METHODS FOR THE ASSESSMENT OF STRUCTURAL STRENGTH OF NAVAL SHIPS

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SUMMARY

The ability to survive plays an important role in naval ship design. Because of the probability of major structural damage, this leads to specific structural design solutions.
The basis for the calculation of damage resulting from a given threat is available and is validated. The tools for the calculation of ultimate strength for intact and damaged conditions are also available and generate consistent results. By application of both methods the measure of decline of seaworthiness resulting from battle damage can be determined. The outcome can be utilised for design considerations and necessary improvements. New structural design concepts are to be considered in order to prevent catastrophic failure because of losses in longitudinal strength after enemy action, when large deformations and / or destruction of essential structural parts occur. The findings of this paper present an engineering approach and several viable ideas.

CONTENTS:

Methods for the Assessment of structural strength of naval ships

1 INTRODUCTION

In the structural design of naval combatants not only the intact structure is considered, but the residual strength of the hull after structural degradation caused by wartime damage is also one of the design considerations.
The aim is to design the structure in such a way that for the most probable (designated) damage scenario the ship still has sufficient structural integrity to either maintain operational or at least be able to reach port.

This residual strength design concept may also be of value to the designer of merchant ships. Damage tolerant structures could contribute to the safety of ships carrying dangerous cargoes. This paper will briefly describe the methodology used in naval ship design, the authors have no expertise with merchant ship design. The methods used are specifically related to the damage types relevant for these ships, and as such not directly transferable to normal ships. However some of the methods used could contribute to the already existing interest in merchant ship design in this topic.
Possible applications in design of these vessels are of course completely different.

2 NORMAL SEALOADS & AVAILABLE METHODS

The methods for determining the adequate safety measures introduced in structures are still under investigation. Despite the progress made in ship design by the introduction of statistics and reliability procedures there is not yet a solid bridge across the gap between theoretical approach and practical experience. It is well known that a wave length of about ship length gives the maximum load and a design wave height of about L/20 had already been found in the last century. This was modified by several authors with regard to wave statistics and the probability of excedance. But it is impossible at the present time to verify one of these proposed formulas as the "correct" one. All methods have some merits and some shortcomings with respect to simplicity, universality or more individually oriented design considerations. Classification societies and navies use formulas which fit well into their field of application.
Several ways of numerical description e.g. $H = 0.6\sqrt{L}$, $H = L/(12+L/20)$ and $H = 8$ m for frigate sized ships, see Figure 2.1, offer comparable results in terms of structural scantlings and safety since the allowable stresses play the other part in the evaluation of adequacy for a design.
So the permanent discussion about an economical and/or safe design has to deal with efforts for the production of today and with assumptions for the operation of tomorrow.
In order to get information about the probability of survival after damage it is necessary to perform additional numerical

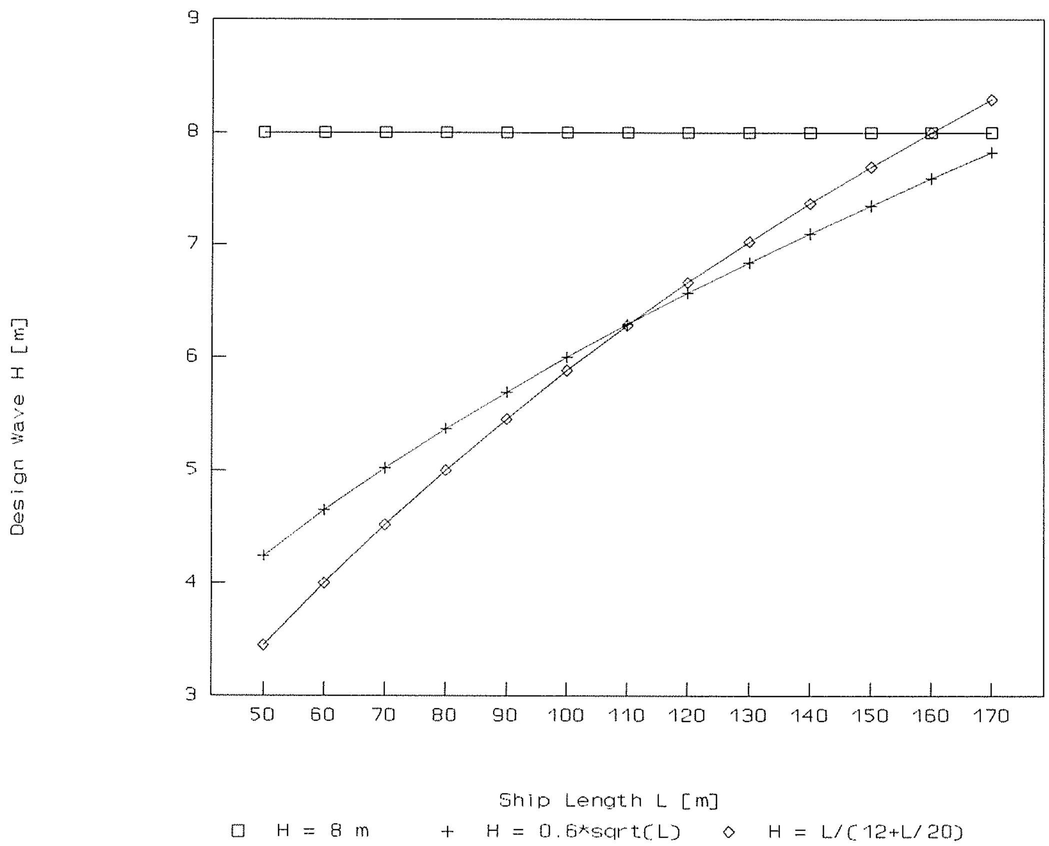

Figure 2.1 Typical Design Wave Heights for frigates

calculations for navy ships with regard to strength reduction by local structural destruction. Some recommendations for increased residual strength are given in [1].

Even if the design load is used only as a reference and absolute factors of safety or probabilities of failure can not be verified by experimental data it is possible to assess the advantages of structural solutions.

In case of blast effects of enemy weapons 2 modes of structural damage are to be considered. If it is a relatively small weapon one can expect no ruptures but deformation of structural panels by about centimetres. If it is an antisurface ship missile of common size additional rupture of essential parts of the structure accompanies the deformations. As a reference the intact strength shall be used. Complete information about the influence of such additional "holes" in the ship can be obtained by finite element calculations as only these give sufficient information about the influence of all kinds of structural discontinuities. But since the variety of possible non load carrying areas is infinite one has to make some assumptions. In order to get sufficient information about which assumptions will result in critical structural behaviour we used a slender beam approach. With this the effort is less when a wide variety of structural situations shall be studied. At least the results show which bending moment can be endured and which parts of the cross section are capable of carrying the main portion of the loads.

