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The Durability of Ships Considering Fatigue Cracking

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Abstract

The larger trends related to cracking in ocean going vessels (primarily tankers and bulk carriers) are reviewed on the basis of available data. The typical interrelated causes of such cracking are: high local stresses, extensive use of higher strength steels, inadequate treatment of dynamic loads, adverse operational factors (harsh weather, improper vessel handling), and controllable structural degradation (corrosion, wear, stevedore damage). Three consequences of cracking are then discussed: structural failure, pollution, and increased maintenance. The first two, while rare, are potentially of high consequence including loss of life. The types of solutions that can be employed to improve the durability of ships in the face of fatigue cracking are then presented. For existing vessels, these solutions range from repairs based on structural analysis or service experience, control of corrosion, and enhanced surveys. For new vessels, the use of advanced design procedures that specifically address dynamic loads and fatigue cracking is necessary. As the preferred solution to the problem of cracking in ships, this paper advocates prevention by explicit design by first principles.

1. Introduction

Ocean going merchant ships are complex in geometry, detailing, fabrication, loading, operation, and inspection. The structural safety and durability of these structures is affected by any cracks present, the predominant source of such cracking being fatigue damage accumulation from cyclic loading. The resulting local cracks are normally primarily a maintenance concern. Service data [see ABS 1987] suggest that during the lifetime of a ship, an order of magnitude estimate for structural details expected to fail by fatigue is 1 in 100.

To design structures so as not to sustain cracking damage is in principle possible, but economically unfeasible. Ships in this regard are designed and operated to safety levels that society implicitly finds acceptable, given that a certain level of risk is unavoidable in any human endeavor. The perception of acceptable safety can change over time. Recently, for example, the safety levels for tanker structures have in effect been raised upward because of environmental concerns. Those for aging bulk carriers are in a similar state of change, because of increasing unacceptability with the present state of affairs.

Against the above backdrop of structural complexity, inevitability of local cracks, changing societal demands, and also traditional reliance of design procedures on empiricism and experience, this paper discusses the larger causes, consequences, and control of local cracking in ships, and addresses the following: Cracking Trends, The Dominant Causes of Cracking, Consequences of Cracking, Cracking in Existing Vessels, and Life Cycle Control of Durability using Advanced

