ABSTRACT: This paper discusses the damage stability of generic bulk carriers following a collision. The damage stability is calculated and average survivability is estimated for the world fleet of bulk carriers using data from the HARDER project. Generic results have been compared to specific results using the HARDER approach. The average survivability given collision with water ingress of bulk carriers is also estimated based on records of recent bulk carrier accidents and it is demonstrated that the HARDER results are in general agreement with historic data. A simplified approach to estimate the conditional survivability using simple event trees is also presented. Furthermore, it is estimated that the introduction of double side skin on bulk carriers will enhance the survivability of bulk carriers with approximately 5 – 7.5 %. Finally, the longitudinal strength on bulk carriers is considered in relation to collisions, and it is concluded that the longitudinal strength is dimensioned by other flooding conditions already included in the rules.

1. INTRODUCTION

A bulk carrier that experiences flooding of one or more cargo holds or machinery spaces is exposed to the risk of losing its stability and thus suffers the risk of sinking. Several accident scenarios can cause flooding of a bulk carrier, e.g. corrosion and fatigue causing loss of side shell integrity, water ingress through hatch covers in rough seas, grounding and collision with another vessel. In the current study, the latter scenario is focused.

In general there are two main approaches to minimize the risk associated with collisions, i.e. reducing the frequency of collisions and minimizing the consequence of a collision. Enhanced navigation systems and bridge procedures are examples of the first, while improving the crashworthiness or damage stability of the ship is the most important means to minimize the consequence. Another measure is to increase the longitudinal strength of the ship, although it is unclear whether this will have any significant effects on the consequence of collisions. In addition one can improve emergency response and life saving systems in order to reduce the number of fatalities and thereby the consequences if stability is lost. The stability of the ship will be affected by a number of issues such as the watertight subdivision of the ship, whether it is single sided (SSS) or double sided (DSS) etc, and these will be considered in this paper.

The International Maritime Organization (IMO) imposes numerous requirements, for example the International Convention for the Safety of Life at Sea, SOLAS (2001), on all types of ships involved in international trade. Bulk carriers are no exception, and there are even additional SOLAS requirements applicable for bulk carriers regarding damage stability, structural strength etc as well as an International Convention of Load Lines, ICLL (2002) that bulk carriers are required to comply with. Although current maritime regulations are comprehensive, they are constantly revised and modified. New rule proposals are continuously developed and evaluated, and for example emerging standards regarding double side skin constructions on bulk carriers are currently being considered.

The recently completed HARDER project carried out work on harmonisation of damage stability regulations at IMO based on a probabilistic concept of survival, Rusås (2003), Lützen and Rusås (2001) and Laubenstein et al. (2001). The probabilistic damage stability concept is applicable to all ship types, including bulk carriers. The project also investigated numerous records of historic collision accidents and produced various damage distribution functions and both the model and these distributions will be referred to in this paper.

This paper first briefly introduces the HARDER model and outlines the main concepts and results of the HARDER project. Next, collision and damage stability of bulk carriers will be discussed and records of historical collisions of bulk carriers contained in the Lloyd’s Register Fairplay (LRFP) database will be investigated. Subsequently, a survivability index based on HARDER data will be estimated, and the survivability found from HARDER will be compared to historical data. Finally, the issue of longitudinal strength in relation to collision scenarios of bulk carriers will be briefly addressed before the conclusion.

2. THE HARDER MODEL

The EU project HARDER was initiated in order to assist the work on harmonization of damage stability regulations in IMO. The aim of the project was to systematically investigate the validity, robustness, consistency and impact of harmonized probabilistic damage stability regulations on new and existing ships and to formulate new harmonized probabilistic damage stability regulations covering all types of vessels.