3 COMBAT LOADS & CONSEQUENT DAMAGE PREDICTIONS

While designing a warship a constructional naval architect takes into account all seagoing loads (e.g. hogging, sagging, slamming and green water). He is committed to safeguard his future asset against these natural threats.
Warships are complex, sophisticated and expensive weapon platforms. It will be out of question in times of war or conflict to allow these "high value targets", to be taken out of action or even be lost by just a single blow of a weapon system ("cheap kill").
The design philosophy is evident, the ship has to sustain a certain level of damage in a conflict scenario where it is threatened.

Anti Surface Ship Missiles

Anti Surface Ship Missiles (ASSM's) are intended to enter the ship a few meters above the waterline and to detonate inside the ship's hull.
When an ASSM penetrates the ship it will rupture part of the ship's skin at entrance. Inside the hull the warhead detonates and loads the ship with highly lethal phenomena; blast, high velocity fragments, (horizontal) shock and fire.
The phenomena fragmentation and fire will be dealt with briefly in the next paragraphs and will not be elaborated upon.
However the warship designer must take all these phenomena into account, in order to design a survivable ship in a balanced way.

3.1 MISSILE DAMAGE LOADING PHENOMENA

3.1.1 High Velocity Fragments

Warheads of ASSM's possess a strong metal casing to generate highly lethal shrapnel and to be protected against projectiles of Close In Weapon Systems (CIWS) [2]. The masses of these fragments vary from tenth's of grams to hundreds of grams. Velocities range up to 2500 m/s. These fragments can be penetrate bulkheads, decks and the skin of the ship. Life fire trials have shown that the irregular fragment holes in general don't influence the failure of a structural component. They are a danger to components, cabling and firemains etc.
Reduction of the fragmentation effects on the ship systems, can be achieved by designing particular geometric arrangements and using ballistic protective materials [2].

3.1.2 Fire

One should keep in mind that a missile fire will heat the steel structure, which will have a considerable influence on the mechanical properties of the structural material. Missile fires generate very high temperature loadings, but other type of fires can also be started like cellulosic and hydrocarbon fires. Figure 3.1.1 depicts an impression of these temperature loadings [10]. Figure 3.1.2 gives the influence on the steel properties [10].

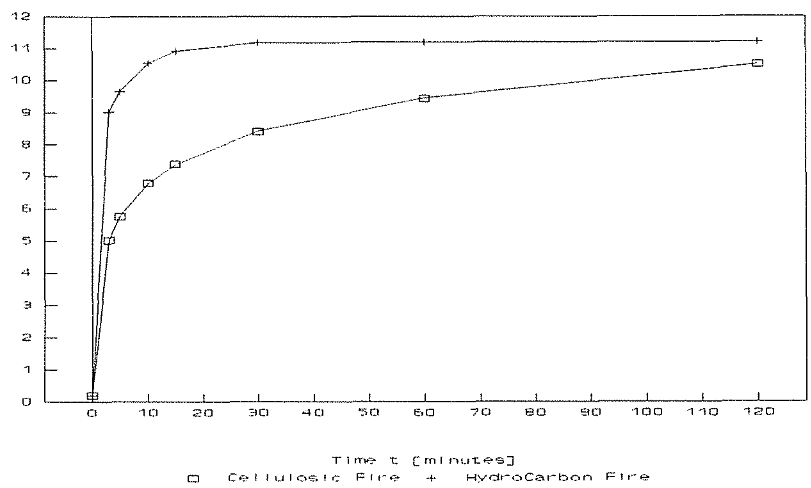

Figure 3.1.1 Cellulosic and HydroCarbon Fire

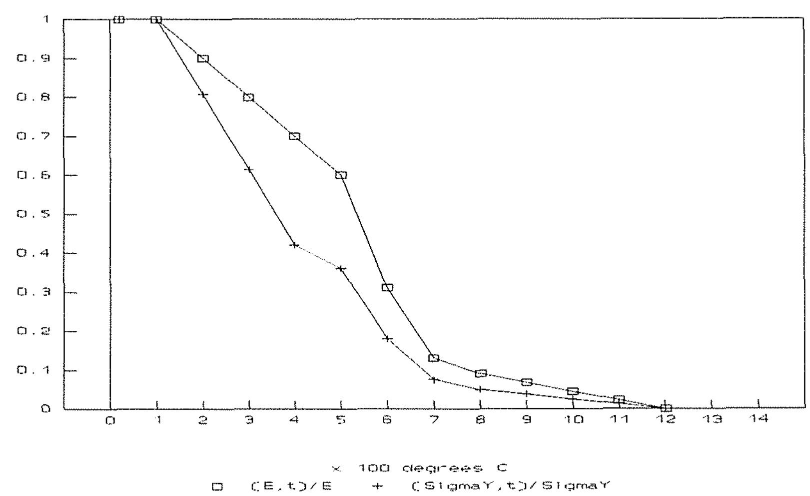

Figure 3.1.2 Yield and Young degradation

3.1.3 Internal Warhead Detonation Pressure Loadings

The above mentioned damaging phenomena already form an enormous challenge to the warship designer; but the primary damaging effect of an explosion inside a ship is the pressure built up from the detonation of the high explosive (e.g. TNT). The enormous pressures emanating from the explosion are able to wreck bulkheads, decks, deckheads and the skin of the hull. This damage can jeopardize the total integrity of the ship. The internal explosion pressures which have extreme dynamic properties can be divided into two phases the "Blast Waves" and the "Quasi Static Pressure", see Figure 3.1.3

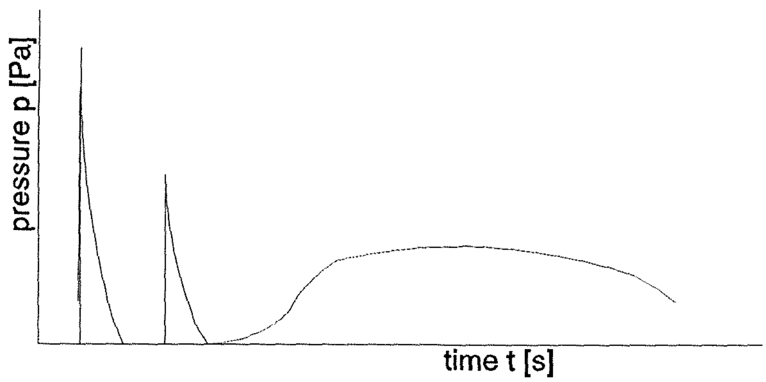

Figure 3.1.3 Blast and QSP pressure history

3.1.3.1 Blast Wave loading

At detonation the of the warhead an initial spherical shock wave is generated in the compartment, this blast wave is reflected several times at the boundaries of the compartment. Structural elements like bulkheads, decks, deckheads will therefore be loaded by various blastwaves. The peak levels of these blastwaves will amount to several decades of bars, but last relatively short to the natural response time of the structures.
The blastwaves will in general not induce total rupture of the elements. They will generate high shear forces at the boundaries of the structural components, which can commence initial cracks.

