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COMMITTEE V.1

DAMAGE ASSESSMENT AFTER ACCIDENTAL EVENTS

COMMITTEE MANDATE

Concern for the extent of damage and local and global residual strength of ship structures, after accidental events. Such damage is to be the result from small and large energy events such as wave impact, green water, slamming, dropped and impacting objects, local overload, collision, grounding, explosions, fire and similar. The assessment shall be conducted in both the absence and presence of ageing effects such as fatigue cracks, corrosion and local dents. The assessment shall also include the effects of temporary repairs and mitigating actions following the damage.

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KEYWORDS

Residual Strength, Accidental Damages, Collision, Grounding, Fire, Explosions, Recovery, Salvage, In-Service Repair, Emergency Repairs.

CONTENTS

1. INTRODUCTION

This paper contains the report of the Committee, which is a new one that was created to deal with the methods to assess damage and residual strength after accidental events. The name of the committee, being a short one may give a wrong impression about its scope as it mentions damage assessment while the mandate refers that there should be concern for the extent of damage and local and global residual strength of ship structures, after accidental events. Therefore the contents of the report deal also with methods to determine local and global residual strength, including the specification of the appropriate loads.

It starts by providing a description of the type of damages that can be found in the various accidental events. Representative scenarios are described and the typical damages that results from the specific accidents are indicated. Next section describes how in real situations the damaged state is perceived. Thus, inspection methods are described as well as the available approaches to derive information about the status of the structure from indirect measurements.

Loads on the structure are treated afterwards, including the loads that are generated during the accidental situation itself and also after the accident when the ship is in damaged state, often listed and with non symmetric sections. The loads are used to determine ship strength using the assessment methods described in section 5, which deals with various types of components.

If the ship is considered not having enough strength for temporary voyage to repair yard local repairs are necessary. Otherwise she will travel to a repair shipyard and be repaired there. The various types of problems raised in repair are dealt with in the following section.

Finally last section deals with salvage and recovery strategies which are necessary in the cases of very large damage in ships.

2. DESCRIPTION OF DAMAGES

2.1 General description of damages

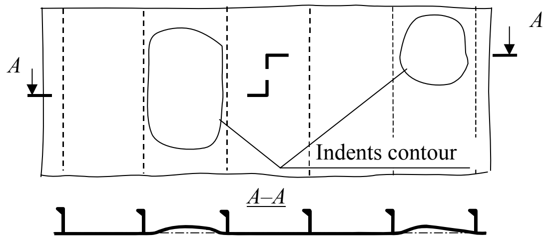
According to Konopelko (1990), damages to the hull occur in 53% of ships' accidents. On average, each ship of the world fleet suffers hull damage once in 10 years with two ships out of one hundred damaged ships being lost. More updated statistics on ship losses can be found in Guedes Soares and Teixeira (2001).

A great variety of incidents exist, such as collisions, grounding, explosions and fires, severe storms, etc. Therefore, a great variety of hull structure damages exist as well. An example of classification of hull damages after collision is given in Table 1, related to MV "Mozdok" (Egorov, 2006a).

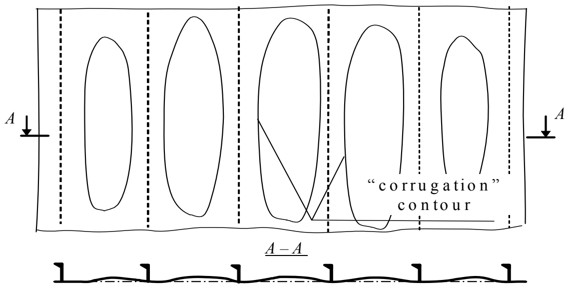
Besides holes, there are many damages of the hull that can be identified, such as rupture of elements (infringement of integrity of a hull structure element due to exhaustion of its plastic deformation limit), cracks (infringement of integrity of a hull structure element due to fatigue) or one-time overload in area of indents or bulges resulting from buckling, as well as different kinds of deformations that are observed after accident (Egorov 2007).

The following types of residual deformations can be defined (see Fig. 1): indentions (local plate permanent deflection in some areas between stiffeners); corrugation (permanent deflections of several adjacent areas of plate between stiffeners); dents (local permanent deflection of a panel, which includes the plate and supporting stiffeners); bulge (permanent deflection of the stiffener‘s web plate or the stiffener’s attached plate).

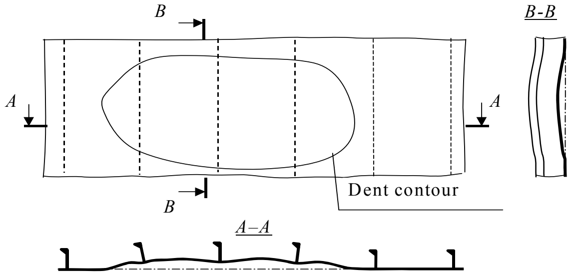
Indention



Corrugation



Dent



Bulge

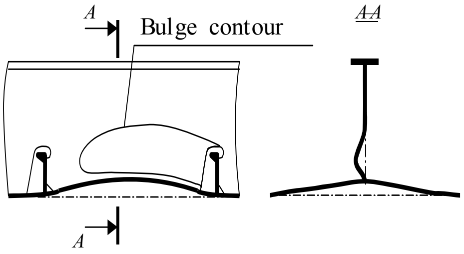


Figure 1: Types of permanent deformations

Table 1
Classification of incidents' damages of vessel's structures influencing the hull strength

Type of hull damage	Example on MV "Mozdok"
Holes in elements of the midship	1. A hole in starboard (StB), Fr. 92-106 (hold No 3), area 35 m^2, length 7 m, height 5,5 m. 2. A hole in a lower deck of hold No 3, width 1-2 m, length 6 m.
Rupture of longitudinals and plates	1. Carlings of forecastle deck have ruptures through the whole height 2. Rupture of forward transverse coaming-carling from StB forecastle deck. 3. Top plate of StB coaming on the main deck in the area of hold No 1 has a rupture through the whole width. 4. Top plate of StB coaming on the main deck in area Fr. 136 (hold No 2) has a rupture through the whole width. 5. Longitudinal stiffeners of main deck in area Fr. 96-97 (hold No. 3) breaks through the whole height. 6. Rupture of forecastle deck in area of coaming bracket debonding.
Cracks in shell and framing	1. A crack of longitudinal coaming in StB on the forecastle deck with length 1200 mm and 45 mm opening at coaming. 2. A crack in StB carling on forecastle deck with length of 150 mm and opening of 3 mm.
Out-of-plane deflection of longitudinal Girders, deformation and buckling of longitudinals	1. StB coaming on forecastle deck inclined toward the hatch opening by 40 degrees, the top edge has left the vertical plane by 700 mm. 2. Portside (PtS) coaming on forecastle deck unwrapped inside of the hatch by 10 degrees, the top edge has left the vertical plane by 110 mm. 3. The top edge of the main deck StB coaming in the area of hold No. 2 left the vertical plane by 600 mm while the coaming has inclined toward the hatch opening by 40 degrees. 4. The top edge of the main deck StB coaming in area of hold 2 has left the vertical plane by 110 mm while the coaming has inclined toward the hatch opening by 10 degrees.
General deformations of grillages	1. The forecastle deck received significant permanent deformations inside the tweendeck; the maximal deflection is up to 200 mm. 2. The main deck has received significant permanent deformations inside the tweendeck; the maximal deflection is up to 200 mm (hold No 2). 3. The main deck of hold No 3 is deformed in area of the damage hole, the maximal deflection is up to 300 mm.

Deformation and buckling of brackets and stiffeners of longitudinals	1. Brackets of forecastle deck StB coaming torn off the deck. 2. Brackets of the main deck StB coaming of hold No 2 torn off the deck.
Deformation and buckling of transverses	1. Aft transverse coaming on forecastle deck from StB was deformed inside of the hatch up to 225 mm. 2. In the upper tweendeck of hold No1, the web plates of all reinforced beams are deformed, the beams' brackets have buckled; the bulges are up to 180 mm in depth. In the same place, the brackets of all ordinary frames have buckled. 3. In the lower tweendeck of hold No1, the brackets of reinforced beams on StB have buckled. 4. Forward transverse coaming on the main deck on StB was deformed toward the hatch opening (hold No 2). 5. In the tweendeck of hold No 2 the brackets of the StB reinforced side frames have buckled; bulges up to 200 mm. 6. The reinforced side frame 99 StB in the tweendeck is completely destroyed.
Damages of transverse bulkheads	1. Webs' flange of the forepeak bulkhead is deformed in places where the longitudinal deck girders are connected to webs. 2. A hole in transverse bulkhead Fr. 99 StB with area up to 4 m^2.

The assessment of the effect of incidents on the hull structure strength and ship survivability is based on the damage dimensions, i.e, length, height, depth. The assessment of the effect of changed external loads on the hull structure is based on data for the wind and wave conditions during the incident and the distance to a place of refuge, which determines the greatest possible wave load. Therefore, statistical data for damages resulting from incidents is necessary both in the design stage and in the process of developing operative methods to save the ship.

Until now, the Classification Societies' requirements for damaged vessel survival regulate their trim and stability (bulk carriers, tankers, chemical tankers, gas carriers, passenger vessels, and also dry-cargo vessels with length greater than 80 m; for other types only if the damage dimensions are significant). For damage stability calculations of sea-going ships at design stage, the length of the hole ℓ is taken as a function of the ship's length (see Table 2). For ships with a length smaller than 100 m, the design lengths of the holes and the available statistical data are very close. For oil tankers, chemical tankers and gas carriers the design and statistical data are close for lengths up to 200 m. For vessels of greater length, the SOLAS and MARPOL requirement are lagging behind the average statistical data.

The Classification Societies' Rules recommend accepting the holes height, h, equal to the ship's depth; for grounding of gas carriers' $h = B_1/15 \le 2$ m, for oil tankers and chemical tankers $h = B_1/15 \le 6$ m.

The available statistical data show that the normative dimensions (see Table 3) are not improbably large. However, on repeated occasions, these normative values have been substantially exceeded (see Egorov, 2006b):

- Passenger ship "Andrea Doria" has been rammed up to the CL;
- Ferry "Queen Victoria" has received as a result of collision a hole depth up to 0,4B,

where B is the ship's breadth;

- The MV "Meiku Maru" has been cut in two;
- During collision in 1965 of the dry-cargo ship "Andulo" with a supertanker the former has developed a hole depth up to 2/3 B;

Table 2
Design and statistical length of damages

Reference	Type of vessel	Length of hole
SOLAS	Passenger vessel for international voyages and vessels	$\ell = 0{,}03L_s + 3 \le 11$ m , where L_s– minimum length of a part of the vessel located of below limiting line of immersion
MARPOL	Oil tanker, chemical tankers and gas carriers; all other ships types	$\ell = 1/3\,L_1^{2/3} \le 14{,}5$ m, where L_1 – 96% of waterline length measured at height, equal to 85 % of the minimum theoretical ship's depth, or the length from the forward stem's edge up to the rudder axis on the same waterline if this length is greater than the former
MARPOL	Bottom holes in gas carriers, oil tankers and chemical tankers	$\ell = 1/3\,L_1^{2/3} \le 14{,}5$ m (in area 0, ... $0{,}6L_1$) $\ell = 1/3\,L_1^{2/3} \le 5$ m (in area 0.3,.... $1{,}0L_1$)
MARPOL	Rupture of bottom shell of oil tankers 75000 DWT and greater	$0{,}6L_1$ from forward perpendicular
MARPOL	Rupture of bottom shell of oil tankers from 20000 to 75000 DWT	$0{,}4L_1$ from forward perpendicular
Russian Maritime Register of Shipping	Ice damage (vessels with high ice category)	$\ell = 0{,}045L_л$m, (in area 0, ... , $0{,}4L_л$) and $\ell = 0{,}015L_л$m, (in other areas), where $L_л$– Length of a vessel at maximal draught at which the requirements for the corresponding ice category will be executed
Yuniter (1973)	391 collisions, 124 groundings, (81 loss of vessels)	$\ell = 0{,}0585L + 1{,}25$
Yuniter (1973)	312 collisions	ℓ = 4,38 for L < 100 m, ℓ = 9,97 for $L \ge$ 100 m.
Yuniter (1973)	245 collisions	ℓ = 4,38 for L < 100 m, ℓ = 9,97 for $L \ge$ 100 m.
Yuniter (1973)	77 grounding	ℓ = 2,23 for L < 100 m, ℓ = 4,61 for $L \ge$ 100 m.
Alexandrov (1983)	Collisions	$\bar{\ell}$ = 7,3
Alexandrov (1983)	Grounding	$\bar{\ell}$ = 7,8
Gavrilov (1978)	Groundings with bottom plate damage (28 USA tankers)	$\ell = 51{,}4$ (taking into account all damages – dents, cracks, etc.)
Alexandrov (1983)	Collisions and groundings (554 cases)	$\bar{\ell}$ = 3,89 (L = 30,...,70 m) $\bar{\ell}$ = 8,02 (L = 70,...,130 m) $\bar{\ell}$ = 3,89 ($L \ge$ 130 m) $\bar{\ell}$ = 1,640 + 0,0544L

- Due to explosion in 1969 on the tanker "Maktra", the depth of damage had reached 21 m. (44% of breadth);
- Due to explosion in 1969 on “Kong Xookon VII ", the hull had been damaged through the whole breadth ($b \approx B$);
- During collision with another vessel in 1971, the aft part of MV "Shavit" was almost separated from other hull and kept only on a starboard side shell;
- In 1970, the tanker "Yugansk", after a collision with the floating plant "Menzhinskiy", had received a hole depth up to 0,4 B;
- In 1972, the dry-cargo ship "Republika de Columbia", as a result of collision, had developed a hole depth up to 1/2 B;
- In 1990, the dry-cargo ship "A.Kizhevatov", as a result of collision, had developed a hole depth up to 1/2 B.

Table 3

Holes’ depth – design dimensions and assessment

Reference	**Type of damage**	**Length of hole**
SOLAS	Side shell damages at collisions	$b = 1/5B_1$ m, where B_1 – maximum theoretical ships’ breadth measured on the middle of its length at a level or is lower than the highest LWL of vessel subdivision into compartments
MARPOL	Bottom damages of oil and chemical tankers	$b = B_1/15 < 6{,}0$ m
MARPOL	Bottom damages of gas carriers	$b = B_1/15 < 2{,}0$ m
Russian Maritime Register of Shipping	Damages at contacts – stationary vessels, chemical tankers, supply vessels, vessels with high ice category	$b = 0{,}76$ m
Alexandrov (1983)	Collisions and groundings	$b = 0{,}028L - 0{,}13$

According to Aleksandrov (1983), a hole of outer and inner bottom occurs in 85% of grounding cases and is located below the operational waterline in 96 % of cases (for collisions, the latter figure is about 80 %). Similar data are given by Yuniter (1973) noting that the hole of the outer and inner bottom is located below the operational waterline in 85,7 % of grounding cases.

It is not necessarily in all incidents that the damages cover the whole ship’s depth although there are cases when it happens. For example, the loss of the "Andrea Doria" after collision (i.e., h = H), where H – ship’s depth; the MV "Meiku Maru" is cut in two; the hole of tanker "Lutsk" after collision (i.e., h = H), etc.

Gavrilov (1978) provides data for the consequences of the grounding of 28 USA tankers during the period 1969 – 1972 where the average depth of the damage is given as 0,63 m. For tankers with deadweight smaller than 3000 DWT, the average depth of the damage is 0,39 m. For vessels with deadweight greater than 10000 DWT - 0,77 m. In 90 % of all incidents, the depth of the damage was less than B/15. Based on these data, the standard value of the depth of damage resulting from contact or rupture was determined as 0,76 m.

The areas of holes are rather great. If their mean value (Aleksandrov, 1983) is described by the function $S = 0{,}144L – 2{,}72\ m^2$, it will correspond to a value of 22 m^2 for L = 160 m but in some cases this value could be much greater. For example, the area of a hole of the dry-cargo ship “Moon Dok" (L = 160 m) generated in the collision with the tanker "Dubna" was equal to 135 m^2; in another case the ore carrier "Smederevo" had a hole with an area of 250 m^2.

It is necessary to take into account that the holes are not the only damage of the hull as a result of grounding, collisions or explosions. According to Aleksandrov (1983) the ratio between the hole’s area and the whole area of damage is around 0.127 although in the calculations the value of 0.5 is proposed.

