

RISK ASSESSMENT OF DOUBLE-SKIN BULK CARRIERS

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SUMMARY

This paper refers to work performed in WP6 of the International Formal Safety Assessment study of Bulk Carriers led by the Royal Institution of Naval Architects. It outlines the results of task 6d, where the main objective was to determine whether the new Chapter XII of SOLAS is sufficient also for bulk carriers of double skin construction. The study reported here covers the following aspects: a review of the design of double skin bulk carriers, accident statistics, identification of hazards that are specific to vessels with double-skin, investigations of structural strength and survivability, and finally cost-benefit analysis.

1. INTRODUCTION

As part of the Formal Safety Assessment study of bulk-carriers, carried out by an international consortium led by the Royal Institution of Naval Architects (RINA), the Ship Design Laboratory of the National Technical University of Athens (NTUA-SDL) have undertaken to investigate, within the set time-frame, whether the new survivability and structural requirements of SOLAS Chapter XII are sufficient for covering also bulk-carriers with double-skin construction. In this paper will be explained the main findings of this investigation, which has included the following parts:

1. A review of the design and structural arrangement of doubled-skinned (DS) bulk-carriers, with emphasis on their major differences compared to the single-skin (SS) type.
2. A search into the casualty database of Lloyd's Maritime Information Services (LMIS) for accident records of DS bulk-carriers.
3. Derivation of the list of hazards that are specific to DS bulk-carriers. The main objective here was to single-out those hazards that could lead to different consequences for the DS as compared to the SS bulk carriers, as well as those hazards that can be considered as intrinsic to the DS. Earlier submission to IMO, [1-3], and generic lists of hazards have been used for this.
4. A search into Lloyd's Register's incident database for corrosion and fatigue occurrences for DS versus SS bulk-carriers, at various locations of the holds' structure.
5. An indicative comparative assessment of the strength in the hold No. 1 of a DS with that of a SS vessel.
6. An analysis of survivability of a double-skin bulk-carrier for the case of asymmetric flooding.

The introduction of the double skin is an effective risk reduction measure, however the wide-scale adoption of such a measure depends on the economics of its implementation versus the implied reduction of risk in quantitative terms. This varies depending on whether the implementation concerns a new construction or an existing vessel. For the latter case it depends further on its remaining period of service and to a lesser degree on bulkcarrier type. Based on a review of data from two independent sources we have come to the conclusion that the introduction of the double-skin represents a cost effective measure for newbuildings. Furthermore, it is quite probable that a conversion to double-skin is still cost effective even for a 10-year-old bulk-carrier. These matters are discussed in more detail in the following sections.

2. STRUCTURAL DESIGN ASPECTS OF DOUBLE-SKIN BULK-CARRIERS

Two key advantages can be identified for the double-skin concept of bulk-carrier construction: the existence of redundancy in case of penetration of the outside shell from a low to moderate energy impact; and perhaps more importantly, the fact that primary structural members need no longer suffer from corrosive effects by being in direct contact with the cargo. Further benefits arise with respect to hull damage during cargo loading and off-loading: the external skin is no longer in direct contact with mechanical tools (grabs), therefore the damage and detachment of frames that often arises from such contact can be prevented. Double-sided structures have flat sides in the cargo holds and as a result, pounding, scraping and jarring are not required at the final stage of the cargo discharge process, something that contributes also to a lower probability of damage in the hold. Also, the discharge time is reduced.

A typical Panamax double-skinned bulk-carrier has a six-hold arrangement which is different from the established design pattern of seven holds for the conventional Panamax type. Whilst the draught remains similar with the draught of equivalent single-skinned bulkers, however the stronger inner bottom plating which they have counteracts the higher stresses that could be experienced during loading. The double-hull structure makes the vessels stiffer and helps to prevent hold flooding in the damage condition. Therefore, from this point of view, this vessel is safer than one with a single-skin structure. If the bottom is damaged, the fuel oil tanks are not likely to be penetrated, since they are no longer located in the double bottom; hence pollution is prevented. The smooth-sided cargo-hold design reduces the need for inspection and facilitates maintenance. Due to their lack of stiffeners, the internal hull is easier to clean, and maintenance and repair of hold coatings are more efficient and less costly. Another, not so obvious, benefit is the protection of the cargo against variations of the external temperature.