3.1.3.2 Quasi Static Pressure

The blastwaves are followed by the so called "Quasi Static Pressure" (QSP) build-up. This QSP is formed by the heat effects and additional gas effects; QSP is only generated in case of internal explosions. The level of the QSP will be several bars. The maximum level of QSP and the total loading time are of course governed by "venting" of the explosion gasses into the atmosphere or adjacent compartments.

Although the level of QSP is relatively low in comparison to the levels of the blastwaves, the QSP can have the most destructive power. This is caused by the relatively long loading phase in comparison with the structural response times.

A first approximation for the QSP is given by Weibull [1]:

$$QSP = 2.25\ 10^{6}\ (M_{explosive}/V)^{0.72} \qquad [Pa]$$

where:

V = Volume of the compartments with explosion gasses [m^3]

3.1.4 Internal Gas Explosion Pressure Loadings

The preceding paragraphs gave an impression of "typical navy ship design" pressure loadings, caused by weapon effects; the detonation of high explosives.
However high pressure loadings can also be generated, under more civil conditions; gas explosions. As commonly known, three phenomena are necessary for this to occur; the release of flammable gas, the possibility to mix with air (oxygen) and finally a source of ignition.
The pressure built up in case of such an explosion is highly dependent on the level of venting but fully contained the expanding gases can theoretically develop an overpressure up to 800 kPa (8 bar).
In general these loadings will be less "impulsive". Typical commercial ship structures will not be able to bear these loads, which will result in failure. Figure 3.1.4 gives a "generic" explosion pressure history.

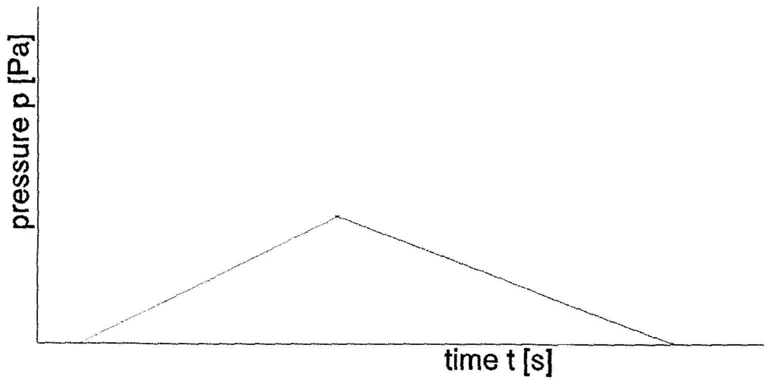

Figure 3.1.4 "Generic explosion pressure history"

3.2 DAMAGE PREDICTION FOR INTERNAL EXPLOSIONS

3.2.1 Damage prediction techniques

Damage assessments for internal explosions can be performed by various means. The two boundaries for this large prediction domain are on the one hand complex Finite Element or Finite Difference (FE/FD) codes and on the other hand the use of simple semi-empirical relations.
For the assessment of structural strength in naval design, the extend of the damage is the necessary input information. Detailed analysis of how this damage has been achieved, which is a necessity for the development of explosive resistant structures, is now less interesting.
Intermediate approaches, like one-dimensional and single degree of freedom (1-DIM/1-DOF) systems come in handy at this stage. Semi-empirical relations can be used as well, on the condition that all input parameters are within the "fit-boundaries" of the empirical "database".

3.2.2 Semi-Empirical Techniques

Semi-empirical relations like the "Blast Damage Radius" and the "Plate Failure Formula" respectively give information about the radius of damage inside the structure (BDR) and information which structural member will fail when loaded with the determined QSP level (PFF) respectively.

BDR:

$$R_{damage} = a(L/(\sigma_y . T))^b \ (M_{explosive})^{1/3}$$

PFF:

$$QSP = (S.T.\sigma_y)/(F.K.L)$$

where:

L = average distance between decks
T = plate thickness
a,b = empirical "fit" constants based on critical strains
S,F,K = empirical constants depending on type of structure
σ_y = Yield stress of constructional material

Note that both formulae indicate that Sigma Yield and plate Thickness can be exchanged.
However a disadvantage of semi-empirical relations like the "Blast Damage Radius", depicted in Figure 3.2.1 from [1], is that these techniques yield "Sure-Safe" or "Sure-Fail" answers to the problem. Only go/no-go criteria for the total failure of the load bearing elements are given. A structural member outside the "Blast Damage Radius" is available to carry loads, inside it is not.

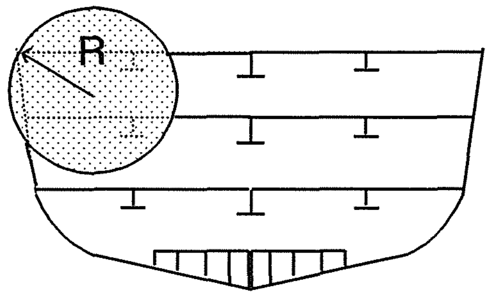

Figure 3.2.1 The Blast Damage Radius in a worst case position

As will be put forward later in this paper "The buckling problem" is of prime importance for a study in global structural strength. After an explosion, it will not only be important which structural members still exist, but the condition of these members will be of prime interest as well. Are they still elastic, or are they plastic now. How large is their deflection ?
This information does not become available with semi-empirical approaches. Still, these techniques can be useful for "Quick Look" analyses in combination with "Slender Beam Approaches".
A way to determine this "predeformation" is to use "Intermediate" Damage Prediction Codes.

3.2.3 "Intermediate" Damage Prediction Codes

"Intermediate" Damage Prediction Codes [3], like the TNO-PML DAMINEX code, treat the response of the structure one or two dimensionally (1&2-DIM) and with a single degree of freedom system (SDOF), see Figure 3.2.2.