Work within the HARDER project has been carried out in several work packages. The first tasks were to collect and analyse data of actual damages and update the existing IMO damage database containing damage location, length, depth and height. Subsequently, procedures for calculations and computer simulations of the probability distribution of the damage penetration, length and height were formulated. These distributions are then utilized to study, by means of model tests and numerical simulations, the behaviour of a damaged ship in seaway and to derive rational boundaries for the survival of the damaged vessel. The results and factors derived within the project were then to be tested for validity, robustness and consistency for at least 20 sample ships and equivalent levels of safety between the requirements resulting from deterministic stability rules (SOLAS) and the framework of HARDER were to be demonstrated. Finally, the probabilistic concept were to be implemented in naval architecture software and its impact on new
ship design were to be investigated before the new and validated procedures for probabilistic damage stability were written down in a format applicable for submission to IMO as a rule proposal.

Simply put, the HARDER model consists of the following steps: 1) probability distributions of non-dimensional damage location, damage length, damage penetration, and vertical extent of damage. These data were based on a comprehensive review of casualties and also compared to computer simulations to determine the expected damage size. 2) A survivability factor, the s-factor, describes the probability of survival given this extent of damage. The s-factor is based on predicting the critical wave height for the collision, and the probability of survival is equal to the probability that this wave height is not exceeded. The wave height at the time of collision is derived from the damage database and the critical wave height is calculated from the characteristics of the specific ship. 3) The attained subdivision index, A, is then calculated as the sum of the survivability given all possible damages and this corresponds to the total survivability of the ship. 4) A required index, R, is found that ensures that an equivalent level of safety compared to the SOLAS regulations is maintained.

In short, the main concept of the HARDER approach can be summarized as follows, where p and v represents the probability that a portion or portions of the ship are damaged, restricted longitudinally and transversely (p) and vertically (v) respectfully, s is the survivability factor and A and R are the attained and required subdivision indices.

\[ A = \sum p \cdot v \cdot s > R \]  

3. COLLISION OF BULK CARRIERS

According to a recent FSA relating to the generic vessel risk of bulk carriers, Hoffmann et al (2003), collision between two ships is the second most frequent accident type involving bulk carriers, second only to accidents of the Hull/Machinery/Equipment category. In a collision between two ships, the ship being struck will normally be the one receiving the greatest damage and the one with highest probability of loosing its stability. This is due to the fact that ships receiving an impact and thus damages only in front of the collision bulkhead will survive in almost all situations. This will be the case of most striking ships but not for struck ships and the latter will have a much higher probability of water ingress into one or more of its compartments aft of the bulkhead.

The collision scenario would consist of the following events: 1) Collision, 2) Water ingress given collision, 3a) Collision damage extending through the side shell and initiating flooding into the cargo holds (or machinery spaces), 3b) Collision damage extending through two cargo holds and 3c) Collision damage extending more than two cargo holds. As far as the damage stability is concerned, the scenarios 3a, 3b and 3c, i.e. the probability distribution of 3a, 3b and 3c given 1 and 2 and the survivability of these scenarios, are covered by the HARDER model both for single and double side skin constructions. The frequency of serious collisions and the frequency of flooding can for example be obtained from statistical databases containing records of historical accidents and world fleet statistics.

4. RECORDS OF HISTORICAL ACCIDENTS

In order to validate the HARDER calculations of survivability of a specific ship type given collision and to enable comparison with actual accident statistics in recent years, a survey of previous accidents of bulk carriers has been performed. The survey will also indicate the probabilities of events 1 and 2 above; collision and water ingress given collision.

The Lloyd’s Register – Fairplay (LRFP) database has been utilized as the base of the current survey. All bulk carrier accidents included in this database from and including 1990 to and including 2002 have been searched, and the accidents involving collisions have been isolated. However, ships of sizes below 20,000 dead weight ton (dwt) has been omitted from the study.

The database contained 1,691 records of accidents involving bulk carriers above 20,000 dwt resulting from a total exposure of 55,299 ship years during the considered period. Of these, 393 records of accidents involving collision were identified. It was assumed that less serious accidents are underreported, but for serious accidents it is believed that the database is adequately complete to provide sufficiently accurate estimates of the actual accident frequencies.