In Fig. 1 is shown a DS bulk-carrier at the construction phase from Oshima, the Japanese shipyard which has pioneered the construction of such vessels [4]. Instead of modifying the principal hull dimensions in order to compensate for the reduced cargo hold space, they have used smaller topside and hopper tanks, Fig. 2.

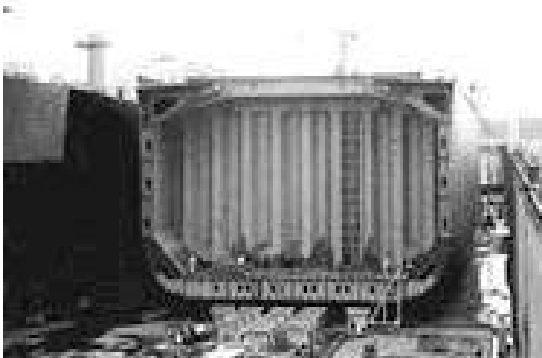


Fig. 1: Construction of a double-skin bulk-carrier at Oshima shipyard [4].

The geometries of holds for a single-skin and a double-skin design can be compared against each other in Fig 3, on the basis of a recent collaborative project between Germanischer Lloyd and the German shipyard Flensburger Schiffbau-Gesellschaft [5]. In this case the lost volume due to the extra skin was compensated by reducing the height of the double-bottom as well as the size of the hopper and topside tanks. To facilitate fabrication, inspection and maintenance, the width of the

double-side skin was set to 1.0 m. The relatively small space between the two skins reflects the fact that the extra skin is not regarded so much as a measure against collision, but it is rather seen as a measure against corrosive effects in the hold. The side ballast tanks were designed as L-shaped. For ballast are used also the upper wing areas and the fore and aft peak. The double skin helps also to achieve a more homogeneous stiffness with respect to the transverse strength of the hull [6].

The double-hull design was derived from a 225.0 m long single-skin vessel. The cargo space was comprised of seven holds. Six of these had the same length while the tanks for the consumables were placed around the engine room. A finite element study was carried out for the vessel with the double skin and an important finding was that the thickness of the inner bottom in the empty holds (2, 4 and 6) should be increased due to the reduced height of the double bottom. The higher double bottom influences also the thickness of the bottom girders and the inclined plating of the hopper tank. The reinforcements that needed to be introduced are summarised in Fig. 4.

Several structural design alternatives of the double-skin arrangement were investigated in this project. The first was a typical structure with longitudinal stiffening and transverse webs. Another alternative was a vessel

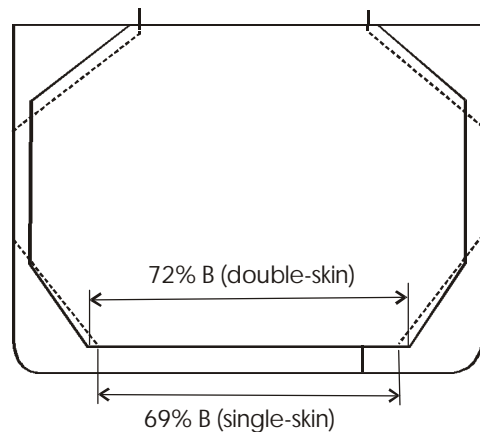


Fig. 2: Comparison of the layout of a typical cargo hold of a Panamax for DS and SS construction.

equipped with transverse webs at each frame. A third alternative was based on a mixed longitudinal and transverse framing; and a fourth had a rather unusual, curved shell as inner skin. These authors have calculated the difference in the resale value of a double-skin compared to a single-skin after 15 years of operation to be about \$200,000 and also, the reduced cost due to less cleaning time in ports to amount to \$12,500/year. An extra benefit arises from the lower risk of being “off-hire”.