The available statistics of hull damages confirms these conclusions. In reality the hole occupies a rather small space in comparison with the zone of damage - cracks, ruptures and deformations of plates and framing. It is necessary to note that the functioning of longitudinals in this zone changes substantially. These changes are caused by the loss of their cross-sectional area, reduction of the attached plates, tripping of stiffeners and large permanent deformations, change of the support of the main supporting members, and buckling. There is also the so-called "shadow" effect of the damaged area, i.e. as a result of the damage, a zone exists of physically intact longitudinals, which do not participate or only partly participate in hull girder bending in cases of large permanent deformations, destruction of the side structure reinforced transverses , transverse bulkheads leading to reduction of the hull girder strength.

Thus, in general, according to the statistical data, the holes dimensions used in the standard calculations are close enough to their mean values, which allow for the recommendation of these dimensions for strength calculations of damaged ships at design stage.

Based on the statistics for actual damage dimensions and the increase of still water loads resulting from the intake sea water, it is possible to unequivocally assert that it is necessary to consider essential reduction of the overall hull girder strength resulting from ship’s incidents, see Egorov (2007):

1. Increase of the still water loads can occur in collisions with vessels and other objects; grounding, explosion; during salvage operations – anti heeling, unloading before removal from ground or during fire extinguishing.
2. Increase of the still water loads can occur not only in collisions or other reasons (flooding of the supertanker "Marpessa", etc.), but also during removal from a grounding incident by unloading (10 % - 15 % from the initial displacement).
3. Change of loading can occur by virtue of properties of the cargo in the flooded compartment – oil spill, dissolution of raw sugar, etc.

Besides still water loads, the wave loads play a significant role in the ship's survival. Using the detailed analysis of ships' incidents of the Norwegian fleet for 1970-78 and of the Japanese fleet for 1965-74, Alexandrov (1983) noted that the greatest number of failures occurs in calm and moderate weather with weak wind and a condition of the sea from quiet to average. Yuniter (1973) also notes that failures usually occur at rather favorable condition of the sea (a wave and a wind less than 5 Beaufort scale), which usually allows to neglect the wave load during salvage operations.

However, such conclusions can be made only for cases that did not end with ship's loss. If one considers only accidents of sea-going ships, the importance of weather conditions increases. So, according to Lloyd's Register (1988), in 1987, of 43 ships lost due to groundings, 18 ships were lost during a storm.

According to Yuniter (1973), only 14,5 % of all incidents occur in high seas; the others occur in ports, channels, rivers and in a coastal 12-mile zone, i.e. in areas of intensive navigation. Certainly, groundings occur only on shoreline. However, collisions with vessels and other floating objects occur rather frequently in high sea. For example, 9 from 31 cases in 1987 have taken place there. Thus, as noted by Yudovich (1972), in high sea, when the ships' speed is high, the results of collisions are most catastrophic.

In damage statistics, the subsequent towing of the damaged ship to the nearest port of refuge, and then - to a place of repair is not taken into account at all. For example, tanker "Exxon Valdez", grounded on a reef at the Alaskan coast, after removal, had been towed to the San Diego port (distance of 2200 miles). The ore carrier "Smederevo", after receiving a hole at Chilean coast, had been towed to Far East (distance of 10 thousand miles), which required calculations of the damaged ship's strength considering the effect of wave loads in the heaviest stationary seaway during the voyage from the place of incident to the place of a refuge (see Egorov and Kozlyakov, 2004).

Due to hull damages, a number of events occur leading to reduction of the hull girder strength (see Egorov, 2007) such as: loss of longitudinals, asymmetric bending, warping and stress concentrations. The hull girder strength is preserved for ships with small damages in stormy weather; ships with substantial damages but not exposed to wave loads; and in cases when the ship's crew and the salvage company actively and consistently fight for the ships' survival.

2.2 Damages due to ship collisions

2.2.1 Ship collision scenarios

The determination of the damage of a ship involved in a specific collision comprises the definition of the "loading" during the collision incident and the application of an acceptable method to calculate the structural response. In such a case the "loading" should be described by a set of input parameters rather than solely from the force, which is applied on the impacted structure and depends, among other factors, on the relative stiffness of the structures that collide. In particular, the description of the loading on a ship involved in a ship-ship collision includes the speed of the colliding ships, collision geometry. i.e. striking location, impact angle, relative orientation between striking and struck vessels, loading conditions - full load and ballast conditions are usually considered - draft, trim, bow shape, ship hull and striking bow structural arrangement, sea conditions, wind and current, and ship maintenance level. Human response may also affect the consequences, in particular the possibility of occurrence and the details of the scenario itself.

The values of these parameters, which define the collision scenario, may be taken as those that would have the most unfavourable consequences, or those that have a pre-defined level of occurrence. A more delicate approach could consider the probability density function of each parameter and finally calculate the risk of the colliding ship. In any case the hypothetical scenarios should represent situations that are as close as possible to those encountered in reality. Collision scenarios between ships and marine structures have been addressed in ISSC committee reports on Collision and Grounding of 2003 (Paik *et al* 2003, Paik 2006) and (Wang *et al* 2006).

Samuelides *et al* (2008) investigated ship to ship collision scenarios that are included in existing rules and regulations or have been applied in the design process of a ship, and present data concerning the distributions of the kinetic energies of ships travelling worldwide and examples of use of these distributions for the prediction of the energies that are available to cause structural damage in particular collision cases. The authors further include quantitative examples of the "loading" according to rules and regulations or derived from the energy distributions, which is to be used in the design process of a ship.

Design against collision has been an issue since the design of nuclear powered vessel "Savannah". At that time it was decided to design her collision protection, in a way to withstand a collision with a T2 tanker at full load, i.e. a ship having a displacement of 23000 tons, and a full design speed of 15 knots (Dodd and MacDonald, 1960). The decision took into account a survey of the world's merchant fleet and the distribution of the maximum kinetic energy based on full load displacement and the design sea speed. The survey revealed that at that time the number of ships having a kinetic energy greater than 2.6×10^6 tons-knots^2 (approximately 671MJ), which corresponds to the energy of the selected striking ship, falls off rapidly. The calculation of the damage of the target ship as well as the bow of the striking ship was performed using the formula of Minorsky (1959). In order to use the pioneering formula, it was necessary to use as input parameter the entrance angle of the striking bow, which was taken equal to 57.2 deg., and the vertical relevant position of the two ships. The latter was selected so as to result in the most unfavourable situation. The analysis showed that the nuclear vessel could withstand the collision with the T2 tanker travelling with 15 knots without damage of the reactor compartment. The volume of the damaged material outside the this space was calculated equal to 2,89 $m^2 \cdot cm$ for the target and 2,46 $m^2 \cdot cm$ for the striking vessel respectively.

A design approach similar to that followed in the case of Savannah, has been adopted for the collision protection of the First Nuclear Ship of Japan (FNSJ) (Ando, 1969). An investigation to assess her performance in case she is involved in a ship-ship collision aimed in the calculation of the critical speeds of 15 striking vessels versus her navigation speeds. The 15 ships had displacements varying from 6,360 tons to 239,000 tons and navigation speeds varying from 15 knots to 20.8 knots. The analysis showed that in some cases the navigation speed of the striking ship was higher than the critical speed, but it was claimed that the most probable percentage of the world fleet capable of penetrating the reactor compartment of the FNSJ was 0.7%. It was further noted that as low speeds are used in harbours, a collision resulting to rupture in a harbour area is practically impossible.

Later Woisin (1979) designed the collision protection barrier of Otto Hahn on the basis of a series of large scale collision tests.The striking bows selected for the tests were the models of bows of existing ships and the impact speed corresponded to their service speed.

The above mentioned procedures that have been followed for the design of nuclear powered vessels, took into consideration the world merchant fleet at the time of design of the vessels, and the collision scenarios that were considered were those that could potentially release relative large amount of energies. However, the absolute amounts of energy are not large, in comparison to the energies that may be released today in case of a ship-ship collision, because both the size of the vessels and their speed has been increased considerably.

Almost thirty five years after the construction of Savannah, the Ministry of Transport of Japan published in 1995 an official notice, KAISA No. 520 that specifies that ships carrying irradiated fuel must have a structure that can resist a collision with a T2 tanker travelling at full speed (Kitamura and Endo, 2000), namely it re-iterates the collision scenario used for the design and construction of Savannah, although the composition of the world fleet looks is different from that in the 50ies and 60ies. According to the regulation the collision between a 7,000 tonnes double hull target vessel, which is typical for transportation of the fuel between Europe and Japan, and the T2 tanker would release an amount of energy, which equals to 206 MJ. This amount will be available to cause structural damage and will be partitioned in case of a collision, between the energy that will cause damage to the side structure and the energy that will deform the bow of the striking vessel.

In an information Paper on Formal Safety Assessment on crude oil tankers, submitted to IMO by Denmark, (IMO, 2008), the Table 4 is included which specifies typical damage penetrations and their associated probability of occurrence. The figures are based on damage statistics. No collision energies are associated to these damages.

Table 4
Penetration Depths and Probabilities For Crude Carriers (IMO, 2008)

Probability damage will lie entirely below the tank, Regulation 23				
Ref. Ships	Z_{DB} (m)	Ds (m)	z/D_s	$P(z<Z_{DB})$
PANAMAX	2.04	19.80	0.1030	0.783
AFRAMAX	2.30	21.00	0.1095	0.784
SUEZMAX	2.80	23.10	0.1212	0.803
VLCC	3.00	31.50	0.0960	0.776
			Average P (z<Z)	0.78

2.2.2 Classification guidelines for design against collision

Germanischer Lloyd (2004) was the first Classification Society to the authors' knowledge, which introduced non-compulsory rules concerning strengthening against collisions. In accordance with those, a notation COLL followed by a number 1 to 6, is added to the class of the ship, reflecting her behaviour when involved in a collision, relative to the behaviour to a single hull ship that has no particular design to resist collision with ice or other object. The determination of the notation is based on two quantities. One is the critical speed of the striking vessel. The other is the ratio of the "critical energy", i.e. the structural energy absorbed by the structure of the ship under consideration before occurrence of unacceptable damage to her hull, to the critical energy absorbed by the un-strengthened ship. COLL3 indicates, for example, that the structure of the double hull tanker under consideration may absorb 4 to 6 times more energy before rupture of the skin of her tank rather than a single hull tanker, and additionally the critical speed of the striking vessel is at least 2.5 knots. The respective values for COLL2 are 3 to 4 and 1.5 knots.

In order to evaluate these quantities the ship in question is tested in eight collision cases, all with a ship of roughly the same displacement, but with various draught combinations of the striking and struck vessels. The bow of the striking ship is assumed to have a bulb in four cases and no bulb in the rest. If these provisions are applied for the collision analysis of a 275 m long Suezmax tanker having a maximum draught of 17 m and a ballast draught of 9 m, then the difference of the draughts between the striking and the struck vessels will be ±2 m and ±6 m. Zhang *et al* (2004) used the scenarios prescribed in the regulations and a FE code to investigate the collision behaviour of an ice-strengthened 90 m long multi purpose cargo ship, and found that after investigation of the prescribed collision cases, 8 in total, the average energy absorption capacity for her ice strengthened side shell before penetration of the inner hull is 21 MJ, which corresponds to a central and right angle collision with a ship of same size travelling with a speed of 7 knots.

More recently Egge *et al* (2007) reported a combination of a method to assess the collision behaviour on one hand and the SOLAS requirements for probabilistic damage stability of the other. According to the analysis the strengthening of the side shell to withstand collision could increase the attained subdivision index. Consequently, it could be possible to reduce the wing tank width of a tanker or to increase the allowable KG.

The DNV rules for Compressed Natural Gas (CNG) carriers (Dnv, 2004) include a special section for collision damage analysis. A collision frequency analysis is required to be conducted for new projects, for a characteristic vessel trade. The analysis is to determine the annual collision frequency and associated collision energies of striking vessels, based on vessel sizes, types and speeds and determined from traffic data for the selected trade. If applicable, traffic data for the actual trade is not available, or no specific trade rather than world-wide trading is planned, relevant traffic data for North Sea trading acceptable to the Society may be used. Collision damage analysis is required to demonstrate that for the ship sizes and energies determined by the analysis, the energy absorption capability of the ship side shall be sufficient to prevent the bow of the striking vessel from penetrating the inner hull, thus not damaging the cargo tanks. For the purpose of the calculations it may conservatively be assumed that all the collision energy will be absorbed by the struck ship side and that the collision is right angle and central.

In absence of more specific information, the striking ship may be assumed to be a 5000 tonnes standard supply vessel with a raking bow and a stem angle of 65 degrees. It shall be demonstrated by calculations that the side of the CNG carrier has an energy absorption capability Es not less than given by following equation without the bow penetrating the inner hull:

$$E_s = \max\left\{\frac{13\cdot\left(L_{pp}/100\right)^2}{1+0.8\cdot\left(M/m\right)}, 10\,\mathrm{MJ}\right\} \tag{1}$$

where Lpp is the length between perpendiculars of the CNG vessel in m. The results of the application of the above formula for the case of a striking ship of 5000 t and for a 306 m long struck ship, having a full load displacement of 120300 tonnes equals to 118 MJ

The European Agreement concerning the International Carriage of Dangerous Goods by Inland Waterways (ADNR) was updated in 2000 by the Central Commission for the Navigation of the Rhine. According to this update ships travelling at the Rhine intended for the carriage of dangerous cargo must have a side structure with particular structural features defined in the regulations. Furthermore, the code prescribes a maximum allowable tank size of 380 m^3. The ADNR further prescribes that structural designs other that those defined in the Agreement may be accepted, even in the absence of a risk based assessment of the ship, if the designer proves that in the event of a lateral collision with another vessel having a straight bow, the structure may absorb 22 MJ without any rupture of the cargo tanks and the piping leading to the cargo tanks. Such energy is high for the collisions cases between ships travelling in river Rhine.

Taking into account the above mentioned requirements Vredevelt *et al* (2004) presented a risk based analysis that shows that a novel side structure with increased crashworthiness for a 8500 ton DWT chemical tanker with 758 m^3 tanks can have a better safety performance in case of a collision than the conventional type of ship with

380 m^3 size of tanks. In March 2008, the river Rhine authority, has adopted this approach and defined a method to determine the risk associated with accidental outflow of dangerous cargo from chemical tankers or gas tankers (United Nations 2008). Based on the assessment a designer may divert from the prescriptive regulations related to the maximum capacity of a cargo tank or the minimum required distance between the side shell and the cargo bulkhead provided that the tank vessel has a crashworthy side structure. The effectiveness of the crashworthy side structure must be demonstrated by comparing the risk of a conventional construction (reference construction), complying with the regulations, with the risk of a crashworthy construction (alternative construction). It is interesting to note that the method specifies cumulative probability density functions for collision energy with which the struck ship will have to cope in a collision. It is also interesting to note that grounding is not seen as a cargo spill scenario. The method is based on the concept of equivalence and it does not give any absolute risk values.

Table 5 that follows summarizes the requirements of existing rules and regulations concerning ship-ship collisions that have been presented above.

Table 5
Scenarios For Ship Ship Collisions – Codes & Regulations

Code/ regulation	Target vessel	Displacement	Impact speed	BOW TYPE	Energy absorption capacity
KAISA 520	Irradiated nuclear fuel	23000 tons	15 knots	T2 tanker	
ADNR In-land shipping	Intended for the carriage of gases	ships travel in Rhine have displacement <10000 t	Maximum speed of ships in Rhine is 12 knots	Vertical wedge type	Alternative requirement for alternative structural arrangements and in the absence of risk based assessment: 22 MJ
GL Rules for classification and construction …2004		As target vessel		Raked contour, with and without bulb	
DNV	Compressed Gas Carrier	Minimum can be taken as a 5000 ton supply vessel			$\max\left\{\frac{13\cdot\left(L_{pp}/100\right)^2}{1+0.8\cdot\left(M/m\right)},10\,MJ\right\}$

Three - KAISA 520, ADNR and DNV - out of the four codes that have been presented concern particular ship types – ships for transportation of irradiated fuel, chemical and CNG carriers - that present severe hazards in case they are involved in a collision. The GL rules are in principle applicable to all type of ships. However the latter do not prescribe any mandatory requirement, but provide a tool to compare a ship that is strengthened against collision actions with an unstrengthened ship.