The objective is to investigate the probability of a bulk carrier retaining its stability following a collision as comparison with HARDER estimates. All vessels involved in a non-serious collision incident would obviously retain its stability, thus only serious accidents are further investigated. The database contained 144 records of collision accidents regarded as serious. These records includes both striking and struck ship, collisions resulting in flooding or no flooding of one or more compartments of the ship, ships that sunk and ships that survived the collision, records with a collision as the first event and records with collision as subsequent event, e.g. subsequent to machine failure, and accidents resulting in fatalities as well as accidents were no fatalities occurred.

In the present study, both accidents with collision as the first event and accidents with collision as a subsequent event to e.g. machine failure have been included. In an FSA of generic vessel risk, such as the one that has been published for bulk carriers in Hoffmann et al (2003) or in the large number of IMO submissions to the Maritime Safety Committee (Sessions 74 to 77), the accidents are normally categorised after the initiating event. Due to this categorisation, one should assume a slightly higher probability of a serious collision than what is found in such generic vessel risk FSAs. Of the 144 serious collision accidents included in this study, 134 or 93 % of these had the collision as the first event. The remaining 10 accident had another incident such as machine failure as the first event. When comparing the probability of collision with other studies, this should be kept in mind.

Of the 144 serious accidents, 51 reported flooding and 93 did not. This corresponds to 35% probability of flooding and 65% probability of no flooding given a serious collision has occurred. An accident were categorised as including flooding if one of the following were reported: flooding, sprang leak, took water, leaked/spilled as well as any reported accidents resulting in ruptures, gash or holes below the waterline. Of the 51 accidents involving flooding, four of these reported flooding in the forepeak only, and may be assumed to represent striking ships.

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Of all the accident records, 14 included ships that either sank or would probably have sunk if it were not beached deliberately following the collision. This corresponds to a frequency of about 27% for the ship to lose its stability if it experiences flooding due to a collision. For ships where other parts than the forepeak only are flooded, a frequency of 30% will lose its stability. 6 of these ships actually sunk subsequent to the collision.

6 of the serious accidents that were studied contain reports of fatalities or missing people. 2 of these were on board ship that did not sink, including one accident where the accommodation area above the waterline was damaged in the collision. 4 accidents where the ship involved 1, 26, 27 and 29 fatalities respectively. Thus 67% of all collisions with bulk carriers that result in sinking of the vessel also involve fatalities.

All the above findings can be summarized in the event tree illustrated in Fig. 1. According to this, there is an average frequency of 2.5 \times 10^{-5} per ship year for a bulk carrier of any size bigger than 20,000 dwt to loose its stability due to a collision. The probability of water ingress due to a collision is 9.2 \times 10^{-4} and the probability of loosing stability given water ingress in other compartments than in front of the collision bulkhead is about 30%. The potential loss of life (PLL) is at 1.5 \times 10^3. These numbers correspond to current single side skin (SSS) bulk carriers and for double side skin (DSS) these numbers are expected to be lower, which will be considered below.

A final note from studying the historical data of collisions of bulk carriers is that only one incident is reported where the ship broke in two and sank following the collision. In this incident, the struck ship was literally cut in two by the striking ship and received such severe damages that it sank very quickly. For the sake of subsequent discussions it should be noted that it is highly unlikely that increasing the longitudinal strength of this ship would have prevented it from sinking, as the damage it received was big enough for the ship to be lost from loss of stability regardless of whether it broke in two or not.

5. DAMAGE STABILITY

In the following discussion of damage stability for single sided skin and double sided skin bulk carriers, it is initially assumed that a double sided bulk carrier will survive all damages that do not penetrate the double skin. This might not always hold true, however, and there is a possibility that asymmetric damages penetrating only the outer skin on one side of the vessel will cause asymmetrical flooding. This kind of asymmetric collision damage might influence the stability and increase the probability of capsizing. Nonetheless, these effects are not considered in the current study, and reservations against possible effects this might have on the discussion are made. The positive effects on collision scenarios of introducing double side skin to bulk carriers might thus be somewhat exaggerated in the subsequent discussion due to this assumption.