The double-hull concept may be applied also over a limited region of a ship's forward part which, quite obviously, is at a higher risk against flooding. It can be applied in particular for the hold No. 1 for which also there are special provisions in SOLAS' Chapter XII. According to the Korean study [3], the fitting of a double skin of 0.76m breadth in hold No. 1 generates a significant benefit in terms of risk versus cost. The reduction of the available cargo space was merely 2.6% while the estimated total cost for design, construction and loss of cargo hold space was about 27,084 US\$.

Useful information about typical DS arrangements, structural components required at various locations of the structure and characteristic midship sections can be found also in the Japanese submission to IMO [1].

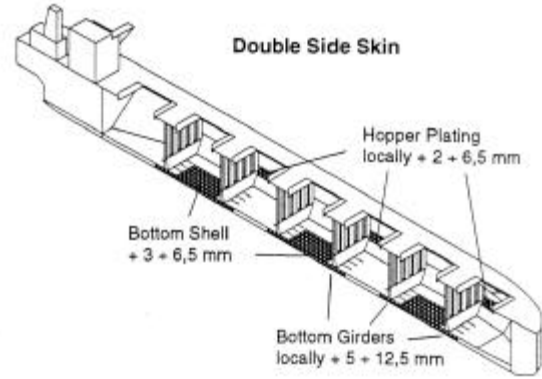


Fig. 4: Typical required structural reinforcements for a double-skin bulk-carrier [5].

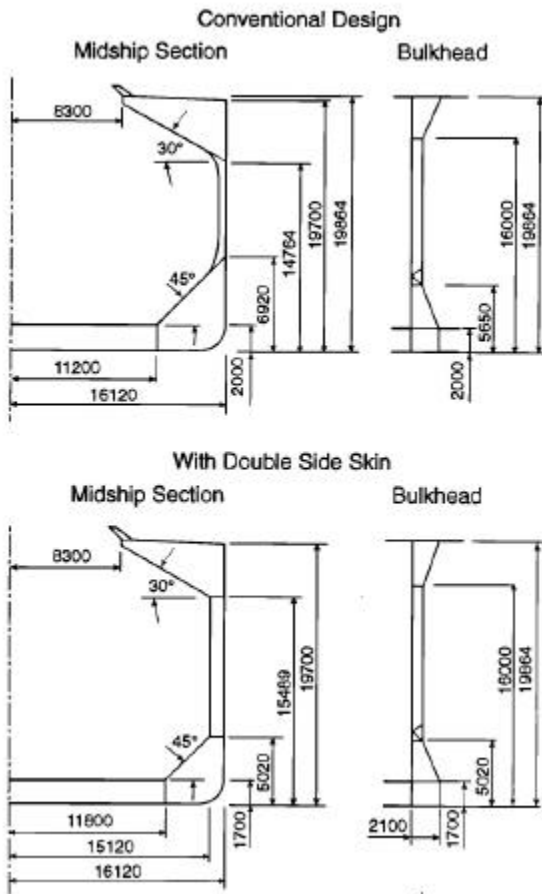


Fig. 3: Comparison of geometry of cargo holds, based on the GL-FSG study [5].

3. ACCIDENT RECORDS FOR BULK-CARRIERS WITH DOUBLE-SKIN

A search in the database of Lloyd's Maritime Information Services (LMIS) has revealed that for the decade between January 1st, 1991 and December 31st, 2000 the number of accidents concerning DS bulk-carriers is extremely limited. Only three accident records were retrieved and notably, all three concerned combination-type vessels. The initiating event was contact with another object. Details about these accidents are shown in Table 1 below:

Ship	Year	Details
1 (Panama)	1991	Bulk-carrier/container vessel, contacted dolphin jetty off Mutsure oil terminal, Shimonoseki. Fore-peak flooded, damages in external hull in way of cargo tanks 1, 2 and 3. Pollution caused by terminal facilities damage.
2 (U.S.)	1994	OBO type, collision with hopper dredger off Manhattan Island, resulting in outer hull puncture on the starboard bow.
3 (Russia)	1998	Bulk/oil type, grounding on sandy bottom as entering Guayanilla Bay. No flooding or discharge of oil.