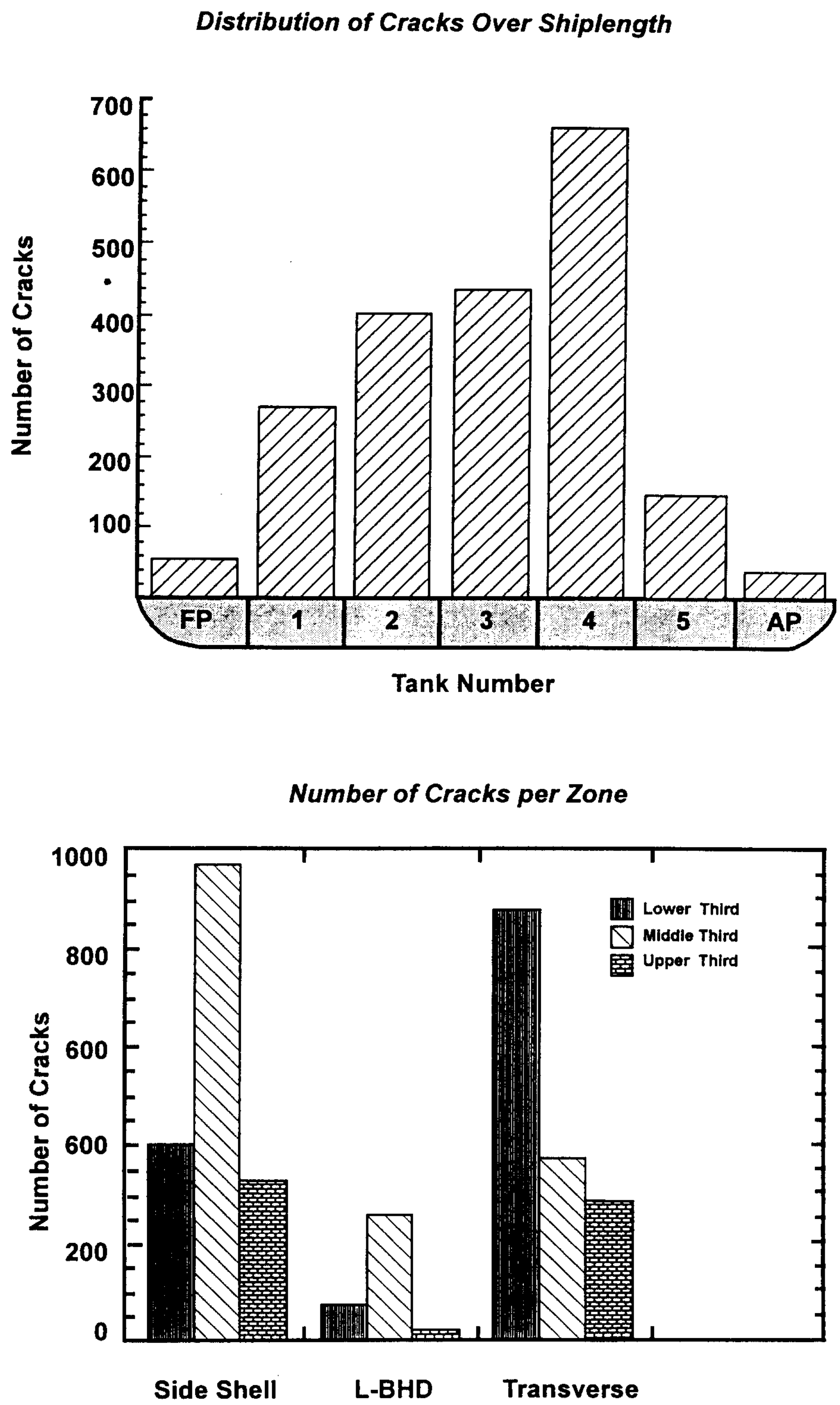

Figure 1. Crack distribution in tankers- Berkeley study

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1.1 Durability and Damage Tolerance

Durability refers to the ability of a structure to remain in a form suitable for its intended function over its service life. Durability is a function of the structure as designed, the reserve strength present (over and above required minima), and systems and procedures designed to maintain structural condition in a satisfactory state, e.g. those for corrosion protection, maintenance and surveys.

Damage Tolerance is the ability of a structure to sustain a certain level of damage, including cracking, without strength related (catastrophic) failure. Damage tolerance can be characterized by the residual strength of the structure given a level of damage.

In ships, fatigue cracks are potential initiation points for fracture which is characterized by unstable tearing of material. Experience indicates fracture occurrence in ships to be relatively rare. This is primarily because of the good ductility of ship steels over typical loading rate and temperature ranges. Also, cracks typically tend to arrest because of the presence of stiffeners, the use of plating of relatively higher toughness in fracture critical areas of the vessel, and because of changes in load (stress) levels.

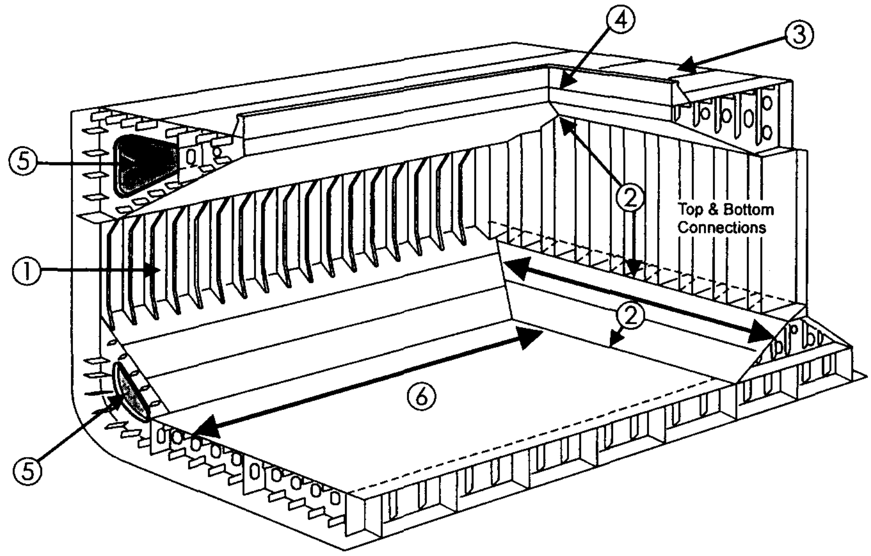
2. Cracking Trends in Ships

An early study by Newport News [see ABS, 1987] indicated that in terms of numbers, a large number of cracks tend to occur at bracket connections, a fact still true today. Nearly 33 % of the over 6800 damages the study identified were in beam bracket connections, while 23 % involved tripping brackets. These results are not surprising, since the stress concentration factors associated with typical bracket connections are high. For similar reasons, another common location for cracking is a cut-out detail.

A more recent study of cracks in tankers [Schulte- Strathaus and Bea, 1991] was undertaken at Berkeley, from which Figure 1 shows the crack distribution along the vessel length. There is a tendency for more cracks to occur in the mid body region. Relatively less cracking occurs forward. Apparently, even less occurs aft. Most side shell cracks tend to occur in the middle third of the shell depth, while in transverse members, they tend to occur in the lower third. ABS' own experience indicates that tanker side shell cracks tend to occur more at the connections at transverse bulkheads than at web frames, and between the laden waterline and 8 to 10m below it.

In bulk carriers, ABS experience indicates that cracking typically occurs in the areas indicated in Figure 2. Bulk carrier cracking can be exacerbated by grab related wear, carriage of heavy cargoes, fatigue damage due to cyclical loading, and corrosion. Corrosion is important particularly with sulfur bearing coals. Corrosion, fatigue and wear increase with vessel age, as may be expected.

Cracks vary in significance. In the case of tankers, the side shell and bulkhead cracking are significant because of the potential for cargo leakage or mixing. In the case of bulk carriers, hold frame end cracking is significant because it can result in the detachment of side shell from the internal framing, this too in an area of high shear stresses. Also, cracking at the transverse bulkhead top is significant because it can cause that bulkhead ends to loose end support. The significance of cracks in a given situation can be determined by the sequence of events that are likely to follow, e.g. by an event tree methodology.