One crucial element of the scenarios is the level of the prescribed energy. KAISA 520, ADNR and DNV prescribe rather modest energy levels that the target vessel should be able to absorb, i.e. energies that are between 10 MJ and 258MJ.

The example of application of the DNV Rules that is given above refers to the collision of a 306 m long CNG, corresponds to a collision between this ship with a 5000 t ship travelling with 13,5 knots – assuming that the collision is fully plastic, centre and right angle.

The KAISA 520 refers to target vessels having a displacement of approximately 7000 tonnes and the scenario that is prescribed for the particular ships involves a striking ship having a displacement of 23000 tonnes and a speed equal to 15 knots, which is a rather medium size ship with "moderate" initial kinetic energy. However, it can be readily shown that if the displacement of the struck ship is relative small, the available kinetic energy to cause structural damage, E_s , has an upper limit, which depends on the impact speed and it is independent from the mass of the striking ship. Assuming a fully plastic, right angle and central collision with the struck ship stationary before the incident, then Es equals to

$$E_s = \frac{(dm + m) \cdot M}{2 \cdot (dm + m + M)} \cdot V_0^2 \tag{2}$$

where V_0 is the impact speed of striking ship, M is the mass of striking ship, m the mass of struck ship, dm "added mass" of stuck ship, assumed equal to 40%·m for sway motion and $\mu = m/M$. When M>>m, i.e. the mass of the striking ship is considerably larger than that of the struck ship, as in the case of the Suezmax tanker that hits the vessel carrying irradiated fuel, which is described in the previous section, the available energy to cause structural damage has a maximum that equals to:

$$E_s = \frac{dm + m}{2} \cdot V_0^2 \tag{3}$$

The above equation presents the upper limit of the energy that is available to cause structural damage when the striking ship has a speed equal to V_0. Figure 2 presents the energy Es in the case of a struck ship having a displacement of 7000 tonnes and assuming an added mass equal to 40% ×7000 t versus the displacement and the speed of the striking ship. Finally if we employee Eq. 4 for the case of the ship carrying irradiated cargo, it is concluded that if the initial collision speed of the striking ship equals to 15 knots, the deformation energy has a maximum of 292 MJ, which is 1.42 times higher than the energy of 206 MJ, which is prescribed in the collision scenario according to KAISA No. 520.

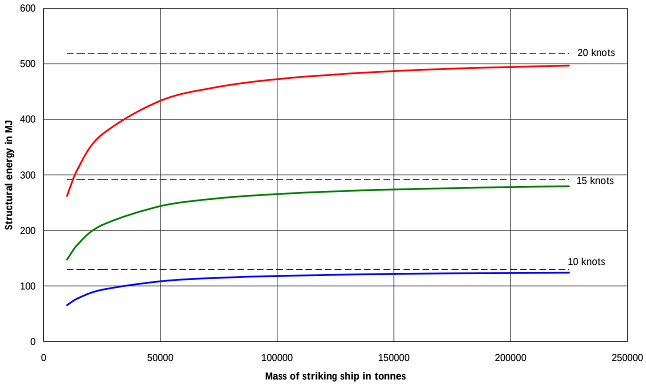


Figure 2: Available energy to case structural damage – fully plastic, right angle & central collision

ADNR refers to in-land shipping, whereby the ships usually travel with low speeds. It is worthwhile to note that the code was employed in order to prove that a ship with a more efficient compartmentation than the existing vessels has the same collision related risk, if a innovative structural design of a double hull side shell is used.

As far as GL Rules are concerned, according to the examples given in Bockenhauer and Egge (1995) the notation COLL2 to COLL4 is given to vessels, which have adequate energy capacity, when they collide with ships having similar size travelling with speed varying from 2.7 knots to 4 knots.

In general, the level of energies that are discussed above, are inferior to energies that are encountered in the open sea. For example a ship of 50000 t displacement, travelling with 16 knots, has an initial kinetic energy of 1693 MJ, which is considerably higher than the level of energies considered by the Rules. If such a vessel strikes a ship of approximately equal size a large amount of energy, will be released to cause structural damage. Investigation of the world fleet and of collision accidents that occurred in the past showed that such “high” energy collisions do happen and there are indications that more than 50% of the initial collision energy is available to cause structural damage. Consequently a design procedure for collision protection should, in principle, take them into account. Furthermore, the investigation of the distributions of the parameters that influence the ship-ship collisions, show that a probabilistic risk-based assessment of the collision behaviour of ships, should include the influence of the collision angle and the friction coefficient between the two ships.

2.2.3 Choice of Collision Scenario

Various scenarios have been proposed for the assessment of the collision behaviour of ships involved in ship-ship collisions. Scenarios in existing codes and scenarios that have been incorporated in the design process may be classified in three categories:

- ✓ Those that suggest one or more specific collision scenarios to test the target/struck ship.
- ✓ Those that suggest that the side structure must be capable to have a certain energy absorption capacity.
- ✓ Methodologies that are based on the pdfs of the parameters of a collision scenario.

The assessment of the struck ship is based either on the capacity of her side structure to absorb the energy without damaging the skin of her cargo holds or on the relative energy absorption capacity of the side structure with respect to a conventional or un-strengthened ship. In order to estimate the kinetic energy prior to impact surveys of the world fleet and traffic in specific waters has been performed. Distribution functions of other parameters that affect the damage in a collision incident are also determined.

In general, the final judgment of the collision behaviour of a ship is highly dependent on the safety targets that are set. If the analysis is deterministic the selection of the "worse case scenario" reflects the desire level of safety. A probabilistic risk analysis will include the target safety level within the definition of acceptable risk. In the design of vessels that present a high hazard if involved in a collision, their design was based on worse case scenarios, which at least in the case of the nuclear powered vessels, cover more than 99% of collision cases. Other procedures set the required safety level at least at the level of safety that is offered by existing designs.

2.3 Damage due to grounding

2.3.1 Probability of grounding occurrence

The probability of grounding occurrence and in general accident occurrence may be computed from statistics based on historical data, expert opinions and predictive calculations. Historical data provide realistic figures, which nevertheless should be used for future predictions with caution, because a) they are relevant to structures, which may differ from those in use today, and b) operation methods are usually improved with time, in order to offer higher safety standards.

Using the data from LR of Shipping's World Casualty Statistics, Zhu *et al.* (2002) reported that the total losses of all ships during the years 1995–1998 are 674 in number and 3.26 million in gross tonnage. Grounding accounts for total losses amounting to 17% in number of ships and 24% in GT. The grounding incident rate for Ro–Ro and merchant navy ship types with lengths greater than 100 m, for incidents in the period 1990–1999 inclusive, is approximately 0.02 per ship year, which is about half the incident rate for ship collision. This figure implies that if it is assumed that the life of a ship is 25 years, every second ship is expected to experience grounding in her life. Only one grounding incident resulted in a total loss, all the others were recovered. The figures were extracted from data of 1800 ship years.

A study by Kujala *et al.* (1999), revealed that according to an accident data base maintained by the Finish Board of Navigation, over half of all impact incidents were groundings and 48% occurred near islands or in narrow waters.

In order to quantify the probability of grounding occurrence and to investigate the effect of various factors on the likelihood and consequences of grounding, Samuelides *et al* (2007b) developed a database of accidents and populated it with data of accidents on Greek ships over 100 GT. The data were retrieved from the records of the Directorate of the Safety of Navigation of the Hellenic Ministry of Mercantile Marine (HMMM), which should cover all accidents of ships sailing under the Greek flag with size over 100GT, from 1992 to 2005. The investigations of accidents of ships over 100 GT, with Greek flag, from 1992 to 2005 revealed that groundings were the most frequent accidents: 47% of the total number of the reported accidents were groundings or caused grounding of a ship. However, only a few of those had catastrophic consequences. Further investigation of the accidents also revealed that:

- ✓ The decrease with time of the total number of accidents is proven to be statistically significant whereas the trend for groundings cannot be given as statistically significant;
- ✓ The dry cargo vessels suffer the most from groundings, 58% of the groundings involved dry cargo vessels, even though the ship-years of cargo vessels in the Greek fleet is 33%.
- ✓ Aged ships, i.e. ships in the between 21-30 years old and 30+ years old, suffer the most from groundings even though the ship-years of the ships in these age categories is relatively low.
- ✓ The ratio of groundings over the total number of accidents is higher for large rather than for smaller ships. From the investigation of the data it was found in every ten accidents for ships between 100 GT and 1000 GT there were 4,2 accidents with grounding and 5,8 accidents with other types of accidents, while for every 10 marine accidents for ships larger than 30000 GT, there were 6,7 accidents with grounding and 3,3 accidents with other type of accidents, and this differentiation was found to be statistically significant.
- ✓ There is a statistical difference between the mean values of the size (in GT) of the tankers that after grounding produced pollution and of those that did not lead to oil spillage; whereby larger ships tend to pollute more rather than smaller.

Table 6 presents the grounding return period on the basis of the accidents that occurred from 2001 to 2005 and from 1995 to 2005.

Table 6
Grounding return period

	1995-2005	2001-2005
Cargo	70	90
Tankers	144	297
Passenger & other	120	182
All ships	110	148

The results reveal that a) considering the period from 2001 to 2005 one obtains a longer return period rather than when considering the period 1995 to 2005, and b) the likelihood that a cargo ship grounds is higher than the likelihood for all vessels, while tankers present the lowest grounding rate. However because of the severe hazards that are linked with the grounding, it is groundings of tankers that usually make the headlines and attract the attention of the public opinion.

Between 1992 and 2005 there were 6 groundings that were recorded to cause pollution. On this basis it was concluded that the probability of occurrence per ship-year is $2{,}1\times10^{-4}$, or one grounding with pollution every 4762 ship-years. Since all groundings that caused pollution involved tankers and bulk carriers, it is reasonable to exclude the passenger and other vessels from the calculations. In this case the probability of occurrence rises to $3{,}7\times10^{-4}$, or one grounding with pollution every 2679 ship-years.

2.3.2 Damage Assessment

The process of ship grounding involves large contact forces, crushing of the hull structure and rupture of shell plating, while interacting with global motions and overall hull strength. It may cause serious consequences. The property of the sea bed, the bottom topology and the grounding scenarios are the governing factors for the damage process. Adequate information on sea floor topology is, however, very limited. Most of the analysis models for ship grounding in the past published works assumed that a rock opened a large part of the ships bottom structures. The damages of hull structures after grounding were classified into five fundamental damage modes, which are: (a) the stretching mode of shell plating and local large deformation, (b) plate perforating model for ruptured plating, (c) plate denting mode for main supporting members and (d) axial crushing mode for intersection of main supporting members and (e) plate tearing mode for plate in plane compressed by sharp body.

The simplified formulae for approximation of energy dissipation and impact resistance of four fundamental damage modes were derived. The overall energy dissipation and impact resistance of struck structures can be estimated by assembly of these fundamental failure mechanisms, (Wang *et al* 2000, Hong and Amdahl 2008).

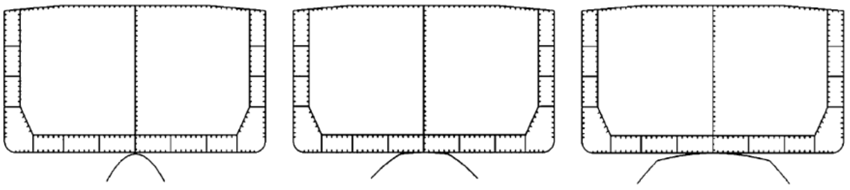
Naar *et al* (2002) investigated the behaviour of various double bottom configurations in stranding damage scenarios. The ship bottom is loaded with a conical indenter with a rounded tip, which is forced laterally into the structures in different positions. The resistance forces, energy absorption and penetration with fracture for four different structures were compared, which were:

- type I, a conventional double bottom,
- type II a structure with hat-profiles stiffened bottom plating,
- type III, a structure with steel sandwich panel in outer bottom and
- type IV, a structure with hat-profiles in both inner and bottom.

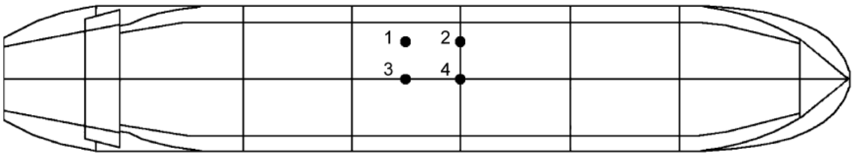
The results showed that the penetration where the tank top fractures is almost the same for the four structures; moreover, the energy absorption at this point of puncture of the inner bottom was quite high for structures II and IV, whereas the weights of those structures are not much higher than for the conventional structure. Structure IV, for example, is 4% heavier than the conventional structure (structure I) but the average energy absorption at the point of tank top fracture is 33% larger than for the conventional structure. Sandwich panels are locally weak due to the small thickness, when a sharp local contact takes place. On the contrary, for a wider shape of contact the double bottom construction will be stronger than conventional stiffened plate bottom.

The effect of different indenter size has been investigated by Wang *et al* (2000). This was done through a series of scaled down double bottom grounding experiments. The study clearly shows that small indenters puncture the hull skin with relative ease, while larger indenters damage the internal web configuration before the shell plating ruptures.

In order to better understand the interaction between the ship hull and the sea bed during grounding, Alsos & Amdahl (2007) investigated the influence of size and shape of sea floor during grounding. Three indenter topologies with four different locations, shown in Figure 3 were examined: (1) “Rock”: Indenters are much smaller than the ship itself, with a paraboloid bottom diameter of 0.2 ship beam; (2) “Shoal”: The “shoal” dimension is about half the ship hull width; (3) “Reef”: An intermediate indenter.



(a) “rock” (b) “reef” (c) shoal



(d) the position of indenters

Figure 3: Three indenter topologies and position (from Alsos and Amdahl 2007)

The traditional rock indenter punctures the skin easily with local structural damage. Large ‘‘shoals’’ indenters, on the other hand, may deform large parts of the hull structure. The web crushing and grillage deformation of the double bottom web may occur. Even though, the outer hull may not fracture, the overall damage may be severe. Stranded ships subjected to tidal changes and the loss in water level, as the ship is displaced out of the water, will yield a re-distribution of hydrostatic forces due to grounding actions. The interaction between the grounding contact force and the hogging bending moment affects both the longitudinal and penetration resistance of the hull. During the process, fracture may not take place, however, the buckling of the longitudinal sections from global bending, and the reduced cross section from crushing caused by the indenter, may severely reduce the capacity of the hull. The bottom damage induced by grounding will reduce the ultimate resistance of the ship hull girder. However, the degree of reduction, which varies with the damage location and the extents, can be regarded as a function of damage extent, mode of buckling failure, and relative shipboard location.

Lee *et al* (2006) investigated the effects of the welding residual stress in a grounding accident. Among parameters of grounding accident scenarios such as the ship speed, the initial striking point, and loading conditions of the ship, the ship speed varies from 10 to 15 knots under ballast condition with/without consideration of residual stress. The initial striking point is at the bow of the centre line of ship. A series of nonlinear numerical simulations with large deformation and fracture were carried out. As a result, two cases with residual stress have longer damage length. The difference seems to be relatively small, but not negligible.

In case of high speed crafts involved in grounding, raking is the damage to be expected, which poses the challenge of making reasonable requirements to damage stability, in particular the length of raking damage. Simonsen *et al* (2004), developed a probabilistic framework for the damage stability requirements, also taking into account the crashworthiness of the ships. They reported a length of damage, counting from the fore end of the vessel, which is less than or equal to the ship length and not less than

$$L_{dR} = 1.12L \cdot GDI^{0.7} P^{1.45} \quad [m]$$

where P is the probability of survival and is suggested to be set to P=0.6, and the Grounding Damage Index (GDI), which is the ration of kinetic energy to raking resistance is calculated as

$$GDI = \frac{0.5MV_s^2}{L\,F_H}$$

where L [m] is vessel length,
M [kg] is vessel mass,
VS [m/s] is vessel service speed,
FH [N] is the horizontal raking force.

The publication gives guidance on how to calculate the grounding force. The formulas are based on basic mechanics, validated and tuned against laboratory and full scale grounding experiments. Simonsen *et al.* (2009) further developed a simplified yet rather accurate expression for the raking force based on raking tests, large scale grounding tests and large-scale FEM analysis:

$$F_H = 0.77\sigma_0\varepsilon_f^{0.71}(t_{eq})^{1.17}(B_d)^{0.83}$$

where Bd is the width of the damage, σ_0 is the material flow stress, teq is the equivalent plate thickness.