The probability that a collision that results in water ingress do not penetrate the inner side skin of a DSS bulk carrier may be calculated from the distribution of penetration depth from the HARDER database. It is assumed that the inner shell is at B/20, corresponding to a distance between the inner and outer of about 1.6 meters for a Panamax with B = 32.2 meters (B denotes the breadth of the vessel). From the distribution density for the non-dimensional damage penetration published by the HARDER project, Rusås (2003), one finds that the probability of penetration into 1 or more cargo holds of more than B/20 is p(z > 0.05) ≈ 0.8. The distribution of non-dimensional penetration depth that has been used is reproduced in Fig. 2.

Fig. 1. Event tree for collision of bulk carriers according to survey of recent accidents

Fig. 2. Probability distribution of non-dimensional collision penetration

However, double side skin will not cover the whole side of the ship, and the estimated effect on the probability of sinking that results from introducing DSS must take this into account. The DSS area is restricted in height to the area between the hopper tank and the top wing tank and longitudinally by the length of the cargo holds. As a crude approximation, one can assume that the length of each cargo hold equals the length of the ship aft of the cargo holds. The longitudinal part of the ship affected by DSS will thus be 5/6, 7/8 and 9/10 for bulk carriers with 5, 7 and 9 cargo holds respectively.

Assuming that the longitudinal damage location is evenly distributed over the ship, in accordance with Rusås (2003), this will also be the ratio reducing the effect of the DSS. In a similar way, it is assumed that the vertical damage location is evenly distributed, and assuming that the height between the hopper tank and the top wing tank constitute on average about 50% of the total height, the effect of the DSS is further reduced by a factor of 1/2. These geometrical considerations are illustrated in Fig. 3.-Fig. 4. In Fig. 3, the longitudinal part of a bulk carrier with 5 cargo holds where DSS will be introduced is indicated, and in Fig. 4 a cross-section of a conventional SSS bulk carrier illustrates the height affected by DSS introduction within the cargo holds of the ship.

Fig. 3. Longitudinal area of a bulk carrier affected by introducing double side skin
The survivability (1 – the probability of sinking) shown in Table 1 has been taken as the average of the survivability results from the HARDER project, Norway and UK (2003). These are average values for current SSS bulk carriers. In order to estimate the survivability of DSS bulk carriers, one assumes that collisions resulting in damages penetrating only the outer skin in the areas where DSS is introduced will not cause the ship to sink. According to the discussion above, the probability of sinking for DSS bulk carriers will be $P_{DSS} = P_{SSS} (1 - 0.2 \cdot 0.5 \cdot \lambda)$, where $\lambda = 5/6, 7/8$ and $9/10$ for 5, 7 and 9 cargo holds respectively. The factor $0.2 \cdot 0.5 \cdot \lambda$ corresponds to the probability of not penetrating the DSS conditional on penetrating the outer shell in the area of the ship side that will be affected by DSS introduction.

The probabilities of damaging 1, 2, and more than 2 compartments have been estimated by using the non-dimensional damage length distribution in Fig. 5. This distribution is based on the HARDER database and is an update of the distribution presented in Rusås (2003) with a shift towards lesser damage lengths. For this generic database and is an update of the distribution presented in Rusås (2004), the effect of DSS on damage stability of bulk carriers was estimated to enhance the survivability with around 2.5 – 4%. This corresponds to the probability of not penetrating the DSS conditional on penetrating the outer shell in the area of the ship side that will be affected by DSS introduction.

It is found that these sample ships have considerably better survivability than the average in the fleet, i.e. the attained subdivision indices are higher than the average. The numbers should be adjusted slightly (by a few percentages) to represent the average survivability and thereby being representative for the average in the fleet. The resulting average attained subdivision index is $A = 0.55, 0.6$ and 0.65 for a typical 5, 7 and 9 compartment single side ship bulk carrier, respectively. For DSS the survivability improves to 0.59, 0.64 and 0.68 for 5, 7 and 9 compartment ships, respectively.