Problems Areas:

1. Hold Frame-Connection to upper & lower wing tanks and side shell.
2. Boundaries of transverse bulkheads and bulkhead stools.
3. Cross deck structure.
4. Hatch corners/hatch coaming brackets.
5. Localized cracking and buckling of web frames and breakdown of coatings in water ballast tanks.
6. Inner bottom plating/hopper plating intersection.

Figure 2. Bulk carrier cracking areas- IACS

3. The Dominant Causes of Local Cracking

The more important causes of cracking in ocean going vessels are high local stresses, extensive use of high tensile steels (HTS), design uncertainties related to dynamic loads, sensitivity of performance to departures from design assumptions, adverse operational factors (harsh weather, service routes, heavy cargoes, vessel handling), and time and operator dependent structural degradation (corrosion, wear, stevedore damage). These causes are normally intertwined. In many cases, design features that, by themselves, were not in the past a problem, may become marginal given a combination of such adverse factors.

3.1 High Local Stress

Increased local stresses result in increased chances of fatigue damage. The time to crack initiation in a welded structural detail is inversely proportional to approximately the cube of the stress range it is subject to. So the fatigue life of a structural detail subject to local stress fluctuations that are 10 % higher than a basis detail is roughly 75 % of the basis. Local stress range increases above allowables can occur from any number of reasons including increased global stresses, barely acceptable structural detailing, increased stress concentration factors, construction defects, and structural degradation due to corrosion and wear.

3.2 Extensive Use of HTS

In the last 20 years, high tensile steels (HTS) have been increasingly used in ships. Their use provides a saving in initial costs since it leads to thinner material. The resulting reduction in steel weight can be significant, perhaps up to 15 %. Unfortunately, the fatigue capacity of a welded structural detail of higher strength steel is little different from that of a similar mild steel structural detail while the operating stresses are higher. In a structure of H32 steel the operating stresses are roughly 30 % higher than mild steel for the same load, while the same figure is 40 % for an H36 structure. With the mild steel structure as comparison base, the fatigue life of an H32 structural detail is 50 % of the mild steel structure, and that of a H36 steel is 40 % of the mild steel structure (assuming that fatigue damage is proportional to the cube of stress). Clearly, any such potential shortcomings of HTS can be designed out, provided they are explicitly addressed in ship structural design.

3.3 Uncertainties Related to Dynamic Loads

Several studies of side shell cracking in tankers, conducted by ABS, have indicated that on the regions of the side shell where cracks had occurred, the major contributor was fluctuating lateral pressure. The types of loads involved (external hydrodynamic pressure and seaway influenced internal cargo pressures) had traditionally not been directly considered in design, and until quite recently the state of technology was such that it was in fact not possible to consider such loads explicitly.

In bulk carriers also, there is now recognition for the need to better address dynamic loads, both internal (ballast, heavy cargoes), and external, particularly in relation to side shell and transverse bulkhead structures. There is also now the growing recognition that the structure should be designed for dynamic loads not only in the intact condition, but also for accidental flooding of the compartment.

3. 4 Design Sensitivity

Certain design and construction factors that are normally adequate, can, in some situations, either contribute to cracking and / or make the consequences of any cracking worse.

A classic example is the use of lapped brackets, which may be perfectly acceptable in some situations, but not others. Another example is the connection of the deck and the transverse corrugated bulkhead in a bulk carrier. Of particular interest is a design where a transverse box structure is not fitted, with the corrugated bulkhead welded directly to the underside of the cross deck plating. With heavy iron ore low in the hold, the cross deck structure tends to deflect upward and away from the bulkhead, and wastage or other defect at the connection bulkhead upper connection detail can promote detachment of the deck from the bulkhead, particularly with thinner scantlings that are inherently more sensitive to corrosion and wear effects.

3.5 Harsh Service Routes and Cargo

As an illustration of the effects of a harsh trade route, we might recall the study of U.S. flag tank vessels trading in the Trans Alaska Pipeline Service (TAPS), carried out by the U.S. Coast Guard in 1990, which seemed to highlight an above average incidence of cracking on that particular route.

In the case of bulk carriers, there is some evidence [BTCE, 1994] that a combination of heavy seas, harsh trade routes, the type of cargo carried, and other factors (such as corrosion and wear) may in some cases lead to an above average incidence of damage. The BTCE study also showed that bulk ships carrying heavy cargo (iron ore) are associated with a larger proportion of failures than would be expected based on their voyage exposure risk alone.

3.6 Structural Degradation

In ships, corrosion is always a concern. In bulk carriers, frequent ballasting / deballasting cycles and the resulting tank humidity can accelerate the corrosion of topside tanks. The worst affected areas are the tank bottoms, which contain the important connections between the longitudinal framing of the ballast tanks and the (typical) transverse framing of the cargo hold. The level of corrosion may be masked by the mud and debris present. In bulk carrier cargo holds, certain cargo such as high sulfur coal can contribute to increased rates of corrosion.

In tankers, corrosion in ballast tanks was recognized to be a problem earlier on, which owners, operators, and classification societies actively addressed through the Tanker Structure Cooperative Forum [TSCF, 1986]. Today, segregated ballast tanks are required to be coated, reducing the levels of general corrosion therein. More recently (1994) the coating of ballast tanks and parts of cargo holds has come to be required in bulk carrier new builds.