2.4 Damage due to fire, blast and underwater explosions

Composite materials are increasingly used for marine structures. The application of composite materials on commercial passenger is controlled by a strict fire safe safety requirement stipulated by International Marine Organization (IMO 1994 & 1998). When the composite plates are exposed to fire, ignition will occur after about 30 seconds, the polyester matrix will be charred, and the plate will be delaminated and cracked. Following ignition, combustion of epoxy resin causes a large reduction in the mechanical properties. The residual shear strength and stiffness correlates with the thickness of burnt region, and the residual tensile strength correlates with the mass loss of the laminate.

Gardiner at el (2004) investigated the flexural and compressive properties of glass reinforced polyester (GRP) plate after exposure to kerosene fuel tray fire for time up to 10m. The residual flexural and compressive properties were measured at room temperature, and were found to decrease rapidly with increasing exposure time.

The risk of fire and of fire-related structural degradation and failure are the challenge to the safe design and accurate structural assessment of composite ship structures. Lua *et al* (2006) developed a temperature and mass dependent heat diffusion model to characterize the temperature and mass dependent heat conduction, energy consumption resulting from the decomposition, and the energy transfer associated with vaporous migration. The temperature dependent thermal conductivity and specific heat capacity are determined for the composite at a given resin decomposition stage using a recently developed small-scale test apparatus. The effects of temperature dependent thermal conductivity, specific heat capacity, and kinetic parameters determined at different heating rates are explored through the application of the temperature and mass dependent fire model to a composite plate subjected to a hydrocarbon fire. The thermal gradient due to fire induces a gradient of structural properties, reduces the overall stiffness, e.g. degradation, and thus reduces the load carrying capacity. Gu and Asaro (2005) proposed an analytical expression for the buckling load obtained from the theory of functionally graded materials. The solutions are given in a relatively simple form, which can be used to guide design practice, to verify large finite element calculations, as well as to provide insights in fire testing.

Teixeira and Guedes Soares (2006c) have presented a reliability formulation that accounted for the compressive loads induced by local thermal loading of plates, as induced by a fire. The collapse strength of the plates were determines by a finite element code that too into account the changes in material properties as the temperature was spreading in the plate.

The sudden energy release associated with the explosion of a high explosive leads to the formation of a superheated, highly compressed gas bubble and the generation of a shock wave in the surrounding medium. If the explosion occurs in water, it will be followed by a gas bubble pulsation. When the ship is attacked by air blast or underwater explosion (UNDEX), the localized failure in a hull panel is severe compared to the global response of ship.

The intensity of explosion determines whether a plate undergoes elastic deformation, yielding, plastic deformation or fracture. When the deformation is in the elastic range, the stress developed in the plate is given as a function of the material and shock wave parameters. As the intensity of explosion progressively increases, the elastic to plastic transition occurs over a specific shock factor. Plastic deformation is predicted as a function of geometric and material properties of the plate and shock pulse impulse. Deflection-time history reveals the reloading effects of the shock wave. As the deforming plate absorbs maximum energy, depending on its strength and ductility, it undergoes fracture. Rajendran & Narasimhan (2006) reviewed the sequence of events of underwater explosion and its effect on plate specimens.

The damage of plate panels subjected to air blasting loading can be classified into three modes namely (a) large deformation or permanent stretch of plate (Mode I), (b) tensile tearing of plate (Mode II) and (c) shearing failure of plate (Mode III). Ramajeyathilagam & Vendhan (2004) conducted a series of near field UNDEX experiments, which covered all three failure modes, similar to that of panels under air blast loading. Brett *et al* (2008) studied the explosive effects in close proximity to a submerged cylinder. The results showed that the primary shock wave impact generated a significant response in all cases; the bubble pulsation was less significant, generating a peak velocity approximately half that caused by the shock wave. The immediate collapse of the bubble onto the cylinder was the most severe impact, inducing a peak velocity approximately twice that caused by the primary shock wave, and brought about significant local plastic deformation. Hung at el (2005) conducted experimental and numerical studies of linear and nonlinear dynamic response of three cylindrical shell structures subjected to UNDEX. They concluded that when the deformation of the cylinder stayed in linear range after impact of primary shock, the bubble pulsation has only small effects on dynamic responses. If the plastic deformations occurred after the impact of the primary shock wave, the deformations increased remarkable after the attack of bubble pulsation.

Zhang and Yao (2008) analyzed the response of a ship under the bubble loading. From the stress-time history curves of typical elements of the structure, it can be seen that the pressure reaches its maximum when the bubble collapses and this validates that the pressure generated by the bubble collapse and the jet can cause serious damage on the ship structure. From the dynamic process of the interaction between the three-dimensional bubble and the ship, the low order vertical mode of the ship is provoked, and the ship presents whipping motion; and the ship does elevation and subsidence movement with the expansion and shrinkage of the bubble.

The shock resistance of machinery and equipment in a naval vessel are related to the ability of the hull to withstand shock damage. It becomes therefore necessary to quantify the hull damage due to underwater explosion and qualify the hull structure for shock resistance. Surface ship shock experiments have been conducted in many countries for shock qualification of ship integrity, systems and subsystems. However, conducting shock experiments to determine how submerged structures dynamically respond to and are damaged by UNDEX are extremely expensive and time consuming. On the other hand the advanced numerical modeling and simulation is a possible alternative to provide usable information to examine the details of dynamic characteristics of ship including component and sub-component level.

Park *et al* (2003) described the measurements of naval ship responses to UNDEX shock loadings, which had conducted for a coastal mine hunter (MHC) and a mine sweeper/ hunter (MSH). Shin (2004) conducted a ship shock analysis using finite element based coupled ship and fluid model. Three-dimensional ship shock modeling and simulation has been performed and the predicted results were compared with ship shock test data. Liang & Tai (2006) investigated the transient responses of a 2000-ton patrol-boat subjected to an underwater explosion with keel shock factor 0.8. The shock loading history along keel, the acceleration, velocity and displacement time histories are presented. Furthermore, the study elucidates the plastic zone spread phenomena and deformed diagram of the ship.

Librescu *et al* (2007) examined the problem of the dynamic response of sandwich flat panels subjected to explosive blast loadings produced by both underwater and in-air explosions, which were carried out in the context of a geometrically nonlinear model of sandwich structures featuring anisotropic laminated face sheets and a transversely compressible orthotropic core. The unsteady pressure generated by the explosion and acting on the face of the sandwich panel includes the effect of the pressure wave transmission through the core.

In order to improve the survivability of warship to UNDEX, Tong at el (2007) proposed a type of rubber shock absorption and isolation structure. The structure uses the principle of energy absorption with structure deformation and shock wave reflection between the interfaces of materials with great impedance mismatch. The shock protective layer (SPL) can be stuck to the outer hull of the ship.

Louca & Mohamed (2008) investigated the behavior of a typical offshore topside structure subjected to blast loading caused by hydrocarbon explosions. Recent developments in the Brazilian oil industry led to the necessity to conduct offshore platforms UNDEX survivability studies. The ongoing research has been segmented in parts, including theoretical and experimental correlated studies. Part of this study involves computer simulation, and, therefore, the necessary validation of the developed models used in such simulations. Motta *et al* (2007) presented a benchmark problem for experimental implementation of a submerged aluminum cylinder submitted to the UNDEX effects.

3. IDENTIFICATION OF DAMAGED STATUS

3.1 Damage identification technologies

Identification of a structure damaged area's status is basically done by the following process:

1. Inspection
2. Analysis
3. Evaluation

In case of a structural damage the inspection process will most likely start with a general overview of the external structure in order to identify and localise primary and secondary damages. The inspection technique to be used is called progressive visual examination. This means that all structuaral details that are not is in accordance with the Shipbuilding and Repair Quality Standard (SRQS) of IACS will be noted and subsequently analysed. SRQS is the generaly accepted standard for these types of work as IACS, International Association of Classification Societies, sets the lowest acceptable technical requirements of the world's ship classification societies. Furthermore IACS has published a number of Guidelines, recommendations and handbooks regarding maintenance, inspection and assessment of various types of ship structures that also most probably will be used.

After the external examination it is time to perform an inpection of the damaged area from the inside of the structure. Areas located below the water surface or confined will be examined by divers aor remotely operated underwater vehicles equipped with a remotely controlled video camera. There are various types of remotely operated examination devices and the driving forces for new types of devices comes from operators of complex installations such as Offshore, Nuclear Power Plants, Refineries and Chemical Industry.
At completion of the external examination there will be an analysis of the inspection's result. It is considered to be a best practice to use a FFS, Fitness For Service, standard in addition to the IACS' documentation. The dominating standard is API 579-1/ASME FFS-1 2007 challanged by the European FITNET FFS Procedure, Revision MK8. TWI, The Welding Institute, have recently released the software ENGFit for the purpose of FFS-analysis, which in a practical way is utilizing various standards and guidelines.

To improve safety and performance of vessels, the capability to identify the damaged structures become an important topic. The combination of measurement and semi-empirical approach to identify the damage status may provide an effective damage assessment method.

Ayorinde *et al* (2008) summarized the developments of reliable low-cost NDE methods for marine composites, especially composite sandwich structures; and had sought to apply low-frequency vibration, ultrasonic, acoustic absorption, thermosonic and acoustic emission methods to the characterization and integrity assessment as well as strain rate and nano-phasing behaviors of composite marine structures.

The measurement Acoustic emission techniques which were first developed in the 50s are widely used in failure detection of structure parts. A recent example of the application of this technology to ship structures can be found in Wang *et al* (2008).

An Ultrasonic nondestructive evaluation method for rapidly inspecting large area composite structures has been developed by the US Navy. This method, called Structural Irregularity and Damage Evaluation Routine (SIDER), was used to rapidly interrogate the entire hull structure to identify the areas that had experienced structural degradation that manifested itself in a structural stiffness change. Crane and Ratcliffe (2007) presented the results of the SIDER inspection of a 1/2-scale GRP corvette hull mid-ship section before and after each of three underwater explosion (UNDEX) loadings and compares the findings with conventional ultrasonic inspection.

Signal analysis technique, e.g. time-frequency analysis or wavelet transform technology were applied to recognize the characteristics of elastic wave of structures for predication of the damage conditions and the location of damage were. Yang *et al* (2008) applied a discrete wavelet transform technology to detect the cracks on the beam and the plate, respectively. The double-cracked beam and a plate with multiple cracks are evaluated by one-dimensional and two-dimensional discrete wavelet transforms.

Several damaged identification method based on vibration measurement were proposed in past years, these methods are based on the acquisition and comparison of the dynamical properties of structure before and after damage of structures, which are the Frequency Response Functions (FRFs), the natural frequency, damping ratio and modal shapes.

Bovio and Lecce (2006) developed a structural damage identification method based on vibration measurement. The method was based on the acquisition and comparison of Frequency Response Functions (FRFs) of the monitored structure before and after an occurred damage. A "damage index" for identifying damage on composite structures was proposed.

Budipriyanto *et al* (2007) described a scheme based on the dynamical characteristics of structures for identifying damage on a cross stiffened plate of a tanker ship model. The amplitude of a function containing the natural frequency, the damping ratio and the response was used as an indicator for damage. The function was obtained from a simulation using a neural network technique which inputs were the model's response.

Xiang *et al* (2008) presented a damage detection method by using only partial measurement of vibration in a suspect region, which can not only locate damaged members but also evaluate damage severities. The first three modes identified by a scalar-type ARMA method on undamaged and damaged structures.

Riveros at el (2008) presented a statistical pattern recognition technique based on time series analysis of vibration data. A 20-m riser model experimentally validation is used for the numerical implementation of this technique. The statistical pattern recognition technique was used to identify and locate structural damage using vibration data collected from strategically located sensors.

3.2 Analysis of accident damage of structures

For accidental limit state and safety assessment associated with collisions and grounding, the resulting progressive structural crashworthiness characteristics should be analyzed to evaluate the energy absorption capability and the crushing force of the structure in the corresponding accidental event in conjunction with the associated criteria. To evaluate the crashworthiness of ship, or estimate the residual strength after grounding and collision, the finite element analysis (FEA) is a powerful numerical method. However, performing a large scale FE-model for damaged ship structures is extremely time-consuming due to the effort required for creating the FE-model, the computation and the post evaluation of the results. Therefore the simplified method is useful to quickly predicate the crashworthiness of ship in early design stage, or to estimate the damage status and the residual strength after grounding and collision.

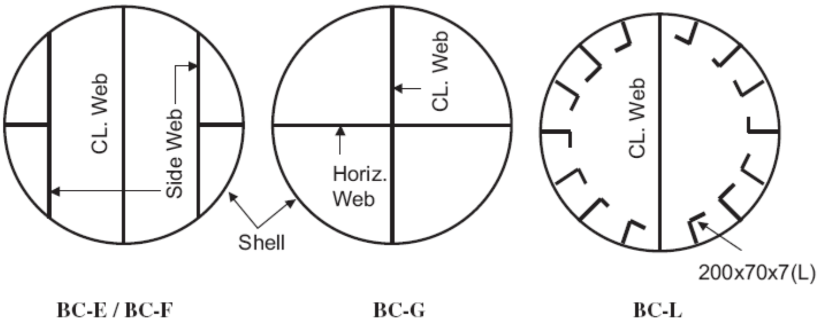
The practical finite element (FE) modelling techniques to accurately and efficiently simulate structural crashworthiness in ship collisions and grounding is demand for predication of survivability of damaged vessels. Non-linear finite element method (FEM) is a powerful tool for analyzing large deformation and elastic-plastic problems. Although the commercial code, e.g. LS-DYNA, MSC-DYTRAN, ADINA or ABAQUS, provide powerful performance for these nonlinear analyses, a reasonable FE-modelling and experience to evaluate the calculated results are still required.

A variety of simplified formulas have been proposed for estimation of crushing force or dissipation energy for different type of failure modes. The accuracy and usability of the developed simplified formulas should be verified by experiments, FEA or both. Although all the approximate methods are based on the rigid-plastic material model, they were derived following different assumption of folding mechanism and distribution of plastic zone.

Wang *et al* (2000) conducted a series of nine tests to investigate the behaviour of double hull structures in a variety of collision scenarios. Four theoretical models were derived and discussed: (a) plate punching model for shell plating, (b) plate perforating model for ruptured plating, (c) plate bending for main supporting members and (d) axial crushing for intersection of main supporting members. Hung (2007) proposed a procedure to calculate the energy dissipation and impact resistance of four fundamental damage modes progressively. Then the overall energy dissipation and impact resistance of a stuck double-hull structures were estimated by assembly of these fundamental failure mechanisms.

Paik and Seo (2007a,b) presented an efficient method for the progressive structural crashworthiness analysis of ship and ship-shaped offshore structures under collision or grounding with small computation efforts.

Yamada and Pedersen (2008) reviewed the simplified formulas for estimating the axial crushing forces of plated structures. The approximate method based on intersection unit elements such as L-, T- and X-type elements and based on plate unit elements were employed in the analyses. The crushing forces and the total absorbed energy for four different designs of large-scale bulbous bow models, shown in Figure 4 were calculated by existing simplified analyses. The experimental results were compared with the results obtained by following approximate methods: Amdahl (1983), Yang & Caldwell (1988), Abramowicz (1994), Wang & Ohtsubo (1999), Paik & Pedersen (1995), Zhang (1999) and Endo & Yamada (2001).



Shell thickness: 12mm for model BC-E, BC-G and BC-L, 10mm for BC-E
Figure 4: Schematic cross section of bulbous bow (Yamada *et al* 2008)

Hong and Amdahl (2008) proposed a new theoretical model for the crushing of web girder under localized in-plane load on the basis of a comparative study of existing simplified methods. The model captured several features of local crushing process of girder which were not accounted by the existing simplified methods. If strain rate effect took into consideration, the calculated crushing force gave some better results than that of the original static formulas. The effect of stiffeners on the crushing resistance of web should not be neglected, when the stiffener is involved in the formation of the first fold. Table 7 summarized the simplified methods for predicting the crushing resistance of web girders.

