the current model may determine if a proposed design is definitely cost effective (as described above), but it cannot determine if it is definitely not cost effective. If it is not definitely cost effective, other considerations have to be made before rejecting it.

When applied correctly, the above analysis should give a wide perspective of the crack costs associated with each location. This is a rough guideline that is very useful when making high level decisions or a series of minor choices. An example is when choosing materials (e.g. high tensile steel) or weld specifications for large areas or for the whole ship. It is also handy when having to make fast decisions during repairs.

If an important decision or design choice has to be made, the above procedure can be used to address the issue more directly. If two widely used designs are to be compared, the ships in the database can first be divided between those with each design type. By conducting a separate analysis for each set of ships, an accurate estimate of the saved crack costs can be determined and then evaluated against the cost of each design. An example of a design choice for which such analysis would be suitable is the choice between a double hull or a single hull configuration.

10. Overall Comments and Conclusions

A procedure was developed to assess the cost effectiveness of fatigue design improvements. This is based on comparing the additional cost of the proposed design (over the current design) with the present value of all the projected crack repair costs of the corresponding location. Several assumptions were made and a simplified version of the model was presented and analyzed. The procedure and the difficulties of collecting the necessary data and applying the model were discussed and suggestions were made for avoiding problems in each stage.

The most important simplification was neglecting the cost of time spent in the ship yard to repair cracks. This simplification is based on the assumption that in the great majority of repairs, other repairs such as corrosion related steel renewals and sandblasting are carried out in parallel. Given that those are more time consuming, the ship would have to spend the same amount of time in the yard irrespective of the number of cracks.

The major limitation of the model is that it neglects the fact that cracks may pose a safety issue or the fact that they may result in an emergency repair which involves additional costs and loss of hire. When making a design decision, the expected cost of failure due to the cracks also has to be included and it may potentially be higher than the present value of the crack repair costs. The model can therefore only accept a proposed design modification but not reject it as that would require additional considerations.

A literature review was carried out of the various statistical surveys that have been conducted over the past 50 years relating to cracks and damages in ships.

Differences in the results of such surveys regarding the distributions of defects suggest that cracks follow different patterns than other damages and that the various kinds of ships exhibit different cracking behaviors. This emphasizes the importance of using a large data sample that is specific to a particular type of damage and ship type and size range when applying this proposed model and procedure.

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