Structural wear due to routine bulk vessel operations has also recently been of interest. The effects of today's very high speeds of loading were essentially unanticipated in vessel design. In particular, grabs today weigh as much as 30 tonnes, and their impact on a comparatively light and possibly corroded structure may be considerable. Wear can also be promoted by bulldozers and pneumatic hammers used to pound cargo loose from the structure.

4. Consequences of Cracking

4.1 Structural Failure

Although rare, cracks can lead to structural failure and vessel loss. Such structural failures are thought to be a factor in the recent spate of bulk carrier casualties. Spontaneous and substantial unstable fracture of the hull girder rarely takes place. Instead, what usually happens is a sequence of progressive failure events which eventually may lead to overall structural failure and vessel loss.

Such a sequence of events (e.g. water ingress through the side shell or hatch cover, loss of a forward transverse bulkhead, followed by vessel plunge) is thought to be implicated in some bulk carrier losses. Such events can occur with little initial external signs, making them hard to detect early enough to prevent vessel loss [Grove, 1992].

4.2 Pollution

It has been estimated that, worldwide, tanker accidents contribute less than 10 % of the nearly 2,400,000 tons of oil that enter the world's seas every year from all sources including natural leakage, land based release and offshore activities. The world maritime operational and accidental losses of oil have actually been on the decrease for some time, as noted in a National Research Council study [NRC, 1991], because of better vessel design (e.g. limitation in cargo tank size, protective location of ballast tanks) and improved operational procedures such as clean ballasting. At the same time, society's reluctance to tolerate pollution has increased.

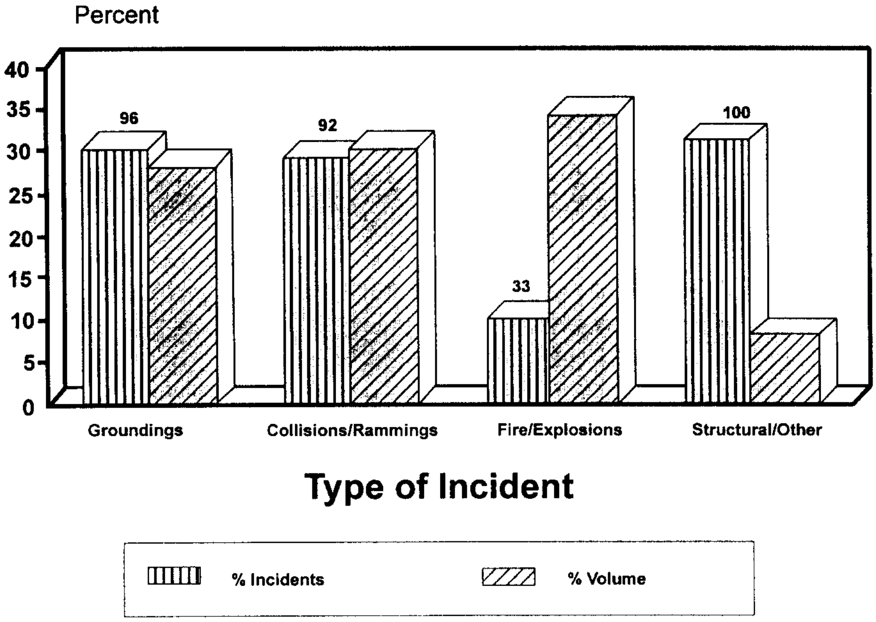


Figure 3. Causes of significant oil spills worldwide -NRC

The amount of oil spilled from 50 major spills of tankers from 1960 to 1990 has been studied by the NRC [NRC, 1991]. The volume of oil lost varied from year to year, and was quite unpredictable as to cause and occurrence. Based on the same study, Figure 3 shows the alleged causes of significant oil lost from tankers worldwide. While apparently roughly equal volumes of oil are lost from groundings, collisions and fire and explosions, that lost from "structural / other" causes is significantly lower. It is worth emphasizing that these observations pertain to a subset of all tanker casualties, in fact about 6 % of the total. In the other 94 %, no oil was lost.

Instances of significant pollution, when they occur, can result in considerable near term damage to the environment, depending on where and when they occurred. Costs related to such damage fall under many categories: a) clean-up expenses, b) restoration costs, c) lost use and non-use values. The third category includes intrinsic values such as the depletion of sea life. Clean-up costs are typically large, the highest to date being the Exxon Valdez (reportedly in excess of $ 2 billion).

Legal claim payments are one way to judge the total costs of a spill, and are said to be about $ 30,000 per ton of oil spilled typically, but can be as large as $ 100,000 per ton [NRC, 1991]. U.K. P & I club data [1993] indicates that of their major pollution claims, over 100 involved a total of $ 132 million, i.e. an average claim amount of $ 1 million each. About 12 % each of the total number of pollution claims were caused by bunkering, collision, valve and shell plate failure. Tankers accounted for about 1/2 the number and 2/3 of the total value of claims.

4.3 Increased Maintenance Costs and Down-time

Most steel renewal occurs because of corrosion, and cracks are typically addressed by local repairs. Data on maintenance costs and down-time pertaining to such occurrences are difficult to provide. We will now illustrate some of these costs, with the disclaimer that what follows is an incomplete list. In particular, we have omitted the cost of down-time, which is substantial.