Table 7
Summary of the simplified methods for predicting the crushing resistance of web girders

Method	H		P_m/M_0	$P(\delta)/M_0$
Wang & Ohtsubo (1997)	$0.811b^{2/3}t^{1/3}$	0.67	$\frac{11.68}{\lambda}\left(\frac{b}{t}\right)^{1/3}$	--
Simonsen (1997)	$0.671b^{2/3}t^{1/3}$	1	$\frac{14.76}{\lambda}\left(\frac{b}{t}\right)^{1/3}$	$\frac{4b}{H\sqrt{1-(1-\delta/2H)^2}}+\frac{12H}{bt}\delta$
Zhang (1999)	$0.838b^{2/3}t^{1/3}$	0.75	$\frac{11.26}{\lambda}\left(\frac{b}{t}\right)^{1/3}$	$4.37t^{-1/6}b^{2/3}\delta^{-1/2}+4.47b^{-1/3}t^{-2/3}\delta$
Simonsen & Ocakli (1999)	$0.377b^{2/3}t^{1/3}$	1	$\frac{18.72}{\lambda}\left(\frac{b}{t}\right)^{1/3}$	$\frac{3b}{H\sqrt{1-(1-\delta/4H)^2}}+\frac{22H}{bt}\delta$
Hong & Amdahl (2008)	$0.395b^{2/3}t^{1/3}$	067 ~1	$\frac{17.0}{\lambda}\left(\frac{b}{t}\right)^{1/3}$	$\frac{1.2b}{H\sqrt{1-\alpha^2}}\left(2+\frac{\alpha}{\sqrt{3+\alpha^2}}\right)+5.56\frac{N_0H}{b}\delta$ $\alpha=(1-0.3\delta/H)$
H =characteristic crushing depth of web, λ_0 = the effective crushing factor, M_0 = plasticity bending moment, $M_0=\sigma_0t^2/4$ or $M_0=\frac{2}{\sqrt{3}}\frac{\sigma_0t^2}{4}$ Pm = mean crushing force, $P(\delta)$= instantaneous crushing force.				

Yamada *et al* (2007) presented a tool can calculate external and internal dynamic, structural deformation for both the striking and the struck ship is evaluated independently using rigid-plastic simplified analysis procedure. The developed tool was applied to the collision scenario where a VLCC in ballast condition collides perpendicularly with the mid part of another D/H VLCC in fully loaded condition. The results obtained from the present tool are compared with those obtained by large scale FEA, and fairy good agreements are achieved.

4. GLOBAL AND LOCAL LOADS IN DAMAGED STRUCTURES

4.1 Loading on Grounded Vessels

4.1.1 Loading patterns on vessels that ground

Loading patterns that have been used for the behavior of ships that suffer grounding may be classified in the following groups:

a) *Loading patterns that are defined prior to the incident and remain constant during the grounding.*
b) *Loading patterns that take into account the 6 degrees of freedom; motion of the ship with respect to the sea-bed.*
c) *Loading patterns that are associated with the global response of the ship during*

grounding and/or after the ship is set aground.

d) *Loading patterns that are defined prior to the incident and remain constant during the grounding.*

Methods for simulation of groundings that employ such scenarios usually define the orientation of the grounding forces either directly or indirectly by defining the relative path of the sea bed with respect to the bottom of the ship. The result of the simulations is either the function of the grounding force vs. the longitudinal damage or the grounding force vs. the transverse penetration – this particular case of grounding is referred to as stranding. The analysis may be static or dynamic and may be performed with analytical techniques that in most cases result in closed-form equations - or numerical techniques. Analytical techniques are developed for the determination of the collapse load of the structure that suffer the impact and/or the cutting load that is induced in the ship's plating as the sea bed advances through it, and are based on several assumptions, whereby the more usual are: a) the loading pattern remains unaffected by the grounding actions, b) the collapse mode is defined a priori, c) the material has a rigid plastic behavior, and d) inertia effects are considered negligible. Strain-rate effects on yield stress may be taken into account by adjusting the yield of the material using the well known Cowper-Symonds equation. Recent work on analytical methods for the prediction of grounding behavior is that of Hong *et al* (2008, 2007).

In FE simulations the loading scenario includes the a priori definition of the motion of the sea-bed with respect to the bottom structure. The simulations are mostly performed using commercial explicit codes, LS-DYNA, ABAQUS, which may include the inertia effects and various material models. Recent finite element simulations of groundings have been reported by Zhang *et al* (2006), Samuelides *et al* (2007a), Alsos *et al* (2007). Paik and Seo (2007 a,b) propose to perform collision and grounding simulations using a method which that is based on the discretization of the structure using large elements and referred to as the "idealized structural unit method" - ISUM.

Loading patterns that take into account the 6 dof motion of the ship with respect to the sea-bed

Grounding actions may affect the motion of the ship and consequently the orientation of the load with respect to the hull. Analytical simulation techniques that take into account the motion due to grounding loads and update during the incident the loading patterns are included in computed program DAMAGE that is based on the work of Simonsen (1997). The program includes two modes of computations: an uncoupled mode and a coupled mode, i.e. a mode that takes into account the effect of ship motions. However it was found that the sway and yaw motions do not affect the results (Simonsen *et al*, 1996) and they are therefore neglected.

Explicit finite element codes may account for the motion of the ship either as rigid-body or as flexible beam finite element simulations that include the effect of the ship motion have been reported by Kuroiwa (1996). The author performed a finite element analysis that took into account both the structural response of the bottom structure and the vertical motion of the vessels during the grounding. The longitudinal reaction force was found at the initial stages of the grounding to have a peak of 60 MN. After the rupture of the collision bulkhead the resisting force varied between 16 MN and 35 MN, whereby the maxima occurred when the transverse frames provided maximum resistance. The computations showed a large vertical force which reached 80 MN and lifted the ship upwards during the incident. As a result of the lift the tip of the rock moved towards the bottom plate as the ship moved forward on the rock: thus, the penetration of the rock in the hull decreased to 2.25 m from 3 m, which was estimated when the hull came in contact with rock

Loading patterns that are associated with the global response of the ship during grounding or after the ship is set aground.

Ships do suffer from vertical bending while they are at rest on the sea-bed. Research has shown that still water vertical shear force and the corresponding vertical bending moment during the grounding and while the ship rests on the sea bed may be equal or even exceed the design bending moment according to the rules (Pedersen, 1994, Alsos *et al*, 2007). The phenomenon may be more severe in the case of large wave bending moments. Wave loading while the ship rests on the sea-bed and the resulting primary bending response have been examined by Brown *et al* (2004) and Alsos *et al* (2007).

Brown *et al* (2004) developed a methodology for the definition of the motions and the vertical and horizontal wave bending moments that are applied to a stranded ship. The analysis employs the experience acquired from the review of actual groundings. The main observations were that

- ✓ The sea bed may be classified as a) sand, b) clay and mud, c) soft rock and coral and d) hard rock.
- ✓ The grounding includes four distinct phases a) ship underway, b) grounding impact event lasting up to 10 sec, c) orientation and translation lasting up to 24 hours and d) the steady state grounded position with steady state periodic motion in response to waves. Depending on environmental conditions phase b) may be repeated after phase c). In general groundings may last long and a ship that is set aground may be subjected to wave action for months.
- ✓ Ships may run aground bow first or drift aground in any orientation with a portion of the ship length either embedded in or resting on the bottom.

The steady state motion of the ship around her quasi-static equilibrium position is treated as a steady state linear dynamic problem. Results reveal that the vertical wave bending moment of stranded ships may well exceed the design wave bending moment according to URS 11 and on this basis the authors conclude that the dynamic bending moment induced in a grounded ship, which is subjected to wave action, can be significant and must be considered in grounded ship loads and residual strength analysis.

Alsos *et al* (2007) computed the response of the hull of a ship that rests on the sea bed using the explicit code LS-DYNA. The loading scenario has been described by the pressure loads that are applied to the hull as a result of her contact with the sea bed on one hand and the global vertical bending moments on the other. The pressure acting between the sea bed and the hull influences both the penetration of the sea bed in the hull and the vertical bending moments. The vertical bending results in compression of the bottom panels and consequently has an effect on their stiffness as the sea bed penetrates the hull. In this manner the loading from the sea bed is coupled with the vertical bending moments on the hull. Further the authors have investigated the effect of the motion of the aft and fore segments of the hull once a hinge is formed between the two segments.

4.1.2 Observations from actual grounding cases

Samuelides *et al* (2007a) reported on the loading patterns that are applied to the bottom structure of a ship that grounds and the subsequent structural response/failure mechanisms. The investigation was based on the review of six rather well documented groundings, those of

- ✓ a 273,000 dwt VLCC,
- ✓ LNG El Paso Paul Kayser, with a capacity of 130,000 m3,
- ✓ the 131,000 dwt single skin tanker Sea Emperess,
- ✓ naval vessel Valvidia,
- ✓ New Carissa, a 195 m double bottom bulk carrier, and
- ✓ a passenger vessel with 2,200 people on board.

The grounding energies of the cases above varied from approximately 190 MJ to 5,200 MJ.

From the description of the above mentioned grounding incidents, the following conclusions regarding the loading of the bottom structure were drawn:

a) the bottom structure is subjected to a number of loading patterns, which depend, on the topology and type of sea bed and the impact geometry;
b) the loading due to grounding, is not limited in time only in the initial phase of a grounding incident, i.e. when the kinetic energy of the ship prior to grounding is dissipated in structural energy, but may damage the ship's structure days after the incident;
c) structural components that are damaged during the initial incident, may subsequently be subject to serious loading conditions, which may cause further damage;
d) A vessel that grounds may suffer serious damage and nevertheless continue her course, even when she has relatively low energy prior to impact.

A common loading pattern when a ship runs with forward speed on the sea bed is a contact force distribution, which is oblique with respect to the plane of the bottom shell. The figures of the damaged hulls of Sea Empress and El Paso Paul Kayser reveal that the shell of the vessels were subject to such type of loading while they were moving forward in contact with rocks. In the case of Sea Empress the side shell has been removed from the action of the rock, while in the case of El Paso Paul Kayser it appears that the side shell was pushed inside the double bottom space, as shown in Figures 5 and 6, (Weverscove 2008).

The bottom structure may also be subjected to transverse loading, when the ship moves vertically towards the sea bed, a mode that may occur statically or dynamically. Such a transverse load is static when the ship sits on a rock, which supports its weight, and dynamic in case the ship is relatively light and the wave action causes a repeated impact of the bottom to the sea bed - pounding impact. The 273,000 dwt VLCC seems to have suffered from transverse static load on the double bottom structure, while New Carissa suffered from pounding impact. Transverse loading on the bottom plate also occur when the ship moves towards to the sea bed as a result of tidal actions. When the load to the bottom is transverse and the ship does not move horizontally, the bottom structure – girders and floors –suffer from crushing.

Figure 5: El Paso Paul Kayser

Figure 6: Sea Empress

Loading on structural elements of the hull of a ship that rests on the sea bed may also result from hull bending either in the horizontal plane or in the longitudinal plane of symmetry of the vessel. The latter is the result of wave action on the hull, but it may also occur when the ship rests on a projection of the sea bed. In the case of New Carissa, for example, scouring action developed a pinnacle under the vessel in the area of the mid-ship section, which caused hogging stresses to the ship's hull.

Horizontal bending, such as the bending of Valvidia, results from the wave action on a side of a vessel, which is supported by the sea bed on her opposite side. In this case each wave impact caused bending that created compressive stresses on the side that is subjected to impact and tension on the opposite side. Plate and beam elements in the side subjected to impact may suffer from buckling.

The examination of actual groundings revealed complicated loading patterns that act on the ship hull and that damage may occur days after the initial grounding, the effect of weather conditions in the loading patterns. Thus, a comprehensive assessment of the grounding behavior of a ship should be able to predict the response of the ship structure for days after the initial incident and under unfavorable weather conditions.

4.2 Loads in damaged ships

The distinctive aspect of loads in damaged ships is related to the damage itself. Damages may involve the ingress of water with the consequences of changing the ship displacement and even its atitute. This later aspect may also have influence on the wave loads, which start then being induced in a non-symmetric floating body and the strength criteria will also be applied on the global bending of the hull on an inclined hull.

Methods are available to predict the effects of progressive flooding of ships in ship stability and survivability. The process of water ingress is often modelled using a hydraulic coefficient that governs the volume and speed of water ingress.

Works on global loads for damaged ships are relatively rare. In fact, the structural strength of damaged ships in waves is only now being considered in detail in the design process. The studies on global loads in damaged ships are generally carried out in the frequency domain for several damage conditions which result in different trim and heel angles. Folso and Iaccarino (2005) present the results of a numerical study of this kind for a damaged tanker.

Korkut *et al*. (2005) present the results of an experimental study on the global loads acting on a damaged Ro-Ro model in head, stern and beam regular waves of different frequencies and heights. These authors conclude that the damage frequently has an adverse and non-linear effect on the structural loading and that the behavior of the pressure values on the bulkheads which limit the damage is rather complex.

These studies consider only the behavior of the ships in the final damage condition, disregarding entirely the intermediate stages of flooding. The study of the entire flooding process can only be undertaken using time domain models capable of calculating the progression of the flooding. Santos and Guedes Soares (2002) present one such model which combines sufficient accuracy with moderate computational time, making it suitable even for use within Monte-Carlo simulation approaches such as that described by Santos and Guedes Soares (2005b). This approach has also the advantage of taking into account the statistics concerning damage location and extension given in Lutzen and Rusaas (2001), allowing a more comprehensive analysis than before.

Having obtained the entire time histories of the global loads throughout the flooding process, the maximum values can then be used to verify the ultimate longitudinal strength of the damaged ship using the methods described by Gordo and Guedes Soares (2000) or Ziha and Pedisic (2002).

The amount of water that will flood the ship depends on the location and extend of the damage but also on the basic features of the ship in terms of subdivision. Therefore it is possible to combine a transient ship flooding program with the ship subdivision and conduct a Monte Carlo simulation of possible damage locations and consequences in order to assess the probability of the ship surviving that type of damage (Santos and Guedes Soares, 2005a,b).

After water ingress the dynamics of the damaged ship will depend on the ships response to waves but also on the coupling with the dynamics of the fluids inside the ships compartments and there are some codes that are able to take those phenomena into account (Santos and Guedes Soares, 2006, 2007, 2008a).

The loads on damaged ships have been analysed by Folso *et al* (2007) considering the ship in a damaged condition and using a state of the art wave load prediction code. Santos and Guedes Soares (2007b) have analised the changes in still water loads occurring during transient loading and they concluded that sometimes during this process higher loads are experienced than in the initial or final state of the process, which shows that it is important to have the capability of modelling these situations.

In addition to the capability of describing the wave induced loads on a damaged ship, it is also necessary to determine which loads to consider for strength assessments of this kind of ships during short term intervals as required to plan their voyage to a repair shipyard for example. Teixeira *et al* (2005) have discussed this problem advocating that the reference value should only comtenplate the renaining ship lifetime as the reference value.

5. STRENGTH ASSESSMENT TOOLS AND METHODS FOR DAMAGED STRUCTURES

5.1 Properties of aged material by corrosion

Corrosion is classified into several categories.The most prevalent form is uniform or general corrosion, and another one is pitting and crevice corrosion. It is clear that corrosion is a major degrading mechanism of the strength of ships and offshore structures. The reduction of thickness of corroded plates reduces the ultimate strength of framing and plates and finally reduces hull girder strength as well. Corrosion also adversely affects stress concentrations, the fatigue life of structures.

Garbatov *et al* (2007) have adjusted a theoretical model of time variation of corrosion depth by fitting it to a database of thickness reduction measurements in tankers, showing a good quality adjustment. Garbatov and Guedes Soares (2008) used the same model and adjusted it to a set of data from bulk carriers.

Various studies have been reported on the effect o fpitting corrosion and some of them compare with the results of general corrosion. Sumi (2007) replicated the surface geometry of plating with arrays of conical pits in steel plates. He found that elongation to failure was far more significantly reduced by general corrosion than was tensile stress.

Nakai *et al* (2005a, b) conducted a series of tensile tests using specimens with randomly distributed pits to investigate their effect on tensile strength. The tensile strength is little affected by the pitting pattern and total elongation is influenced by pitting pattern. It has been revealed that the tensile strength of randomly pitted steel plates could be predicted the proposed formula using D_{max}(diameter of largest pit) and DOP area ratio of pitting corrosion.

Yu *et al*. (2008) examined the effects of corrosion on the ductile fracture of steel plating. They developed two theoretical models for predicting rupture strain for power law plastic material with corrosion pit imperfection, a 1D model based on a single localization zone and a 3D model based on FEA. Both models indicate a strong reduction in fracture elongation in the presence of imperfections caused by corrosion pits.