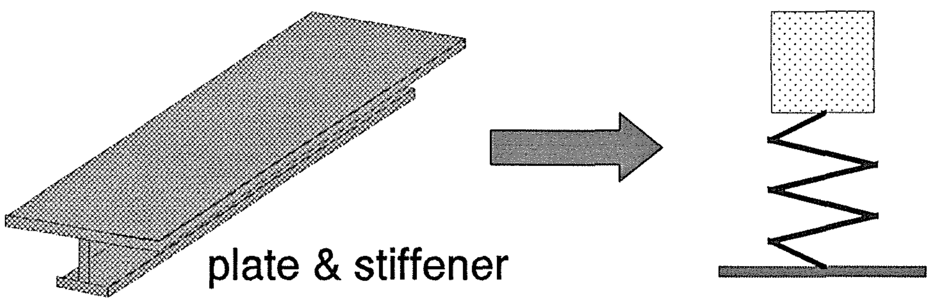

Figure 3.2.2 Construction Transformation in SDOF

In this way the constructional behaviour of the ship's panel is simplified by considering just one dimension. This is the shortest direction, consisting of an effective plate width and stiffener. This direction is highly dominant for ship panels bearing the lateral explosion pressures.
The explosion loadings parameters are generically "styled pressure loading histories", as depicted in Figure 3.1.3.
The structural response is approximated by a single degree of freedom (SDOF) system, in which the centre of deflection is the varying parameter. The equations of motions of the SDOF are then solved numerically in the time-domain.

Simulations with these "Intermediate" Damage Prediction codes, don't just give information about the "go/no-go" failing of structural members, rough information is also delivered about the state of the "non-removed" members; elastic, plastic with information about their centre deflection. Later on it will be put forward that "Load Shortening Curves" are very sensitive to this "pre-deformation".

3.3 GENERIC DAMAGE FOR INTERNAL EXPLOSION

If a ship is under attack and the defence systems fail to intercept the weapon, it is indefinite "how and where" the missile will hit and explode. But "how and where" do influence the amount and location of damage.
Taking all possible hit scenarios into account for the structural strength assessments study is not very economical. An efficient way to tackle this problem, is to simulate a sufficient number of hits and record their accompanying damage pattern. The envelop of damage can then be composed to introduce a generic damage pattern.
The semi-empirical relations and the Intermediate Damage Prediction Codes for this track possess the advantage, that with a relatively small effort a large number of simulations can be performed in comparison with the FE/FD codes.

The outcome for a medium sized missile can for instance be generalized in the failure of the ship's skin, see Figure 3.3.1, over one decks height, failure for both half the deck and half the deckhead in the explosion compartment.
Plastic deformations of all steel plating bordering the explosion compartment are generated with deflections in the order of two to three decimeters.

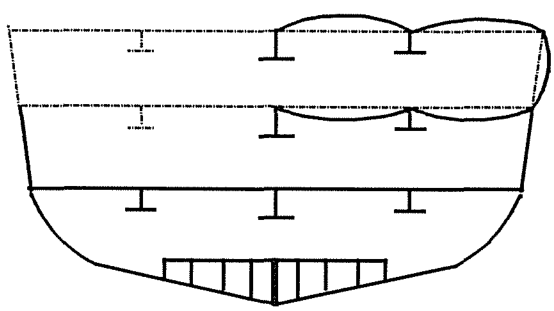

Figure 3.3.1 Example of a generic damage

4 OVERALL STRUCTURAL STRENGTH ASSESSMENT

Depending on the size of the warhead in relation to the ship's structural geometry, the extend of the damage and the severity, can be estimated. The influence of the damage on the residual strength of the ship hull girder can be assessed by the two following models :

1. 2-D slender beam approach.
2. 3-D finite element calculations.

The first model has the problem of selecting the effective members in a cross section, i.e. the effectiveness of a superstructure. The second is more time and cost consuming.

Within the two calculation models different methods can be used to estimate the maximum load the initial or damaged structure can withstand.

The simplest method is to compare the resulting stresses from an linear calculation, either 2-D cross section or 3-D FEM analysis, with the failure stress of the panels in the model. The failure stress of a (stiffened) panel is calculated using analytical equations, often modified to fit test results.
A more elaborate method is to perform a nonlinear analysis using load shortening curves of the panels. These load shortening curves are derived by analytical formulations or by using a 2-D beam model of plate with stiffener or a more general 3-D analysis of a panel. These models may include initial deformation and residual stresses.

4.1 Panel capacity

In all methods, the basic information needed is the behaviour of a stiffened panel under inplane loads. As is known, the capacity of a given panel depends on the initial distortion and residual stress. A well known example of the influence of initial distortion on the capacity of a structural member is given by the Perry-Robertson formula [4]:

with: R = Strength Ratio of Column ($\sigma_{ult}/\sigma_{yield}$) [-]
λ = Column Slenderness Parameter [-]
η = eccentricity ratio [-]

Figure 4.1.1 gives the relation of the mean stress at which the yield stress is reached as function of the initial distortion. The figure shows that increasing the initial distortion will decrease the mean stress at which the member starts to yield which is a measure of the capacity of the member.

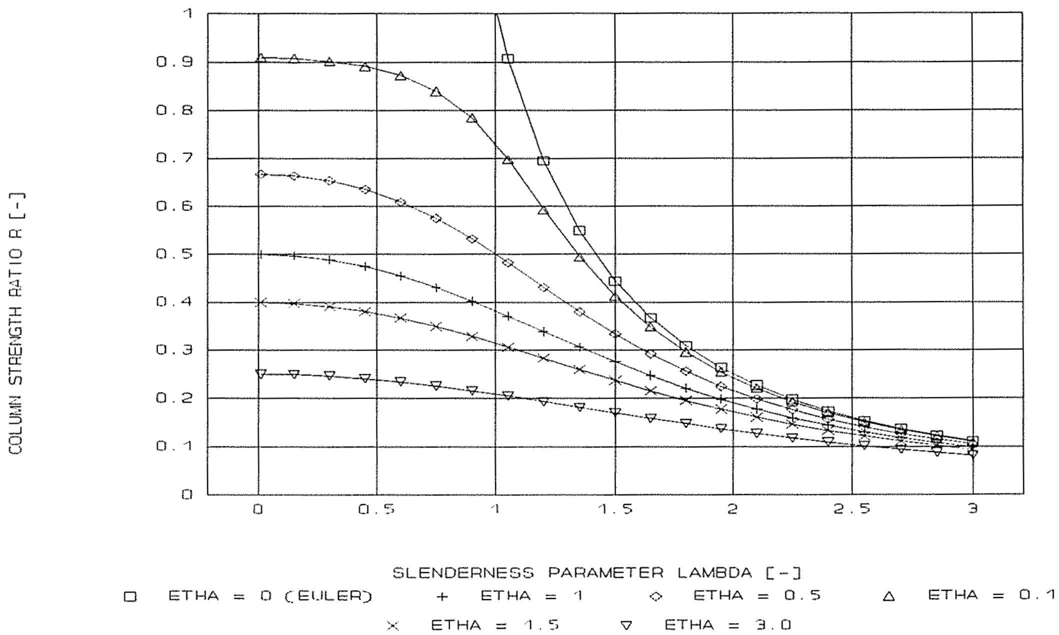

Figure 4.1.1 Perry-Robertson formula

Most analytical formulations give accurate estimates for intact panels with small initial distortions. In case of large initial distortion and high residual stresses these formulations may not be adequate. A nonlinear 2-D FEM beam analysis as described in [5] or an more general 3-D analysis of the plate stiffener combination which include large initial distortions and high residual stresses should be used if highly deformed panels are to be taken into account in the calculation of the ultimate bending moment.