First we start with the obvious question of how much steel is typically renewed on the average? The relevant numbers, according to the Tanker Structure Cooperative Forum [TSCF, 1986] are approximately (in tonnes / ship / 20 year life): a) cargo tanks- 50 tonnes uncoated, 25 tonnes partially coated, b) ballast tanks- 350 tonnes uncoated, 210 tonnes coated, and 130 tonnes partially coated (epoxy and anodes).

What does it cost to renew steel? There are many possible components to such cost, as illustrated by data from a far east yard below:

1. Dry dock charges: for vessels above 150,000 GRT, the minimum charge for the first two days is about $ 0.5 GRT. The charge for each subsequent day is about $ 0.2 GRT.
2 Tank cleaning: ranges from $ 2 to $ 12 per metric ton capacity, depending on type and location of tank, gas freeing and ventilation excluded.
3 Steel renewal: $ 4000 to 5000 per tonne of steel renewed, of which material costs are a small part.
4 Staging: about $ 5 per cubic meter of volume covered.

Evidently, while the amount of steel renewal may be small, the associated life cycle costs can be large.

5. Traditional Control of Cracking

In past classification practice, members were sized for local pressure heads, and the hull girder was required to have a section modulus adequate to withstand still water and wave induced bending moments and shear forces. This is essentially an approach wherein stress limitations are used to control yielding, buckling and fatigue implicitly. Loading manuals were required in some cases. On balance, this experience based approach has worked reasonably well.

In the last 20 years, the design of ocean going vessels has moved toward more explicit consideration of failure modes. Buckling assessments became common. Fatigue calculations started to be made in selected cases. Global and local stresses were increasingly calculated using finite element analysis. These changes, particularly in tanker structural design, came about because of a recognition that vessel sizes far exceeded the rule experience base until then. Also, operating stress levels continued to increase, because of efficiencies gained through advances in knowledge and the use of steels of higher yield strength to save on initial costs.

5.1 Design of Structural Details

The design of structural details to reduce stress concentrations, provide smooth transitions, and reduce local bending, e.g. by providing adequate backing has traditionally been used as a primary defense against fatigue cracking, with special attention paid to the termination of structural members. Related guidance on detail design may be found in documents from the Tanker Structure Cooperative Forum, and the International Association of Classification Societies [TSCF, 1986 and IACS, 1994]. Such guidelines are useful in both design and repair contexts and are largely experience based.

5.2 Tolerances and Weld Acceptance Criteria

Except for plate rolling tolerances, classification societies do not commonly mandate specific construction tolerances for ships. But surveyors do use certain guidelines for judging structural imperfections. These relate to: dimensions of built up sections, misalignments in butt and fillet welded connections, weld undercuts, and plate and stiffener unfairness and out of straightness. For example, undersized, fractured, or missing welding is normally unacceptable, and cracks are to be repaired.

Construction defects are potential sources of cracking. Hence surveys and inspections during construction are important. Such surveys include those at the shipyard, and at steel mills and manufacturers. Surveys during construction are not an alternative to the shipyard's quality assurance. The rules do specify attendance of the surveyor at certain manufacturing and construction activities, as well as at tank testing. However, the overall responsibility for a well built vessel belongs to the builder.

5.3 Control of Corrosion

This is important to the ability of the structure to maintain adequate strength throughout its economic life. Traditionally, a margin for corrosion was built into the classification rules for scantlings. More recently [Chen, et al., 1993], a "net ship" approach has come to be used for member sizing, with an explicit corrosion margin then added to obtain the "as designed" structure. This makes possible the direct treatment of structural sensitivity to corrosion.

In addition to the design corrosion margin, the other important elements of corrosion control in ships are Protection systems (coatings, anodes, and impressed current cathodic protection), Classification Surveys and Owner inspections. For certain types of vessels where corrosion was felt to be a significant problem, classification requirements have tended to emphasize coatings as the solution. For example, ballast tanks in ocean going vessels are now required to be hard coated.

Classification surveys after construction are of three types: annual, intermediate, and special. At annual surveys, the hull is examined for general condition. In special surveys which include dry docking, and occur essentially once every 5 years, the various parts of the hull in which the classification society has an interest are examined in more detail, using close-up surveys and gaugings, and a recommendation is made as to the necessary work to enable the vessel to operate for another 5 years in apparent good order. Intermediate surveys occur between special surveys, and ascertain the general condition of ballast tanks and cargo holds.

5.4 Material Ductility and Deployment

The ferritic types of steels used in ships undergo a change in behavior from ductile to brittle depending on the loading rate and temperature. Metallurgical processing cannot change such behavior, but can change the loading rate or temperature at which such ductile to brittle transition occurs.

The toughness of a steel is a measure of its relative brittleness. Prescriptive steel chemistry and metallurgical processing help obtain a specific level of toughness. In ships, Charpy toughness testing is typically used to quantify the same. With regard to toughness, steel is generally selected and deployed depending on the expected service temperatures and crack arrest needs, the more ductile steels being used for lower temperature applications and for special locations (e.g. the sheer strake).