Nakai *et al* (2006a,b) performed a series of non-linear FE analysis for pitted rectangular plate under compressive and shear loading condition, and revealed that ultimate compressive and shear strength of pitted plate is smaller than that of uniformly corroded plate in terms of average thickness loss and that prediction results of ultimate strength using average thickness loss at minimum cross section would be on the safe side. They also showed that the tensile strength under corrosion is proposed based on the test results and the tensile strength reduction due to pitting corrosion is expressed as a function of DOP area ratio of pitting corrosion, pit diameter, and original thickness of plate. Furthermore, the tensile strength is little affected by the pitting pattern, and the total elongation is influenced by the pitting pattern even if the degree of pitting (DOP) is the same. Nakai *et al* (2006a,b) revealed that the ultimate strength for hold flames could be well predicted by the empirical formula, which was developed in the previous study to estimate the ultimate strength of steel plates under compression and shear.

Ok *et al* (2007) focused on assessing the effects of localized pitting corrosion which concentrates at one or several possibly large area on the ultimate strength of plates. Over 256 nonlinear FEA of panels with various locations and size of pitting corrosion have been carried out. To represent the real structure with a pitted area, ANSYS shell layer model was adopted and the mid-plane nodes in pitted area were artificially moved. They clarified that the depth and width of corrosion were the two dominant parameters on the reduction of ultimate strength of plates while plate slenderness has only marginal effect on strength reduction. When corrosion spreads transversely on both edges, it has the most deteriorating effect on strength.

Jian and Guedes Soares (2008) have studied the strength of rectangular plates with corrosion pits modelled by through thickness holes, while Saad-Eldeen and Guedes Soares (2009) considered cases in which the depth of the pit was smaller than the plate thickness.

Matsushita *et al* (2007) investigated the effect of grooving corrosion in the vicinity of fillet welded joints on the ultimate strength of hold frames of bulk carriers with elasto-plastic FE analysis, and showed that the ultimate strength of hold frame subjected to lateral pressure is affected by thickness loss of the web plate due to general corrosion rather than the local grooving at the fillet welded joint between web and side shell.

Teixeira and Guedes Soares (2006a, b, 2008a) have studied the ultimate strength of uniformly corroded rectangular plates under in-plane compressive loads. It was considered that the corrosion had a random spatial pattern reducing the plate thickness of a random quantify and they used random fiels to represent such pattern. Simulation studoes were made by simulating such fields and then for each realisation a non-liner finite element analysis was conducted in order to thedermine the collapse strength of that plate. In fact the same simulation approach was also used to determine the effect of different inspection policies that Classification Societies could adopt (Teixeira and Guedes Soares 2008b). The inspection policies have been reviewed by Rizzo *et al* (2007) covering the different technologies and approaches adpted currently.

Yamane *et al* (2006) examined the residual compressive and bending strength of steel tubular members with general or pitting corrosion both experimentally and numerically. Based on the obtained results, the applicability of exiting design formula for the evaluation of residual strength of corroded steel tubular members is examined. They concluded that the residual strength can be estimated by using APS strength curves for averaged thickness of corroded plate, and the reduction of strength from original structure by local corrosion is small when the reduction thickness ratio is smaller than 0.3 and is proportionally decrease to SCR (Surface Corrosion Rate) when the reduction thickness ratio is larger than 0.3.

Abdel-Ghany, e tal (2008) have modelled K-T joints of a jack-up rig leg to explore the effect of random pitting corrosion on its strength capacity. The results are presented along with those previously published for the same model for the case of uniform corrosion.

Some work was also reported on the strength of damaged pipelines. Hussein *et al* (2006) considered the reliability of corroded pipelines considering their burst strength, while Teixeira *et al* (2008) dealt with the reliability of pipelines with localised damage.

5.2 Strength of aged or damaged components and structures

5.2.1 Residual strength of damaged components

Guedes Soares *et al*. (2005) studied the collapse strength of a single plate having two types of imperfections that is global weld-induced and local damage induced imperfections. They confirmed that local imperfection, when added to global one, could cause severe reduction of the strength of plate depending on its amplitude, length and position on the plate.

Luis *et al* (2007a,b, 2008) have studied the strength of panels of 3 plates joined transversely and longitudinally and compared their collapse strength with the one from a single damaged plate, showing the effect that the interaction with adjacent plates has. Luis and Guedes Soares (2007) studied the collapse strength of a panel of 3 plates joined transversally and 3 plates longitudinally. The damage-induced imperfection was located only one of the nine plates of the panel. It has been found the effect of local imperfection depends on the slenderness: increases from negligible for stock panels, to significant for very slender ones. They concluded that a local imperfection interacts with the global one and the effect of the position of local dent depends on the overall shape of initial imperfections.

Witkowska and Guedes Soares (2008) investigated the strength of stiffened panes with local dents whose magnitude is $w_t = 0.50\beta^2 \times t$. They concluded that the stiffened panels after being damaged in a form of local dent demonstrate quite good performance. They are not affected much by the damage, the reduction rate of ultimate strength barely reached 1-2% for majority of cases and only for most slender ones it got to around 5 % level.

Paik and Kumar (2006) studied the ultimate strength reduction characteristics of a stiffened panel with cracking damage under axial tension and compression. A series of nonlinear finite element analyses were undertaken with varying the size and location of cracking damage by using LS-DYNA introducing ductile fracture of material. A relevant theoretical model for predicting the ultimate strength of the stiffened panel with cracking damage were studied and simple formula of predicting ultimate strength of cracked stiffened panel was presented.

Nikolov (2008) examined the ultimate strength of damaged continuous plating based on FEA. He concluded that the compressive strength of damaged plating is significantly influenced by the residual stress and pointed up that the simplified methods in CSR for Bulk Carriers may overestimate the ultimate strength for slender damaged plating.

Witkowska and Guedes Soares (2009) have examined the collapse strength of stiffened plates in which the stiffener is damaged. In this initial study a single stiffened plate was examined and the influence of different levels of imperfection was quantified.

5.2.2 Residual strength of damaged girder

Rim *et al*. (2008) conducted the a series of collapse test using box-girder model of 720mm×720mm in section and 900mm in length to investigate the effect of stranding damage size on the ultimate strength of ship structures. From the experimental results, they found that the ultimate strength is reduced as the damage size increased, and the ultimate strength is reduced by about 20% than that of no damaged one when the damaged size is 30% of the breadth of the specimen.

Ren *et al*. (2008) calculated the ultimate bending moment of damaged warships based on Smith method. They showed the statistic characteristic values of residual capability are most evidently influenced by the variability of yield stress and secondary influenced by the variability of broken hole and plate thickness.

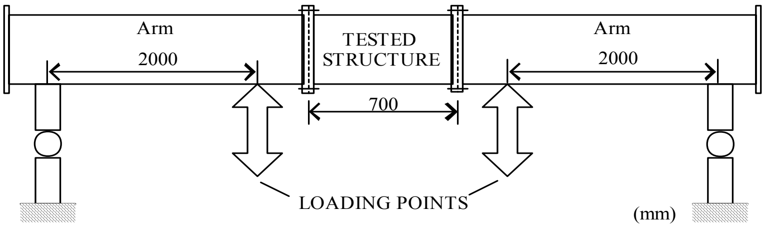


Figure 7: Test set-up of 4point cyclic bending

(a) 6th cycle (b) 48th cycle

Figure 8: Growth of crack under cyclic loading

As for “Collapse behavior of structural members under cyclic loading”, many papers have been reported in civil engineering, especially after the Earthquake in Kobe, many papers have been presented for this topic in Japan. Some papers show that after the large strain yields in the material, the brittle characteristic arises in material, the change of characteristic of material can be the cause of structural rupture. Furthermore, the cyclic loading will reduce the capacity of deformation. Masaoka *et al.* (2006) performed cyclic four points bending test of the box girder structure with longitudinally stiffened plate and also performed a numerical simulation by FEA. Figure 7 shows the test set-up which was performed with cyclic loading. Figure 8 shows the residual deformation of test specimen. By several times of cyclic loading, the loading capacity of the buckling side falls rapidly. Moreover, the local bending deformation is concentrated at the location of plastic deformation and a crack begins to grow from the location is clarified.

As for the hull girder ultimate strength of damaged structure, Endo *et al* (2005) carried out detailed FEM analysis, and clarified the residual strength of a ship which was collided by another ship at side shell. They obtained the result that the hull girder ultimate strength of a 290k DWT VLCC collided by same size tanker at 9-12 knots in speed fell to 75%-90% of intact structure and the shearing strength fell to 65-70 of intact structure (See figures. 9, 10 and table 8).

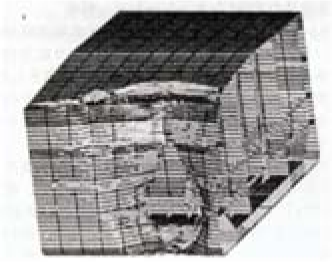


Figure 9: Collision damage at the side shell Comparison of ultimate strength

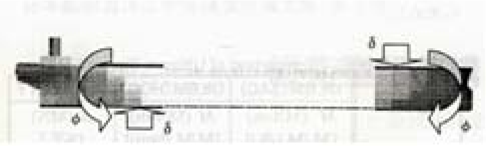
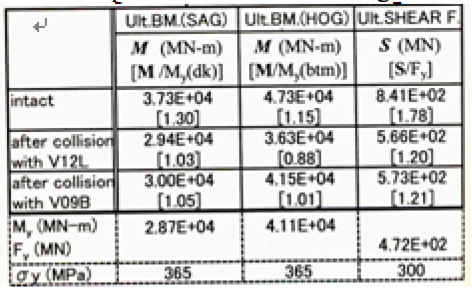


Figure 10: Analysis model for longitudinal strength

Table 8
Comparison of ultimate strength



↵	Ult.BM.(SAG)	Ult.BM.(HOG)	Ult.SHEAR F.
	M (MN-m) $[M/M_y(dk)]$	M (MN-m) $[M/M_y(btm)]$	S (MN) $[S/F_y]$
intact	3.73E+04 [1.30]	4.73E+04 [1.15]	8.41E+02 [1.78]
after collision with V12L	2.94E+04 [1.03]	3.63E+04 [0.88]	5.66E+02 [1.20]
after collision with V09B	3.00E+04 [1.05]	4.15E+04 [1.01]	5.73E+02 [1.21]
M_y (MN-m) F_y (MN)	2.87E+04	4.11E+04	4.72E+02
σy (MPa)	365	365	300

Ozgur, *et al.* (2005) and Das and Fang (2007) investigated the residual strength of single side skin(SSS) and double side skin (DSS) bulk carriers subject to collision damage. Wide range analyses were carried out in both hogging and sagging cases with considering of the intact and damaged scenarios and also considered corrosion effect based on JBP rules. Furthermore the failure probability of damaged DSS and SSS bulk carriers was studied assuming the load effects obtained from the classification rules and American Bureau of Shipping (ABS) guideline, respectively. The simplified method based on an incremental-iterative approach like smith method was employed using a developed computer code NEPTUNE. In order to include damage by collision, all elements failed have been removed from the intact original configuration. They showed that the DSS bulk carriers have higher safety index than the SSS bulk carriers in hogging and in sagging conditions under similar collision damage scenarios, and this index value is greater in hogging case compared to that in the sagging case. Damages in upper side shell and in deck structure lead to reduce the residual strength significantly when subject to in-plane compressive load combinations.

Luis *et al.* (2007) investigated the residual longitudinal strength of double Suezmax tankers after groundings or collision. The calculations were performed using a computer code based on the Smith method. The damage was simulated by removing the damaged elements from the midship section. Luis *et al* (2006) presented a reliability assessment of a damaged hull in which they account for the reduced strength and also for the changes in loading in a damaged state.

Hussein and Guedes Soares (2008) have studied the ultimate strength of intact and damaged double hull tankers designed according to the new Common Structural Rules.

Yoshikawa *et al.* (2008) investigated the residual strength of bulk tanker after grounding. The residual strength of stiffened panel, which deformed 1-2 times of stiffener depth attached bottom, reduced to 80-50 % of intact panel. They calculated the hull girder strength of damaged ship using incremental-iterative approach not omitting damaged parts but considering load-displacement relation of damaged panel, and found that the deduction of ultimate hull girder strength was very small when the damage area is limited between two adjacent girders in bottom.

Alsos and Amdahl (2007) studied the interaction between the grounding actions and the hull bending moment through series of couple FEA. Changes in hydrostatic conditions, as the ship is displaced out of water, were applied onto the FE models though bending moment functions. They clarified that the buckling of the longitudinal sections, from global bending, and the reduced cross section, from crushing caused by the indenter, severely reduced the capacity of the hull.

Amante *et al* (2008) investigated the ultimate buckling residual of damaged stiffened panel and square sectional column composed by stiffened panel, imaging the semi-submergible platforms damaged by a supply vessel collision. By numerical calculations and experiments, they found that strength after collision is 9 % less than intact buckling strength of column.

5.2.3 Reliability analysis of damaged ships

Santos and Guedes Soares (2002) presented a probabilistic methodology of assessing the survivability of damaged passenger Ro-Ro ships though the identification of critical damage scenarios. The static equivalent method was used to calculate the critical sea state the ship can survive in, for a given damage scenario. Monte Carlo simulation is used to take into account the uncertainties in the ship's loading condition at the time of the accident.

Jia and Moan (2008) performed the reliability analysis of a damaged double hull tanker condition upon collision damage. They calculated the load effects for the new floating position after damage and adopted Leira's formula to assess out-crossing rate for the vector load effect process, and then the conditional failure probability. They found that the intact ship is at highest risk in head sea, while it is bow sea which is the most dangerous for the damaged ship.

Parunov *et al*. (2008) investigated the structural reliability of aged single-hull oil tanker. They analyzed the probability of structural failure for three states of the hull; as built, ship hull corroded according to CSR and actual state with measure thickness of structural elements after 25 years of service. And they revealed that the hull-girder reliability of the actual ship hull, with measured thickness after 25 years of service, is still higher than the reliability calculated for the hull with corrosion deduction thickness according to CSR.

Fujii, Kawabe and Yao (2007) investigated a series of progressive collapse analysis applying the Smith's method for evaluation of ultimate hull girder strength and its sensitivities with respect to design parameters and suggested that the ultimate hull girder strength might be sensitive to the progress of corrosion from the numerical results.

6. EMERGENCY REPAIRS AND MITIGATION ACTIONS

6.1 Recovery strategies

One of the main reasons for damage and strength assessment of ships and offshore structures, after an accidental event, is, in addition to assess the remaining safety level, to provide the background for any rescue, salvage and or recovery strategy. These strategies vary significantly depending on the status of the structure, its future and its value.

6.1.1 Emergency

Emergency could be defined to exist, when ship, her crew and cargo are in peril and could be lost following loss of stability, collision, grounding, water ingress, structural collapse, fire, explosion, shifting of cargo, loss of engine power, etc. In any of these events or similar, quick assessment is urgently necessary to evaluate the condition of the vessel in order to predict the short and long term perspectives. For oil rigs, floating and storage units and other floating structures of non-conventional ship shape, the emergency can be defined in a similar way as above.

The initial assessment is always performed by the onboard crew and relevant actions are taken. When the situation is critical and is rapidly deteriorating, often the decision is to abandon the ship and leave it on her own. In such cases rescue operations are initiated to save the crew.

When there is a confidence about the short term perspective, the onboard crew may initiate evaluation of the vessel's condition by themselves or request assistance from ashore. As from 01.01.2007 MARPOL convention in Annex I, Ch.5, Reg.37(4) requires all tankers for oil of 5000 dwt and upwards to have access to shore based computerized programs for the assessment of the damage stability and residual strength in emergency. There is number of software developments and services, providing such assistance. With access to such programs quick assessment is achieved and relevant actions could be taken to prevent further negative development of the emergency situation in short term, and in long term to improve the condition with respect to stability and strength. Building up a confidence about the vessel in emergency, gives time and opportunities to evaluate the condition in more details and plan the short term future of the vessel, crew and the cargo.