Figure 4.1.2 gives the load shortening curves of a H-deck panel of Hr. Ms. Zuiderkruis derived with the program FABSTRAN [5]. The figure shows that both the initial stiffness and the ultimate load decrease on increasing initial distortion. The maximum lateral deflection, caused by blast loading, a stiffened panel can sustain without rupture, equals about 10 % of the span. The initial stiffness of the panel with this distortion is about 35 % of the initial stiffness, the ultimate load decreases to 25 % of the initial value. These results do not include the effect of residual stresses which in most cases will have an additional reducing effect on the ultimate load. If a graph of the ultimate load as function of the initial distortion is made, a similar plot as given in figure 4.1.1 will be obtained.

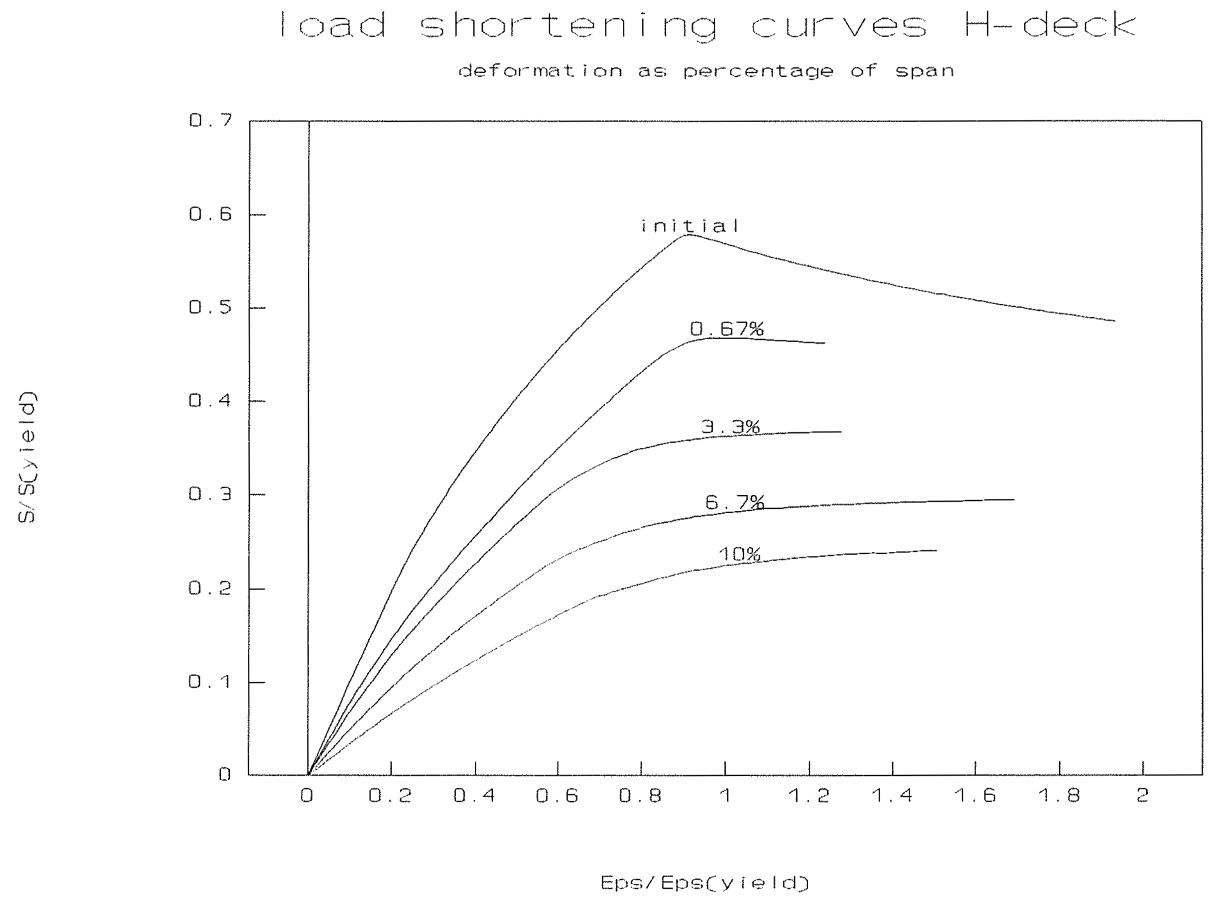

Figure 4.1.2 Load shortening curves

4.2 2-D slender beam models

As mentioned the simplest method is to calculate the stresses at a given bending moment and compare those stresses to the strength of the panels. The cross section is assumed to have failed if the first panel fails. This method does not allow for progressive failure and redistribution of the load over the cross section. This will lead to an underestimation of the ultimate load.

The method which will allow for progressive failure, is to impose a curvature on a cross section. The curvature is transformed into strains at all panels. The load shortening curves give the relation between strain and stress. The resulting stresses are integrated giving the bending moments at that curvature.

Several programs are available to calculate the bending moment versus curvature. Two programmes that use analytical formulations to calculated the load shortening curves are ULSTR [6] and TRAQUE [7]. The influence of initial imperfection and residual stresses is accounted for. The influence of the reduction of the effective breadth of the plating is taken into account by formulas as derived by Faulkner [8].

ULSTR has the small problem that the direction of the curvature is fixed. In case of unsymmetrical sections, as is the case in damaged condition, the direction of the bending moment is different from the curvature. TRAQUE is able to generate the curvature which will result in the bending moment in the specified direction.

FABSTRAN [5] generates load shortening curves using a non linear 2-D beam analysis. A separate programme integrates these load shortening curves, for each different panel geometry one is to calculate, into cross section bending moments as functions of curvature. Although this method is more time consuming, it gives a better description of the post buckling behaviour.

4.3 3-D FEM analysis

The basic assumption in slender beam analysis, i.e. plane sections remain plane during loading, is not always valid. Moreover parts of the cross section may be less effective than assumed in the 2-D slender beam analysis.
In case of damage to a part of the cross section, both assumptions will not be true because the damage is small relative to the length of the ship. Therefore linear 3-D analysis is needed to check at least the validity of the 2-D analysis. A linear 3-D analysis may include the effects of a ruptured structure, i.e. elements removed from the mesh, and deformed structure, i.e. reduced stiffness.

In obtaining the ultimate bending moment, the same problem as in the 2-D case will be encountered. In general curvature will be prescribed, as this will allow analysis of the post collapse state. At each increment of the curvature an iteration to establish the direction of the curvature has to be performed in order to get the bending moment oriented in the required direction.