Higher toughness and ductility may involve a moderate price. Steel grades used in ships are: A, B, D, E, DS, and CS mild steels and AH, DH and EH higher strength steels. All grades except A, CS and DS require Charpy testing of some form. The approximate relative costs of these various steel grades are as follows: A(0.80), B(0.80), D(0.85), DN (1.05), E(1.05), CS(1.00), AH(0.90), DH(1.05), EH(1.10). These costs are normalized to grade CS, which is a heat treated high toughness steel that does not require production Charpy testing. Costs include that for any heat treatment and production testing required by the rules. Grade A steel costs roughly \$ 500 a ton.

6. Control of Cracking in Existing Vessels

In this section, we review approaches to assess / reduce the incidence of cracking in service. Discussed here are the following: Structural Analysis (stress, fatigue), Fitness for Service Assessments, Repair / Redesign of local details, Reduction of loading and monitoring of response, Control of Corrosion and Wear, Fatigue life improvement techniques, Enhanced surveys and inspections, Emergency management systems, and Awareness of human factors.

6.1 The Structural Analysis Option

Stress and fatigue analyses are typically undertaken to identify the possible causes of and solutions to cracking in ships. The procedures are fairly standard, and are similar to those undertaken for new designs, the largest single unknown for existing ships usually being the loading (past and future).

Stress analyses can be useful in predicting stresses in the structural areas of interest, predicting deflections, optimizing local detail design, deciding the appropriate placement or relocation of large openings, and determining the adequacy of structural reinforcement.

Fatigue analyses aim to calculate the damage accumulated within a given period of time. Such analyses may be simplified or direct, a good example of the latter being the spectral fatigue approach that is part of the ABS Dynamic Load Approach (DLA). This procedure involves a) an environmental description by a wave scatter diagram, b) determining the local stress range transfer functions using ship motion and structural studies, c) determining the stress range histogram, and d) calculating the fatigue damage on the basis of applicable S-N data. In a calibrated simplified approach, such as that of ABS SafeHull, the stress range histogram is built up from the extreme stress range possible in the time period together with (given) prior information on the shape of that histogram.

6.2 Fitness for Service Assessments

A fitness for service assessment uses stress analysis (e.g. using the finite element method), fatigue crack growth (FCG) modeling and fracture mechanics calculations. The typical aim is to show that there is no danger of significant crack extension or unstable fracture during a certain period of time, e.g. the voyage duration to reach a repair yard, or perhaps the time until next scheduled dry docking. The decision to repair or not immediately itself is a function of regulatory requirements and risk considerations including possible threat to the environment, and potential liability.

Similar technology could also be applied to assessing the need for rectification of out of tolerance defects in newbuilds, reassessment of NDT acceptance criteria in special cases, judging the effectiveness of specific repairs, and developing inspection plans. It is fair to say , however, that fitness for service assessments are not fully accepted in the marine sector at this time, and that even when such an assessment is made, authorities and owners alike would yet typically (and prudently) opt for cracks to be repaired - even for short passages.

6.3 Repair and Redesign of Local Details

6.3.1 The Existing Approach

Cracks when found are repaired. Small, single, or relatively straight cracks in plating may frequently be satisfactorily repaired by welding, but after locating the end of crack and veeing it out as required. No attempt is made to weld multiple branching or star shaped fractures indicative of fatigue. Such defective areas are renewed / strengthened / modified as appropriate.

Repeated occurrences of cracking in similar areas may indicate a need for structural strengthening or modifications. Options for such modifications may include provision of soft toe brackets, providing backing on the other side of plating and increasing local member thicknesses with a view to reducing stress levels. One can also increase local fatigue strength by measures such as weld toe grinding. There is however no one effective repair strategy to suit all situations, so the best approach is still to avoid the potential problem to the extent possible, by design.

6.3.2 Repair Management Systems

The main component of a repair management system is a purpose written computer program that facilitates the identification of the best repair option in a short period of time. A repair management system may contain the following capabilities for comparing and evaluating repair options rapidly:

1. Graphical representations of repair options
2. Finite element models of repair options
3. Simplified fatigue life estimation procedures
4. Economic trade-off analysis capability
5. A repair record data base

Repair management systems are also useful in facilitating rapid and sophisticated response to potential crises, e.g. where finite element models are prepared and stored in advance.

6.4 Control of Corrosion and Wear

Corrosion and wear are significant compounding factors in the incidence of cracking. Corrosion control measures such as the use of coatings thus help indirectly to reduce the occurrence of cracks or other effects of material degradation.

As previously discussed, corrosion and wear are factors in bulk carrier hold frame end cracking. Corrosion can also be a problem with the corrugated bulkheads in bulk carrier cargo holds, where its uniform nature may make it hard to detect visually. Because of such experience, the hold frames and corrugated transverse bulkheads of newbuild bulk carriers are now coated. Coatings are expensive, and can account for 10 to 20 % of the cost of a vessel in some cases, e.g. double hull tankers.

6.5 Reduction of Loading and Monitoring of Response

The reduction of wave loads experienced by the vessel structure will typically improve fatigue performance, since fatigue lives are proportional to the cube of the stress range (at least). Such load reduction may be possible in specific cases by voyage planning, changes in vessel route, speed and heading limitations, changes in tank fill heights, or (the rare) reduction of vessel length.

The reduction of still water loads producing tensile mean stresses can help in containing the possible consequences of cracking and reducing the chances of unstable crack propagation.