6.1.2 Salvage strategies

Marine salvage is the process of rescuing a ship, its cargo and sometimes the crew from peril. Salvage encompasses rescue towing, re-floating a grounded ship, patching or repairing a ship. Among others, the main aims of a marine salvage are:

- repair the vessel permanently in a controlled environmemt such as during a restricted voyage, sheltered water, in a harbor or repair yard
- prevent pollution or damage to the marine environment
- clear the incident location from obstructions to safe navigation

Very often, depending on the nature of the emergency and its objective, tailor made strategies are developed and performed. It has not been possible to find guidelines or official procedures on how to behave when performing salvage. When salvaging ships or floating structures, cranes, floating and dry docks, and other means can be used to perform lift and repairs for short journeys to safety. Tug, supply and special purpose boats are usually involved in performing the salvage.

As at today there are 102 companies working in the fields of marine salvage, all of them associated in an organization International Salvage Union (ISU), where 55 have status of members and 47 are associate members. All ISU members distinguish between two major types of marine salvage. These are “dry salvage” and “wet salvage”.

Dry salvage occurs when a vessel or floating structure has suffered casualty but is still afloat. Amongst the main types of casualties requiring dry salvage are fire and explosion, collision, grounding and breakdowns. As an example can be reported the case of the MSC Napoli which suffered severe hull damage during a storm in January 2007. After the rescue of the crew the first decision has been to ground the ship off Branscombe in order to avoid a sinking. Then the salvage team re-floated the vessel in order to perform underwater survey which led to the decision of putting the vessel down again to avoid the ship breaking up. After some months, in July, the vessel was re floated and brought to deeper water where the salvage team separated the fore section from the aft by means of a controlled explosion. The fore part was towed to Belfast for scrap. The aft part was left under control of automatic pumps which kept the damaged holds from flooding. (SMIT’s world web site, ISU- Salvage world-September 2007)

Since most of the marine accidents worldwide are groundings, one of the most used dry salvage procedure is the refloating of the stranded vessel. Papanikos and Samuelides (1996) investigated the most common techniques to perform a refloating salvage: cargo removal, use of the tide sea level differences, wave contribution, beach gears, tugs, scouring, buoyancy material, jaking, cranes and launching cradles. For each technique a brief description is reported along with the recent improvements.

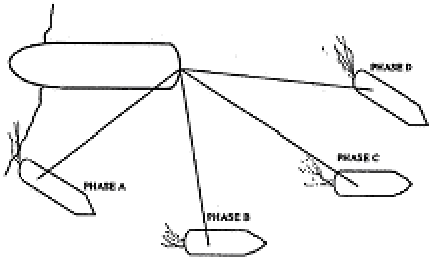


Figure 11: Tug driving a stranded vessel

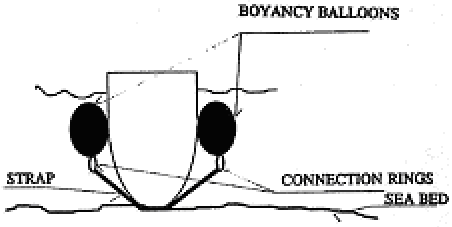


Figure 13: Modern arrangement for the adding of buoyancy balloons

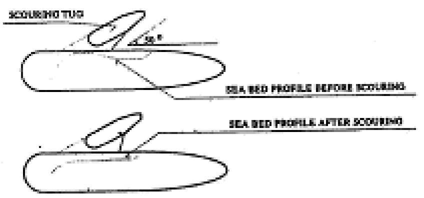


Figure 12: Scouring tug

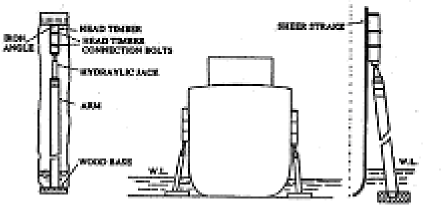


Figure 14: Typical jacking arrangement

State of the art of dry salvage technique in the offshore filed has been presented by Enderlin, Reynolds and Hendershot (2001). In their publication is presented the innovative salvage method adopted to remove the main pass structure of the Shallow Water Protector Platform #3 located offshore Lousinana and damaged by the Hurrican Georges. After performing an HAZID study it was decided to reduce the reinforced concrete deck into modules that were manageable by the lifeboat's crane by Ultra-High pressure Water Jet cutting. In the paper is highlighted how the use of the innovative technique not only removes commercial divers from a hazardous underwater environment of cutting operations but also from any hazard caused by shifting concrete deck sections as they were segmented into manageable pieces.

Wet salvage is performed when the ship or floating structure have capsized or sunk. For this type of salvage can be reported, as an example of the state of the art, the case of the Dynamic Positioned Flexible Fallpipe Vessel 'Rocknes'. The vessel, 166 meters long, capsized in few minutes near Bergen after hitting a shallow. The vessel had to be turned in upright condition and the company SMIT salvage BV performed the operations. As can be seen from Figure 15, first the vessel was secured at her starboard side by means of hold back wires connected to 12 rock anchors each drilled 12 meters down into the rock structure. On the portside the vessel was connected to two pull-barges trough cables connected to her bottom structures passing under the 'Rocknes' surface. Then the winches mounted on the barges pulled into the portside directions forcing the vessel into a rotating movement and finally turning the vessel into an upright condition. In order to facilitate the operation, the portside tanks were pressurized with air and the starboard side tanks were ballasted. (SMIT's world web site, Rocknessalvage web site)

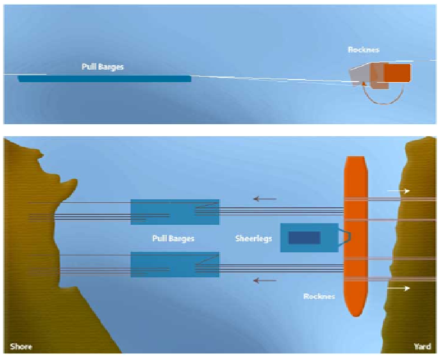


Figure 15: Rocknes Salvage: Technical Drawings

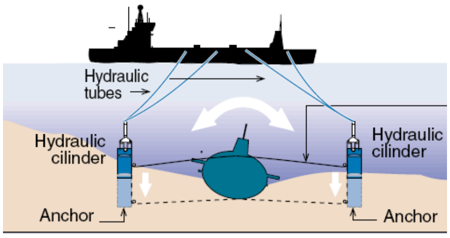


Figure 16: Kursk Salavge: Sawing System

6.1.3 Recovery strategies

In general the recovery operations refer to accidents where the future serviceability of the unit is lost and the operations are intended to reacquire the unit for steel resale, to minimize the negative effect on the environment or other reasons. In this contest the recovery of the Kursk can be mentioned as status of the art.

Due to an explosion in the bow section, the submarine was lost off the Murmansk Pilot Station coming to rest on the ocean floor at a depth of 108 meters. The raising of this unit was performed by Mammoet-SMIT and was a world record since it is the heaviest object recovered at such depths. Due to severe damage, the bow section became unstable and then could complicate the lifting operation when not separated from the submarine prior to lifting. The compartment #1 was sawed off by using a specialised saw wire which was pulled back and forth through the submarine's hull by two hydraulic cylinders on top of two suction anchors placed on both sides of the unit. After this phase, 26 holes have been drilled in the pressure hull of the submarine in order to connect the lifting cables coming from the barge Giant4 prepared for this operation with 26 winches, a special room in the centre part to accommodate the superstructure of the submarine and a heave compensation system to compensate the motion of the barge due to swell. Once raised just below the barge, the Kursk was towed to Murmansk hanging in serrated clamps. On arrival, the Giant/Kursk combination was lifted by auxiliary pontoons in order to sail it into a dry dock. (SMIT's world web site, SMIT's document n. 00.12.0140-R-022)

6.1.4 Emergency dry-docking a full loaded ship

A ship is supposed to be delivered with a dry-dock keel block plan, stating the numbers and locations of keel blocks at dry-docking. It is anticipated that the dry docking will be carried out with empty cargo holds and/or –tanks. USA Coast Guard, MLCA Naval Engineering Division has published a useful guideline/instruction with check lists, intended for dry-docking of USCG ships (USCG 2004).

In conjunction with damage to a ship's hull structure, rudder or propulsion machinery it may be necessary to dry dock the ship immediately in order to prevent further damage. Should it take too long time to off-load the cargo as well as to empty the bunker- and storage oil tanks it is an emergency dry-docking operation. The ship's original dry docking plan not is valid for the ship's actual load condition.

Emergency dry-docking operations of full loaded ships have successfully been carried out (P. Lindstrom private communication). The keel blocks plans have been prepared and/or scrutinized by the use of following empirical keel block calculation rule:

- Minimum keel block area to be used: 1 m^2
- 50 % of the total keel block area shall be located under the ship's keel (longitudinal centre line)
- Maximum surface pressure on each keel block:
    - Swedish-Finnish Ice Class 1A 240 ton/m^2
    - Single hull tanker 160 ton/m^2

6.2 Emergency Repairs and upgrade status

Emergency repair of ship and offshore structures is considered to be the fundamental knowledge by experienced merchant mariners. "Emergency repair" is here defined as the techniques used to prevent leakage and/or maintain the integrity of the hull, compartments, pipe systems etc. (M. Persson private communication). This knowledge is by tradition transferred from man to man when it is applied. It is also transferred between the mariners when they are sharing their experiences. For the time being are these techniques and/or concepts not a part of the formal education of seamen or Merchant Marine Officers. techniques and/or concepts not a part of the formal education of seamen or Merchant Marine Officers (G. Lindblad private communication).

For sailors and officers serving in a nation's Navy is the maintaining of ship's integrity a fundamental part of the training. A curriculum and/or training material has not been found in a public library data base. As a result there of, is this knowledge considered as restricted. Nevertheless, based on professional knowledge and experiences is it known that the fundamentals of "emergency repair" are based on following concepts in various combinations:

- Plugging (wood, rubber, nylon, lead, brass, steal)
- Patching (a plate with sealing substance pressed to the leak)
- Concrete boxes (capturing the damage)
- Composites (expanding foams, glues,)

- Wrapping (duct tape, rubber gaskets, clamps, textiles)

Emergency repairs may be considered as temporarily or permanently. Which one is to the discretion of the actual classification societies' Surveyor. It should be remembered, what is temporarily today may be permanent tomorrow. An example is the shield arc welding technique that has its origin from a Marine Engineer's need of sealing joint leaks in riveted marine steam boilers (Kjellberg, 2004n).

Extensive damages may rarely be permanently repaired by means of an emergency repair technique. It will most likely require the interaction of a number of various engineering disciplines such as Naval Architects, Marine-, Welding- and NDT Engineers. Such repair operations are known as "Integrated Repair Operations" and if required in a hurry, it is known as an "Integrated Emergency Repair operation". The corner stones of "Integrated Emergency Repair Operations" are:

- Inspection, analysis and evaluation of the damage
- Generation and approval of a repair concept
- Execution of the repair concept
- Testing and verifying the repair's quality

There are hand books and standards for each of the above mentioned four (4) steps. To perform a success full integrated repair operation is it required that all four (4) sections are integrated with each other in a purpose full manner. It shall be noted that the knowledge of how to integrating repair operation is not shared by those individuals or organizations how have gained it. In some organization is this knowledge restricted/limited to a reduced number of people. Nevertheless any one aspiring to gain the knowledge of how to integrate a repair operation may organize the work in accordance with the standard ISO 3834-2 in combination with FITNET FFS Procedure, Revision MK8 and IACS Rec.47 "Shipbuilding and Reapir Quality Standard".

It has been recognized that it not is uncommon with cracks in the way of the doubler's longitudinal fillet welds. The cross section of a traditional hull doubler is as illustrated Figure 17, Solution A. It has been noted that M/S MSC Carla's breaking in two parts in the way of hear midship section November 24, 1997, originated from a crack in the way of here longitudinal doubler. For that reason may an alternative cross section design of longitudinal doublers be considered as illustraded Figure 17, Solution B.

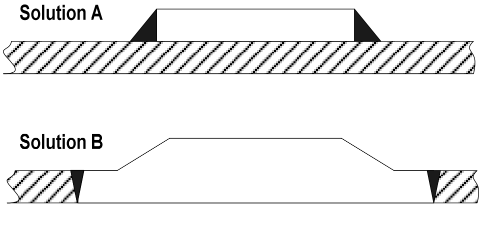


Figure 17: Cross section designs of longitudinal doublers

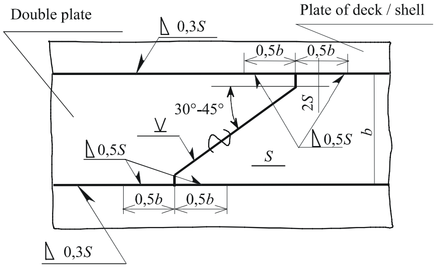


Figure 18: Weld joints of double plates

The primary objective of an "Integrated Emergency Repair Operation" is to minimize the instant risk of the ship. And subsequently bring the ship in sheltered water and finaly to a repair facility. Before that can be done the ship's structural integrity should be secured.

Lindström (2000) has described a successful in-service repair welding operation of a ships hull plate in the way of its conection to the tank top. The in side hull plate was built up by means of welding during ballast voyages cross the North Atlantic Ocean at a speed of about 15 knot. The actual damage repaired was very similar to the grooving corosion illustrated in Figure 19, described in IACS Rec. 96. (IACS, 2007).

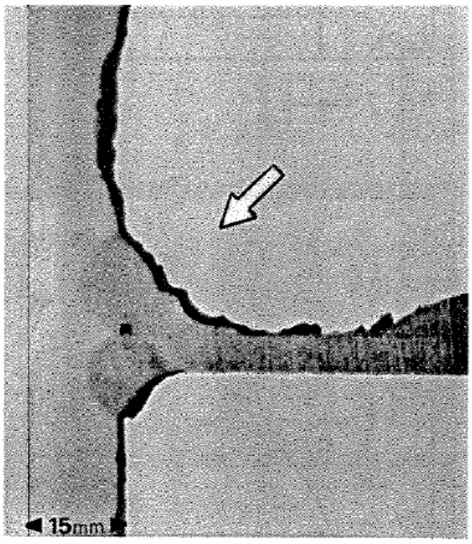


Figure 19: Illustration of grooving corrosion in the way of the hull plate and the tank top

The welding- and marine engineering principles for the technique used. To control the enhanced cooling ratio, from the cold sea water on the reverse side of the shell plating, has been described by Lindstrom and Ulfvarsson (2002, 2003), Lindstom, and Faraji, (2004) and Lindstrom (2005).

Thus the condition of preservation of the longitudinal strength, as a rule, is carried out for vessels with small damages to storm conditions and vessels with strongly damaged hull in absence of the wave additive and at active struggle for survivability by crew and experts of rescuers, including measures on temporary repair.

As a methods of temporary repair, see RS (2004), Caridis (2001) temporary reinforcements, cement boxes, etc. are supposed.

The choice of a method of repair is defined depending:

- on a kind of hull structures;
- on a kind of damage and its numerical parameters;
- area of the damaged structures and its arrangement in the hull;
- possible reasons caused damage; age and duration of the subsequent operation of a vessel;
- a degree of quality of performance of repair works.

The area of the damaged structures is estimated on a degree of its importance in a structure according to purpose, classification of groups of structure elements by Rules of Classifications and in view of requirements to watertightness.

The reinforcement of an element of the hull or its area can be executed with the help of the following means:

- Replacement of an element;
- Double plates for increase in the modulus of calculated sections of the hull and girders;
- Double plates for local reinforcements of structures and maintenance of watertightness;
- External additional structure elements for reinforcement of decks, sides and bulkheads it is possible to carry out;
- Ferro-cement or haydite-concrete.

For example, according to RS requirements, the double plates can have thickness no more than on 50 % exceeding residual thickness of a plate of a supported structure, but no more than 30 mm, width - no more own 50 thickness, but no more than 700 mm. Before installation joint surfaces of a plates and a structures of the hull should be carefully cleared and adjusted. Backlashes between surfaces jointed plates should not exceed 2 mm. Double plates should be established with application of angle welds. Application of plug welds and interrupted welds is not supposed. Butt welds of double plates should have 100 %-s' quality assurance of welding.

Constructive of joints of plates should be carried out in conformity with Figure 18, and their ends - in conformity with Figure 20. Recommended arrangement of double plates is shown on the Figure 21.

Supporting girders can be intercostal. The ends of girders should be fixed on web girders according to existing type of structure in the hull.

Additional girders can be established between existing girders, and also where it is possible on conditions of operation, from a underside of a surface of a plate, for example, on outer side of shell (Figure 22).