Note that all details can be calculated for a specific ship by use of the HARDER model. In the following, a simplified approach has been made by preparing a representative event tree that produce the average results for 5, 7 and 9 compartment ships. In the event trees, the probability of collision with water ingress is extracted from the LRF database, the probability distributions of one, two or more than two compartment damages are found from the distributions of non-dimensional damage length produced by the HARDER project, and the average attained subdivision indices for the fleet are used for 5, 7 and 9 compartments bulk carriers. Based on this, the probabilities of surviving given one, two and more than two compartment damages respectively have been estimated. The event trees are presented in Fig. 6- Fig. 8.

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2 The update of the damage length distribution is due to more detailed investigation of the available statistical data. Some accidents that were previously counted more than once were removed, and the total length of the vessels have been changed from LPP to the slightly longer and more correct length of the buoyant part of the vessels, i.e. the "subdivision length."
The estimated probabilities of survival are presented in Table 3. In Table 4, the resulting total risk for bulk carriers due to collision is presented, based on the survivability estimated above and the historical frequencies of serious collision accidents, e.g. with water ingress.

### Table 3. Estimated probabilities of survival

<table>
<thead>
<tr>
<th>Collision Damage (Water Ingress)</th>
<th>Severe Through</th>
<th># Of Sink</th>
<th>Probability of survival</th>
</tr>
</thead>
<tbody>
<tr>
<td>No No</td>
<td>0.000184</td>
<td>0.1</td>
<td>Survive</td>
</tr>
<tr>
<td>&gt;2 comp</td>
<td>No</td>
<td>0.01</td>
<td>2.208E-07 Survive</td>
</tr>
<tr>
<td></td>
<td>Yes</td>
<td>0.99</td>
<td>2.18592E-05 Loss</td>
</tr>
<tr>
<td>No</td>
<td>Yes</td>
<td>0.52</td>
<td>3.7944E-05 Loss</td>
</tr>
<tr>
<td>Yes</td>
<td>2 Comp</td>
<td>0.21</td>
<td>0.79 0.000139546 Loss</td>
</tr>
<tr>
<td></td>
<td>No</td>
<td>0.06</td>
<td>Survive</td>
</tr>
<tr>
<td></td>
<td>Yes</td>
<td>0.85</td>
<td>5.07 0.00014912 Loss</td>
</tr>
<tr>
<td>A</td>
<td>0.5906</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 4. Total risk due to collision

<table>
<thead>
<tr>
<th>Number of Cargo Hold</th>
<th>Approximate Length</th>
<th>Probability of sinking due to collision per ship-year</th>
<th>Probability of sinking, due to 1 compartment damage SSS</th>
<th>Probability of sinking, due to 2 compartment damage SSS</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>300</td>
<td>0.65 / 0.68</td>
<td>0.93</td>
<td>0.45</td>
</tr>
<tr>
<td>7</td>
<td>220</td>
<td>0.6 / 0.64</td>
<td>0.80</td>
<td>0.34</td>
</tr>
<tr>
<td>5</td>
<td>150</td>
<td>0.55 / 0.59</td>
<td>0.60</td>
<td>0.21</td>
</tr>
</tbody>
</table>

6. COLLISION AND WEATHER CONDITIONS

The HARDER project has also estimated the weather condition at the time of collision between two ships based on the data contained in the HARDER database. The distribution of significant wave height (Hs) from these estimates is shown in Fig. 9 where also the global and North Atlantic distributions are given. The estimates are based on all ship types, but are assumed to be an applicable distribution for bulk carriers as well. It can be read from this distribution that the probability of Hs < 2 meters, which is calm weather, is 0.9. This indicates that collisions are most likely to occur in calm weather and the explanation can be that collisions are associated with fog and/or congested traffic, both of which are associated with calm weather.

It can also be seen from the distributions of the significant wave heights that collisions are associated with notably calmer weather than the average global and North Atlantic weather conditions. This substantiates the assumptions that collisions between two ships are most likely to occur in calm seas.
Historical data is not substantial; the survivability estimated by the HARDER results and the survivability gained from the calculation referred to in this paper, the following coefficients have been used: deepest loadline = 0.4, partial loadline = 0.4 and light loadline = 0.2, and thus reducing the relative contribution from the condition with the highest survivability. Another choice of weight coefficients could thus have increased the survivability obtained from HARDER.