5. NUMERICAL RESULTS

To show both the effect of damage on the capacity of the hull and to compare the results of different models and methods, the midship section of replenishment ship Hr. Ms. Zuiderkruis, is modelled. Figure 5.1 gives the cross section, figure 5.2 the 3-D MAESTRO [9] model including the assumed damage. The panels are stiffened longitudinally, except for the sides and longitudinal bulkhead between bottom and H-deck which are stiffened transversely.

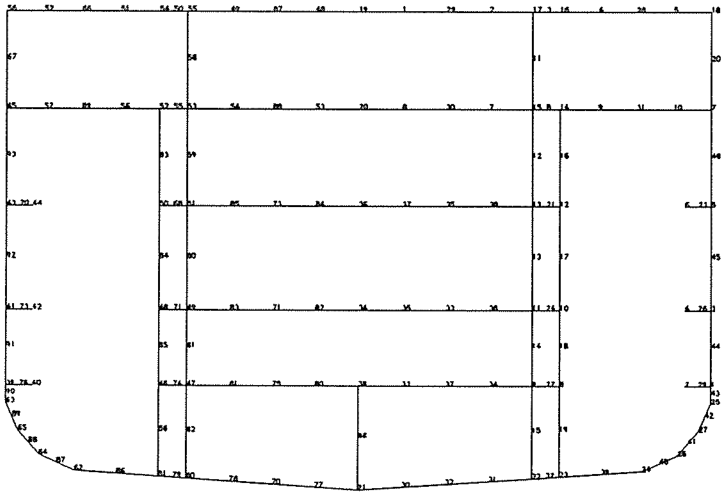

Figure 5.1 Cross section Hr.Ms. Zuiderkruis

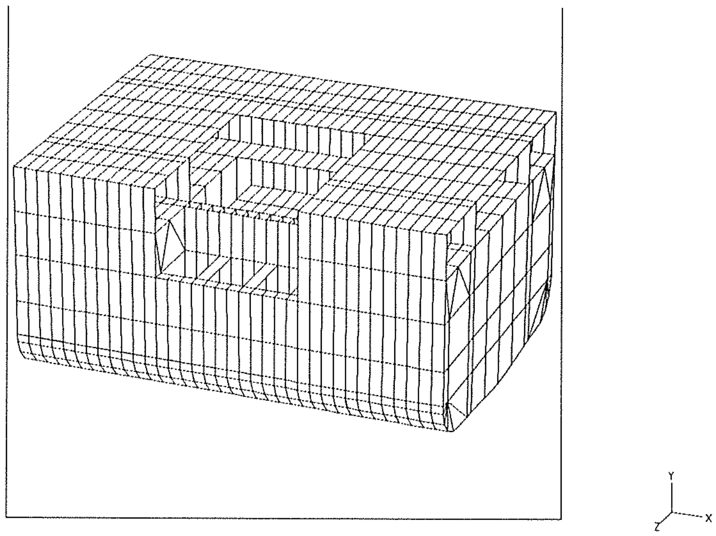

Figure 5.2 the 3-D MAESTRO model

5.1 Stress results

The stresses due to the wave bending moments will increase in the damaged condition. Figure 5.3 shows the calculated stresses on the girth of the ship in intact and damaged condition. The maximum stress, based on mid element results, will increase to 2.5 times the intact value using the 3-D results. As a result the fatigue life, when loading profile and still water bending moment are kept constant, will decrease to only 6% of the original structure.

As already mentioned, the 2-D models have limited accuracy if the extend of the damage is small in relation to the length of the ship. Figure 5.3 shows that the stresses in the deck panel are underestimated by 20% compared to the 3-D analysis. The fatigue life using 2-D results, leads to an overestimation of the fatigue life by a factor 1.7. As the required life time, after damage has occurred, is limited, errors in stresses may not be significant.

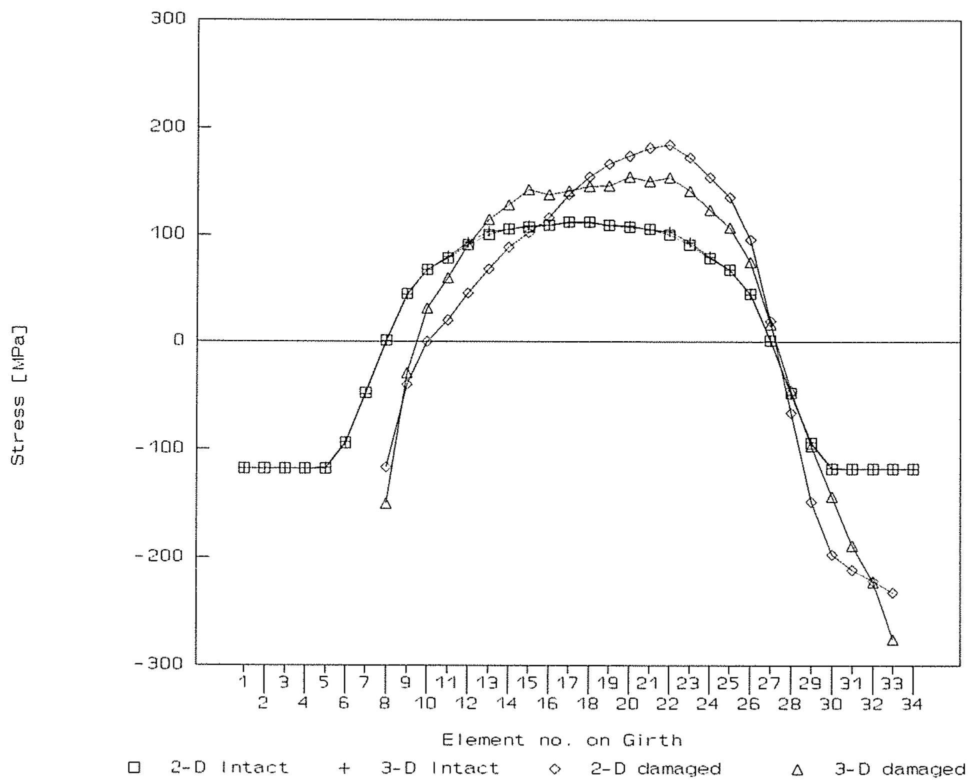

Figure 5.3 Comparison of 2-D, 3-D calculation

The influence of the way damage is modelled, as ruptured and therefore completely ineffective or deformed, is shown in figure 5.4. The maximum stress in case the damaged structure is modelled as highly deformed panels, is much less than the in ruptured case : 1.5 times the intact value instead of 2.5. These stress results show that assuming damaged structure to be completely ineffective, can be rather conservative. In most cases a blast will result in an combination of completely ineffective structure and highly deformed structure resulting in stresses which will be enclosed between the two curves.