Loading manuals and loading computers help in this regard. Hull and hold load and stress monitoring systems can provide valuable real time checks on the load effects being experienced by a vessel, and support proper vessel loading and handling, whether at a terminal or at sea.

6.6 Fatigue Life Improvement Techniques

Fatigue life improvement technology falls in two categories:

- Those that alter local geometry of the weld
- Those that alter the residual stress field at the weld

In the first category are the mechanical and argon arc treatments of the weld. The second category includes methods for relieving residual stresses, or introducing favorable (compressive) residual stresses.

Typically, only the first class of methods is a reliable option in ships, and even then only in local areas in specific cases. Such methods aim to create a smoother transition between the weld and parent metal. Welds toe grinding using abrasive disks or mill cutters is an example. The best results are achievable for butt welds, where the overfill can be completely ground out, or a transition zone given a large enough radius and smoothed profile.

6.7 Enhanced Surveys and Inspections

In accordance with IMO resolution A. 713, enhanced survey requirements for tankers and bulk carriers were implemented in 1993. These emphasized and expanded the then existing survey requirements for annual, intermediate and special surveys as a function of vessel age.

Now, the condition of coatings is also graded and recorded. In addition, the survey program calls for identification of so-called suspect areas, which show substantial corrosion or rapid wastage. If not remedied when found, such areas are subject to special attention during the subsequent time period. Certain related documentation such as summary of hull condition may be retained on board the vessel as well.

The enhanced survey program has a provision for a survey planning document prepared by the owner, well in advance of a special survey. The purpose of the document is to identify critical structural areas, and to stipulate the minimum extent, locations, means and access arrangements for close-up survey and gaugings of sections and internal structures, and to nominate suspect areas for continued monitoring. Survey planning thus helps focus inspection effort.

6.8 Emergency Management Systems

These systems provide man-power and technical assistance to assess and help contain the consequences of an accident. An example is the ABS Rapid Response Damage Assessment Program, which accommodates around the clock multiple responses for enrolled vessels, using naval architecture and salvage analysis software. This particular program offers both hull girder stress and bending moment calculations and also residual stability assessments as standard. Other types of required assistance are also provided (e.g. calculating local stresses using previously developed and stored structural models).

Two other noteworthy types of emergency response services emphasizing procedures and training are: oil spill management exercises and the MARPOL required Shipboard Oil Pollution Emergency Plan (SOPEP), both offered by ABS Marine Services.

6.9 Awareness of Human Factors

Awareness of human factors is important in limiting the undesirable consequences of cracking. Human error is inherent to any system, and cannot be eliminated. It has to be recognized and controlled by management of potential causes and consequences. The three main ways of accomplishing this in practice are: personnel selection and training, implementation of trouble monitoring procedures, and design of durable and damage tolerant structures with adequate reserve and residual strength.

The International Management Code for the Safe Operation of Ships and for Pollution Prevention, commonly referred to as the International Safety Management (ISM) Code, is a management system standard designed to ensure the safety of life, property and the environment. The ISM Code addresses personnel responsibility, management structure, ship and cargo status identification, procedures for deck, cargo and engine room operations, and procedures for navigation, safety, emergency preparedness, maintenance, communications, pollution prevention, etc. Its scope does not include design.

An amendment to Chapter IX of the SOLAS Convention mandates the ISM Code for all passenger ships, and by 1998 all tankers and chemical and gas carriers, and bulk carriers over 500 GRT. The requirements extend to cargo ships over 500 GRT by the year 2002.

7. Life Cycle Durability through Technology

An integrated approach to design, construction, maintenance, operation and inspection of the vessel over its life cycle, using advanced technology, is the ultimate goal. Within this overall framework,

1. The structure itself will be designed using advanced technology, considering various failure modes such as fatigue. Dynamic loads will be appropriately accounted for.
2. Design safety margins will duly reflect the consequences of failure.
3. Durability will be explicitly addressed in design. This includes awareness and appropriate accounting of construction, maintenance and operational factors that affect can structural adequacy, reserve and residual strength.
4. Maintenance of structural condition will be effectively monitored by ongoing in-service inspections and planned surveys.
5. Necessary information data bases will be established and maintained.

In such a philosophy, although structural defects may exist, the incidence of cracking will be reduced, any occurrence of cracking will be monitored, and the consequences of cracking will be contained through appropriate Advanced Design, Condition Assessment and Structural Management Systems.

7.1 Design and Condition Assessment Systems

7.1.1 The Direct Calculation Approach to Design

In systems using this approach, structural and fatigue analyses are performed using directly calculated dynamic and static loads unique to the specific vessel. Stresses in the "as built" structure are then determined by finite element analysis (using a global model of the entire vessel, and any local models as necessary), and checked against allowables for yielding, buckling and fatigue. The ABS Dynamic Loading Approach (DLA), is a good example of an integrated software system for design by direct calculations [Liu, 1992]. An emphasis in DLA is on the first principles based calculation of dynamic loads, reflecting their relative importance. Vessels designed through DLA will have scantlings greater than rule requirements, but not less. Thus the procedure provides an extra margin of safety, resulting in stronger, robust and more durable vessels.