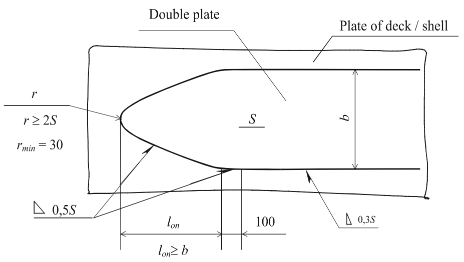


Figure 20: Ends of double plates

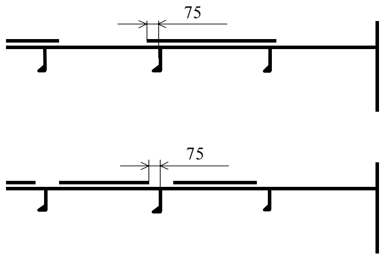


Figure 21: Arrangement of double plates

At repair of girders by strengthening of reinforcement its elements it is necessary to provide strengthening on all length of span. For reinforcement of girders double plates on walls and face plates, and also girders from rolled bars can be used. Recommended scheme of reinforcements of the worn out girders are given on the Figure 23.

The reinforcement of the deformed element of the hull or its area can be executed with the help of the following means:

- cords (double plates, see Figure 24);
- girders;
- stiffeners.

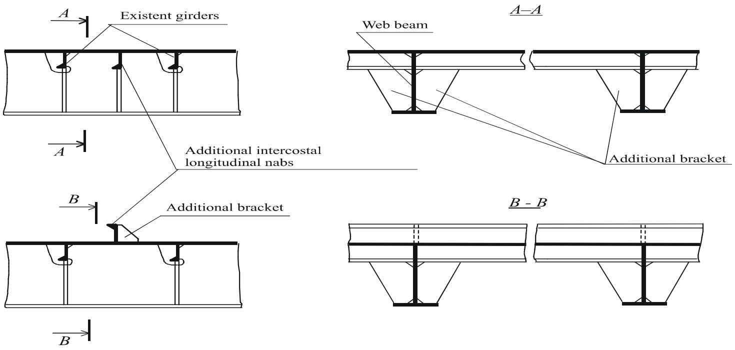


Figure 22: Installation of additional girders.

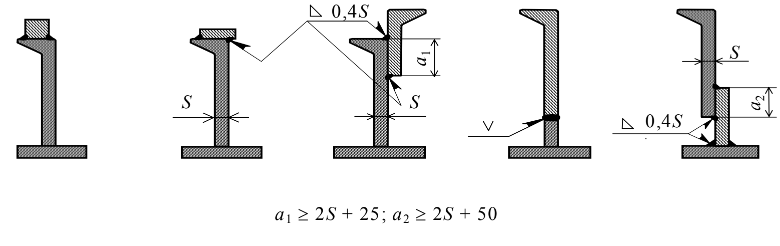


Figure 23: Reinforcement of girders

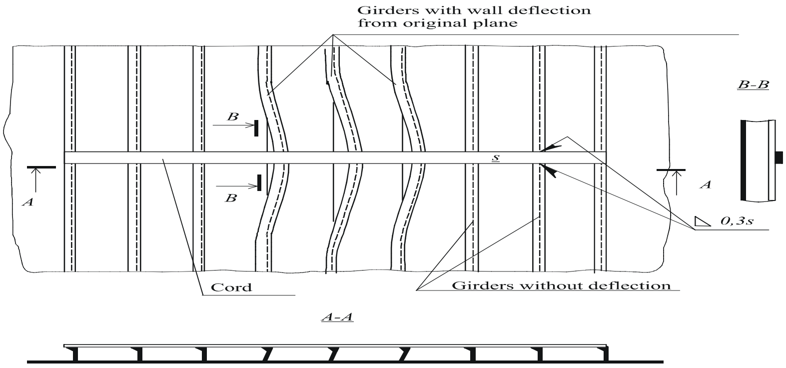


Figure 24: Reinforcement of girders by cords

To repair cracks it is necessary to remove the crack tip by means of stop drilling. The diameter of the aperture should be not less than the actual material thickness. Weld seam cracks and fracture surfaces should be cut down up to the intact metal.

There are two possible repair aproaches, removal of the cause of damage or improvement of the detail's fatigue resistance properties. Specific measures identified by IIW are:

A. Removal of crack
B. Re-weld
C. Surface treatments such as TIG dressing and Peening.
D. Re-weld + post weld surface treatments
E. Bolted splice
F. Shape improving
G. Stop hole
H. Modification of connection detail

The applicability of these methods is shown in table 9.

Table 9
Applicability of IIW methods

	A	B	C	D	E	F	G	H
1	G	G		G	E	G		G
2	F	F	G	E	E	E	G	E
3	F	F	G	G	E	G	G	E
4	F	F	G	G	E	G	G	E

E: Excellent	G: Good	F: Fair	N: No good

The IIW document complement and/or support IACS Rec.47 “Shipbuilding and Reapir Quality Standard”, Part B Repair Quality Standard for existing Ships and the following professional guide line for ship repair operations.

All cracks should be considered as critical until it is proved that the cracks are non-critical. As it is not economically justifiable to waste time and money on evaluations of cracks in ship equipment, all cracks founds have to be removed. The following crack repair strategy can be observed:

- Cracks in butt- and fillet weld seams shall be gouged out and rewelded with a yield strength matching consumable
- Cracks propagating in a plate, structural- or stiffening member shall be cropped out and replaced with an insert, Figure 25

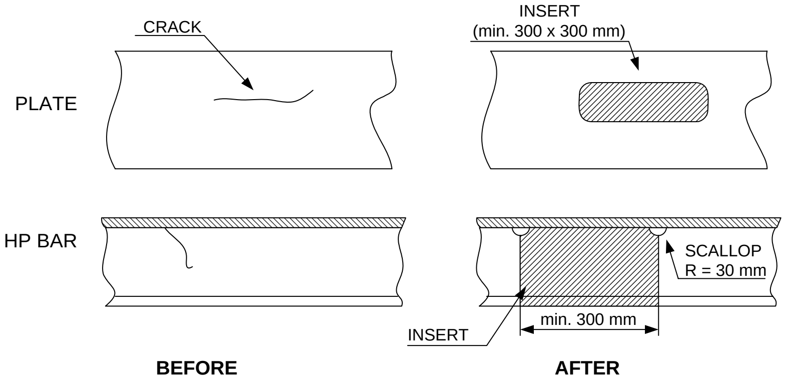


Figure 25: Cropp out of cracks in a ship structure member

- Cracks in fillet weld seams of a cross-junction shall be gouged out and prepared as a full penetrating fillet weld with the use of a yield strength matching consumable (figure 25)

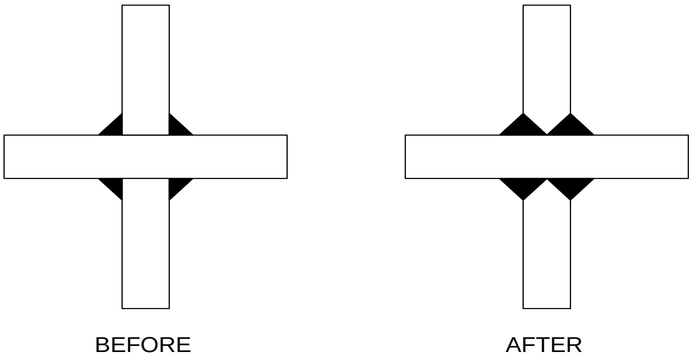


Figure 26: Illustration of a cross-junction before and after a full pentetration fillet weld repair

- Cracks in full penetration fillet welds of cross-junctions shall be examined with respect of alignment. The alignment to be rectified and rewelded as a full penetrating fillet weld with the use of a yield strength matching consumable (Figure 27).

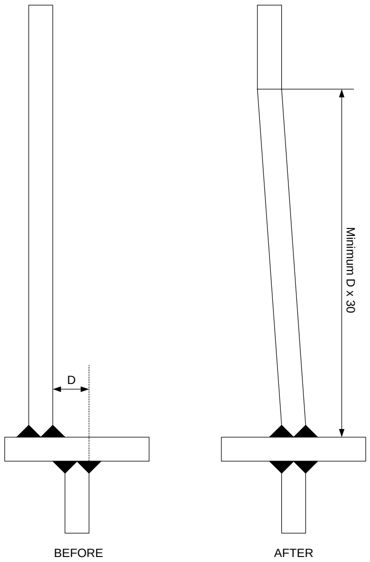


Figure 27: Illustration of alignment rectification in the way of a cross-junction, before and after

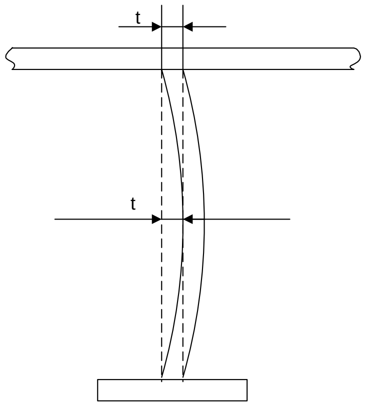


Figure 28: Illustration of a stiffener's deformation

The maximum permitted deformation of stiffeners is the nominal plate thickness. By the time, all members' thickness will be reduced by corrosion. In general the corrosion will be accelerated at deformed members. With that in mind it is important to pay extra attention to the rust protection coating at deformed members (Figure 28).

Deformed deck plates are not unusual and by reducing the distances between the beams the top plate will be stiffened up. Two stiffening approaches are commonly used at repair of deck plates and tank tops, Transversal stiffening and Longitudinal stiffening.

For a typical longitudinal spaced deck, 600 mm, one (1) longitudinal stiffener significantly reduce the numbers of stiffener ends, since the transversal spacing has to be the same as for the longitudinal to give the same stiffening effect. For the sake of increased fatigue properties, careful attention should be given to the design of the stiffener's ends. Figure 29 and 30

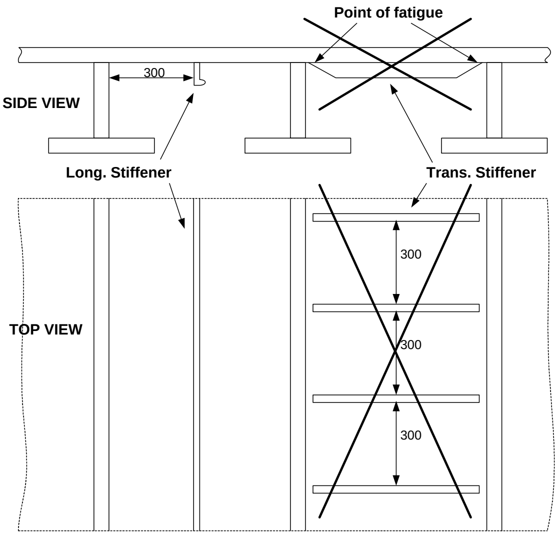


Figure 29: Illustration of longitudinal and transversal stiffeners of a deck plate

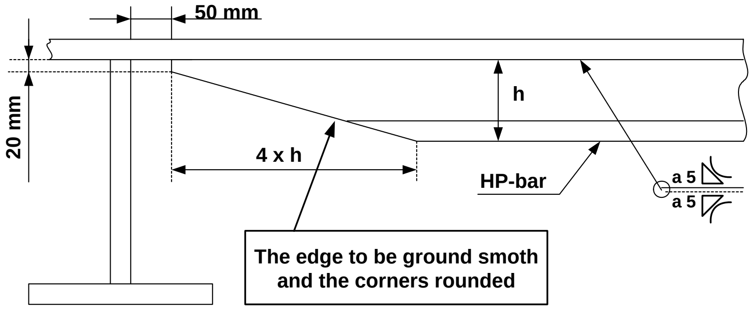


Figure 30: Design details of deck plate stiffeners

In case of local pitting of structural members may an empirical rule for boilers and pressure vessels, be applied. The corroded area can be considered as non-critical in the following circumstances:

1. Pitting affected area to be less than 15 % of a ∅ 200 mm circle
2. Length of the pitting line not to exceed 50 mm
3. Pit depth not to exceed more than 50% of nominal thickness
4. Diameter of any pit not to exceed 15 mm

An alternative approach to be used on areas with local corrosion is to consider and calclulate the affected area as an unreinforced opening in the actual structural member. If the above mentioned approaches have been succesfull should the affected area be sand/shot blasted and painted in accordance with the paint manufacturer's instructions.

6.3 Risk based decision making

Screening the literature on this topic, not many papers or official documents, dealing with this aspect of the salvages, have been found. Papanikos and Samuelides (1996) proposed an action plan to be applied after the grounding of a vessel in order to achieve pollution prevention and rescue and refloat of the grounded vessel by reducing at minimum the resources needed for the refloating operations. The plan divided in three phases is reported below:

"..***phase a:*** To avoid large scale environmental disaster, the sinking of the ship and further grounding of the ship. The means to achieve this goal is provided mostly by naval and salvage techniques.

phase b: To refloat the ship by its own facilities. The tools for refloating are tidal levels, the ship's engine thrust, weight removals on the ship, weight unloading and the use of the ship's anchors as beach gears.

phase c: To float the ship by the salvage crew. This happens by using all the well known salvage techniques and by choosing the cheapest method in each salvage situation.

Obviously phase 3 will not be needed to be performed if refloating is achieved before. .."

Every phase has a very detailed list of items and actions to be checked and performed during the salvage operations.

Enderlin, Reynolds and Hendershot (2001) in their publication on salvage method adopted to remove the main pass structure of the Shallow Water Protector Platform #3 located offshore Lousinana, reported that a formal risk based study of the different options available to remove the concrete deck structure was performed before deciding to cut the deck in small parts by the use of the water jet cutting.

Recently, QinetiQ performed a risk analysis as a basis to decide whether or not HMS Grimsby could realistically sail back to the UK under its own power or if it would need help from another source. To achieve this they first established likely loading on the vessel by performing numerical load predictions using analysis tool PRECAL and in-house post processors. Details of the damage were incorporated into a finite element (FE) model where they were analyzed to estimate the stress levels in the hull and the likelihood of structural instability. These concluded that the ship was not sufficiently seaworthy to return to the UK unaided. Then was to establish the sea conditions in which it could safely operate to facilitate disembarkation of its ammunition. Numerical calculations were again carried out but this time looking at operations in sea states two and three. More detailed survey reports of the damage were available so more accurate representation of the damage could be fed in to the FE model. The results of the calculations for this second phase of work were also completed within a three day period and contributed to the safe unloading of the ammunition.

QinetiQ has also implemented an Onboard Risk Performance Hazard Evaluation System, ORPHEUS. The system provides bridge staff with the means to quantify the risk of operating a ship in extreme weather combining real-time information with a database of previously generated data. This system can be a source of solid assumption when risk based decisions have to taken with regard to the salvage operation of damaged vessels.

Except for the few cases reported below, it seems that risk based approach is not formally and systematically adopted when considering the salvage or rescue operations. Major salvage companies and oil companies confirmed that no official procedures or document are used in order to assess, in a systematic way, the risk related to the eventual salvage operations. A famous case, where the salvage operations could have been based on risk based approach, is the M/T Prestige accident. Probably, in this case, a risk analysis could have helped the Spanish authorities to understand that a safe port of refuge was the only solution to the problem avoiding the dramatic consequences.

7. CONCLUSIONS AND RECOMMENDATIONS

The assessment of the strength and safety of a ship in damaged condition and consequently the definition of a procedure that should be followed in order to identify an emergency response plan after damage, is a complex and challenging task mainly because, a) it is a highly non linear problem, b) there is plurality of damaged cases that should be considered and it is not apparent which are the most critical for the overall safety of the vessel, c) it requires the actual description of the structural elements of the vessel rather than a description of the vessels as built. The report described research efforts that address these aspects.

Advances have been made on the definition of damage scenarios to be considered at the design stage, although additional work and improvements are to be expected in the future.

The importance of better quantifying the loading in accidental conditions has been recognised and some works have been published. This is a topic in which additional work is to be expected and promoted.

A diversity of works has been published on the assessment of the strength of damaged structures, an area that appears as being active in research.

Not much work has been reported under salvage and emergency repair. It is recommended that the international organizations of competence seriously consider the topic of emergency repair and salvage because there is no harmonization between the companies performing salvages and recovery, no systematic way to approach the accidents, there is an absence of guidelines and officially recognized procedures and in many cases no accurate quantitative risk assessment performed before starting the salvage operations.

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