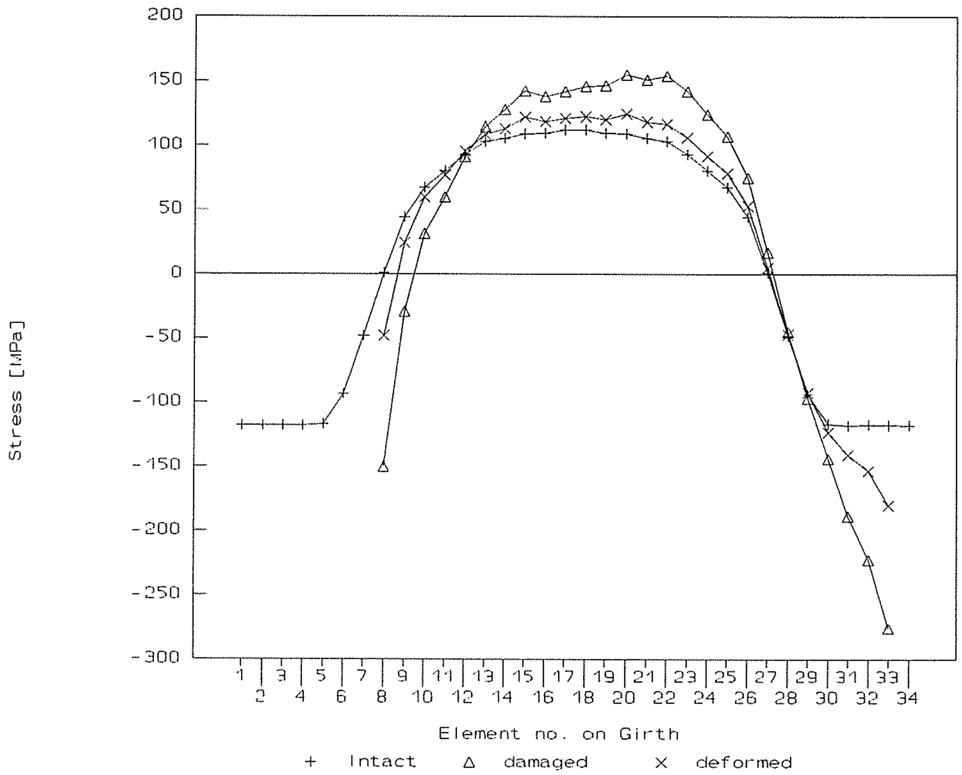

Figure 5.4 Calculation Vertical Bending

5.2 Ultimate Strength

The ultimate strength of the intact and damaged structures are calculated using 2-D models only. The damaged area is modelled as completely ineffective. Figure 5.5 gives the vertical bending moment versus vertical curvature as calculated with ULSTR, a completely analytical formulation, and FABSTRAN, and 2-D finite element beam analysis for separate panels. It should be noted that in the damaged condition the vertical curvature will lead to vertical and horizontal bending moments.

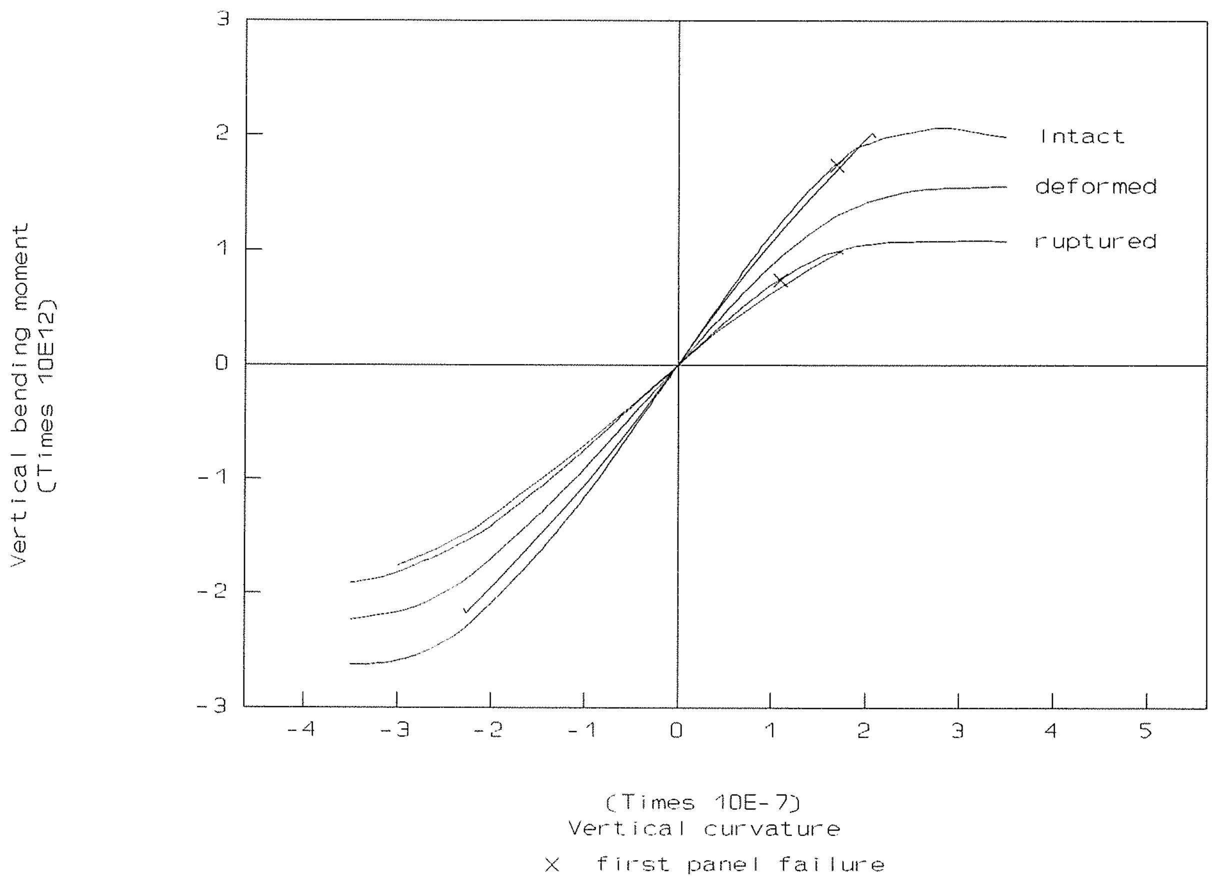

Figure 5.5 Ultimate vertical bending moment

In sagging condition the agreement between the two programmes with respect to the ultimate moment is satisfactory. However, the analytical programme is not able to calculate the capacity after the G-deck panels have failed. In hogging condition this leads to an underestimation of the ultimate load. As deadrise is present in the bottom, after failure of the two centerline panels the load will be transferred to the adjacent panels. The analytical solution has problems doing so.