7.1.2 Design Oriented First Principles Procedures

In this approach, direct calculation procedures are standardized and streamlined together with a very high level of software support, resulting in a true and easy to use structural design system. While a direct calculation approach can be utilized to evaluate any type of ship of any structural configuration, including novel ones that fall outside today's experience base, a system of this type is purpose built for a given vessel class (e.g. tankers). Such a first principles design system would ideally use the "net ship" (i.e. excluding corrosion margin) concept. This facilitates explicit consideration of durability issues and corrosion sensitivity, since the net scantlings required by strength alone are known.

First principles advanced technology is also useful for the condition assessment of existing ship structures [Horne, 1994]. The aim is to give owners, operators, charterers, underwriters, and other interested parties a means to objectively judge the condition of their ships, by survey and subsequent structural evaluation. The evaluation typically compares current and projected conditions of the hull structure with the net ship, so that maintenance requirements including steel replacement may be objectively projected / assessed.

The ABS SafeHull system shown in Figure 4 [Chen, et al. 1993] is a true first principles design system that meets all of the above objectives. An noteworthy feature of SafeHull is the facility for the consideration of hull girder residual strength after damage. Such checks on the strength required to survive damage situations help reduce the risk of post accident collapse or disintegration of a damaged vessel during salvage operations. This results in a damage tolerant design.

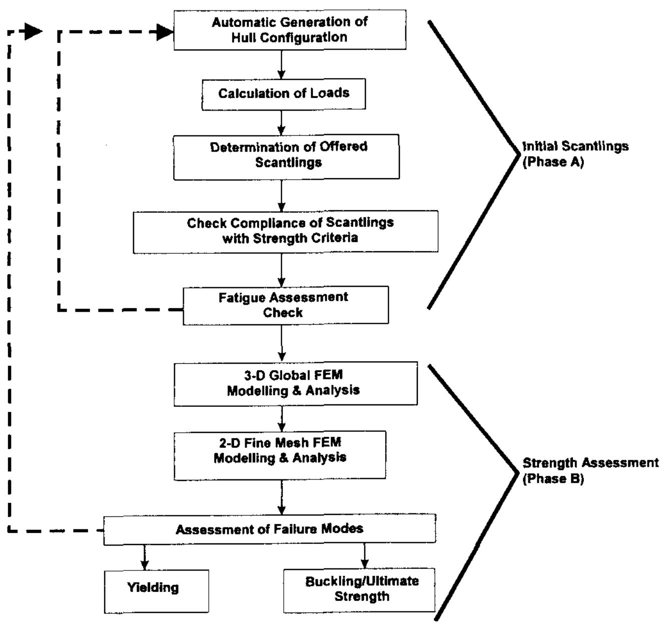


Figure 4. Computer assisted design system- ABS

7.2 Structural Management Systems

The purpose of structural management systems is to monitor and manage structural safety of the vessel, by an integrated approach to the collection, analysis and assessment of information from design, construction, operation, maintenance, inspection and surveys. Central to these systems are information data bases and collections of analysis and assessment tools working off those data bases. Structural management systems may possess the following capabilities: a) hull response monitoring, b) repair management, c) reliability analysis and risk assessment, d) fitness for service assessment, e) stress and fatigue analysis using prefabricated finite element models, f) inspection planning software, and g) emergency response systems.

The types of information used or provided by structural management systems include stress and fatigue life maps of the vessel, incorporation of the effects of actual construction particulars and fit up deviations, tank usage and trading history, inspection and survey data, e.g. for corrosion effects and cracking, and data related to structural modifications and repairs. A schematic of a structural management system is shown in Figure 5.

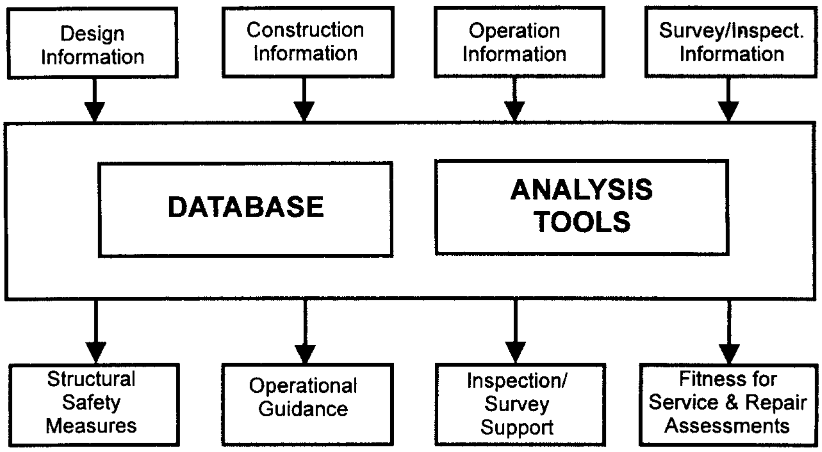


Figure 5. Structural management system

8. Concluding Remarks

In this paper, we have discussed the subject of local cracking in ships, its causes, consequences, and control. Crack free structures are unusual. Cracking typically does not occur due to one isolated factor. Cracks, when found, have to be effectively repaired. Any non-isolated occurrences of fatigue related cracking, particularly early in life, requires in-depth analysis. Any cracking with measurable potential consequences requires appropriate control measures. Above all, there needs to be explicit consideration of fatigue effects up front in design, emphasizing 'prevention' and facilitating 'cure'.

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