Taking all this into consideration, and realising that the deviation between the HARDER results and the survivability gained from historical data is not substantial; the survivability estimated by the HARDER approach can be regarded as being in fine agreement with available historical data.

8. LONGITUDINAL STRENGTH

The HARDER model is a damage stability model, and the assumption is that the ship does not break in two after the collision due to longitudinal weakness, i.e. if it survives the collision stability wise it will survive. A reasonable longitudinal strength requirement is to require that the ship has sufficient longitudinal strength to survive those damage scenarios the damage stability calculations suggest that the ship survive, as the introduction of more strength will not reduce the probability of sinking. In order to determine whether introducing more strength would be a cost effective measure, some crude considerations have been made.

It is assumed that increasing the longitudinal strength is only relevant for the range of non-dimensional damage penetrations of b/B = 0.25 – 0.45 as other intact and damage scenarios deliver at least 25% reserve strength in calm weather. For larger damages it is assumed that the ship will be lost due to loss of damage stability and for smaller damages, the longitudinal strength is assumed to be non-critical. In the above range it is thus assumed that the survivability of the ship is solely dependent on the longitudinal strength. This assumption is obviously unrealistic and is only made to test if additional longitudinal strength should be considered as an option. Furthermore, it is assumed that the longitudinal strength is proportional to the remaining intact breadth of the ship after the collision, i.e. S ~ (1 – b/B). A collision resulting in non-dimensional damage penetration of for example 0.45 thus correspond to a remaining longitudinal strength of 55% of the intact ship prior to the collision.

Cost = 50 t/meter x 220 meter x 0.01 x $ 1,000/t = $ 110,000 (2)

This will increase the survivability with 1.3% and thus the following reduction in fatalities over a typical ship’s lifespan of 25 years, with an average potential loss of lives PLL = 0.0016 fatalities per shipyear (f/sy) due to collision of Panamax bulk carriers:

$ΔPLL = 0.0016 f/sy x 25 sy x 0.013 = 0.000525 fatalities (3)$

Keeping in mind that the assumptions made (cheap steel and that all ships have sufficient damage stability to survive if they do not break in the considered range of penetration depths) indicates that the calculations significantly underestimates the cost, the following GCAF is obtained:

$GCAF >> $ 111,000/0.00052 = $ 211 million (4)$

As a comparison to the GCAF value found in Eq. (4), it should be noted that a GCAF criterion of $ 3 million was proposed for use in IMO in Norway (2000), and this has been the criterion used in all decisions made regarding bulk carrier safety in IMO. The cost effectiveness of introducing additional longitudinal strength according to the above crude considerations, are clearly exceeding this proposed value beyond all the uncertainties involved and the
approximations made.

Thus it should be rather obvious from these crude calculations that it will not be cost effective to introduce more strength to make the ship survive damage conditions. A further support of this view is that the HARDER results give predictions that are in agreement with historic data and the HARDER approach assumes that strength is not an issue. Neither was any records found in the accident database of ships that were lost due to insufficient longitudinal strength.

9. CONCLUSION

The survivability after collisions of bulk carriers has been estimated based on both the HARDER model and by investigating records of previous collision incidents. The results from the two approaches are found to be in agreement and thus the validity of the HARDER approach has been substantiated. The average survivability of a typical bulk carrier is found to lie in the range of 60 – 70 % given flooding of one or more compartments.

The introduction of DSS bulk carriers is assumed to enhance the damage stability related to collision compared to current SSS bulk carriers. By simple means, this paper has estimated an improvement of 5 – 7.5 % in the survivability for DSS compared to SSS bulk carriers. However, it is emphasized that the negative effect of asymmetric flooding introduced with the introduction of DSS is ignored. The estimated positive effect on damage stability from DSS introduction is thus considered to be somewhat exaggerated. In addition, it has been demonstrated that the introduction of more steel into the ships in order to increase the longitudinal strength and thus prevent ships from sinking will not prove cost effective. On the contrary, the longitudinal strength is assumed to be of negligible importance regarding collision of bulk carriers.

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