Figure 5.5 shows the influence of the way the damage is modelled. In the worst case all affected panels are assumed to be ruptured. If all affected panels are modelled as highly deformed, the calculated ultimate bending moment increases by 40% relative to the worst case. As degradation of the panel is a function of the distance to the origin of the blast, the real capacity of the damaged cross section will between these two extremes.

Figure 5.5 also shows the point at which the first deck panel will fail according to the 3-D MAESTRO calculation, if the cross section is loaded with a sagging vertical bending moment. In the intact case the ultimate moment is underestimated by 20%, in the worst damage case by 35%. The conclusion therefore is that a linear 3-D analysis is inadequate if a reasonable estimate of the ultimate moment is needed and the 2-D slenderbeam models are preferred, despite the limited accuracy with respect to stresses.

6. ENHANCEMENTS

The results indicate that damage will reduce the ultimate strength to about 50% of the intact value. In general the still water bending moment of a navy ship is relatively small compared to the wave bending moments in intact condition. In damaged condition the loading condition may greatly change due to flooding or by waste water of fire fighting. This may lead to a very small capacity to carry sealoads. In case of merchant ships the still water bending moment is relatively large. Immediate failure of the hull girder may occur even in still water. If an ship is to survive significant damage, damage tolerant design is required.

Damage tolerant design can be achieved in several ways. In the first place damage tolerance can be achieved by optimizing the structure taking into account possible damage without altering cross sectional area. In case of the Hr.Ms. Zuiderkruis the side hull and longitudinal bulkheads are transversely stiffened because in intact condition the loading of these panels is low. Changing the stiffener arrangement in these part of the structure, the ultimate strength is increased by 20%. With respect to the intact loading condition, these parts of the structure will be redundant.
In the case of frigates transversely framed panels are not used very often. Optimizing the structure within the same structural weight by changing stiffening direction is therefore not possible. Additional strengthening of the structure is needed. In this case a balance must be found between an acceptable probability of failure which is a function of residual strength and loading, and the weight increase involved.
Figure 6.1 gives a very simplified example of the problems. The residual strength is assumed to be uniformly distributed between the initial strength and the strength in case of maximum damage. The figure shows the probability of failure as a function of the ratio of residual strength and demand (L/D), for different levels of initial strength ratio (M/D). The figure shows that increasing the initial strength ratio (M/D) reduces the probability of failure at the same residual strength level. The main problem in this method is to derive realistic probability functions for the capacity in damaged conditions. The shape of the distribution has to be established as well as the parameters.
Moreover it may be assumed that in damaged condition the demand is reduced by change of heading and reduction of speed. In present-day design a generic damage case and seastate is specified in which the structure must survive.

The vulnerability engineer has several methods at his disposal to achieve this goal. The designer may plan to limit the extent of damage, to protect and to harden key-systems,

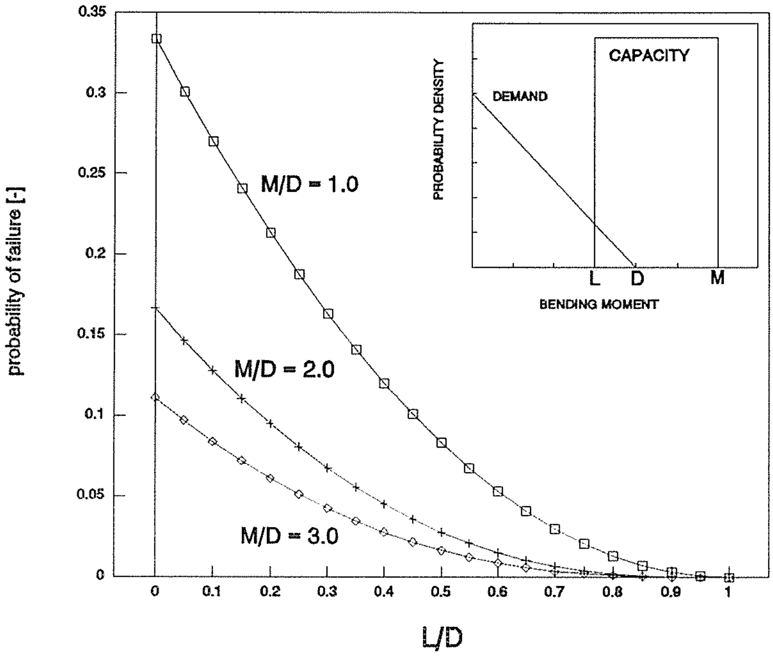

Figure 6.1 Probability of failure

arrange systems in a clever way or make them redundant. All in order to lower the impact of a hit on the ship as a system. Although useful for optimizing the survivability of the ship, there is no point in taking all these measures, if the conditions are not met for the carrier of all these systems; the hull. For this reason the design philosophy of the vulnerability engineer must be; firstly to remain afloat, secondly keep mobile and finally continue fighting.

The most effective way to provide sufficient survivability, is an increase of strength for the damaged situation (L) with little or no increase for the intact situation (M) in order to keep weight penalties low. This can be achieved by rearranging structural material and/or changing the steel quality. Since the fatigue life after damage is limited to one week (~ 50,000 cycles), high stresses are allowable in the remaining effective structure. But increasing the yield stress without changing the geometry (spacing, stiffener and plate thickness) brings little advantage as the ratio of ultimate stress and yield stress will decrease.

Rearrangement of material offers several advantages. If the deck plating is concentrated near the shear strake, the resulting thickness will bring the buckling stress up to yield level. The location of the material far from the centre line also increases the section modulus for horizontal bending thus reducing the stresses for that load direction, which can be substantial in case of list after damage. The new German frigates of the "Brandenburg" class adapt that idea. Structure of high buckling strength, forming box girders, provide a high ultimate bending moment for intact and for damaged situations. These box girders show sufficient load carrying capacity even if their support from the adjacent bulkheads gets lost by damage. Their plate thickness offers resistance against blast and fragment damage so that no degradation of performance will result from weapon effects. The plating between the box girders are kept as thin as possible and practical. In principle, this idea is applicable also for resistance to underwater explosions effects but the weight penalty seems to be prohibitive.

Bulkheads are also structural members of primary importance. They create subdivision but also form the support for longitudinal structural members. Therefore blast resistant bulkheads do not only provide damage containment within the directly hit compartment, but also ensure that the longitudinal members, the box girders, are supported after damage.

The proposed solutions are also capable to merchant ships where explosion damage can also cause serious consequences. Possibly the risk assessment in these areas will prefer conventional solution by reason of the company's economy.

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