Table 1: Accident records of double-skin bulk-carriers between 1991 and 2001.

4. HAZARDS SPECIFIC TO DOUBLE - SKIN BULK-CARRIERS

The hazards that are relevant to DS bulk-carriers and whose consequences are different compared to the SS have been determined, by reviewing available generic lists of hazards.

4.1 Data collection and review

In the Japanese submission to IMO [1] four main hazard categories were discussed: structural failure in the cargo hold; structural failure of the fore end part; water ingress through opening; and, structural failure of aft end part (no data). The data is focused on hazards that are relevant for “Capesize” bulkers with single side-skin. From these 4 categories only the first two could accommodate differences between DS and SS designs.

In the IACS submission [2] a total of 51 hazards that could influence watertight integrity have been identified, 10 of which were considered as posing an unacceptable level of risk, 38 were ALARP and 3 were characterized as broadly acceptable. This study did not contain data on other accident categories such as fire, explosion, machinery failure, grounding etc. As contributing to the top event (loss of watertight integrity) four categories of hazards were identified: Structural failure, failure of hatch cover securing systems, water ingress through access hatches and water ingress through internal piping systems and pipes penetrating the weather deck. From the hazards listed in the IACS HAZID worksheet, relevant to DS bulk carriers are only those in the structural failure category, especially, side-shell failure.

A complete FSA study for the flooding of the No1 cargo hold was presented in the Korean study [3]. Such a flooding scenario is a high probability one, since it is the reason for approximately 40% of all bulk-carrier casualties. Two of the risk control options (RCO) considered were based on a double skin structure for hold No1: one with a distance between inner and outer plating of 0.76 m. and the other with a distance of 1.0m. Fault

trees for these two, partially double-hull, configurations were determined. The hazards identified as affected by the RCO measure of adopting the double skin are the following:

- Chemical damage due to cargo
- Mechanical damage due to poor cargo handling
- Mechanical damage during unloading
- Inadequate design criteria

A large collection of hazards has been compiled by MCA in the context of the current international RINA ledstudy on the basis of submissions to IMO from 10 countries and also the non-Governmental Organizations BIMCO and IACS. A special coding system was developed for the registration and prioritisation of the identified hazards. A final generic list of hazards with 248 entries has been produced from an initial list of 1129 records.

Perhaps the most complete analysis of the causal factors that result in a bulk-carrier accident can be found in the French submission in the context of the current international RINA ledstudy [7]. Based on results of a risk contribution tree analysis, it proves that the most significant risk for bulk-carriers in terms of number of accidents was side-shell failure (coded as B4, Figs 5 & 6). The distribution according to type and also according to particular causes is shown in Table 2. Despite the fact that these accidents relate to single-skin bulk-carrier designs, it is evident that double skin construction would greatly contribute to the reduction of fatalities. The side-shell Failure (B4) criticality, expressed by the Expected Number of Failure (ENF) and the Barlow-Proshan Importance Index (BP) is shown in Table 3. The BP Index is a measure of the contribution (and importance) of an elementary fault event to the overall system unreliability. It quantifies the number of system faults that are caused by the failure of a particular event (here side shell failure) versus the total number of expected failures for the system (here bulkcarrier).

Table 2: Frequency data (by [LMIS]) [7]

Name		All sizes h ⁻¹	Mini h ⁻¹	Handysiz e h ⁻¹	Handyma x h ⁻¹	Panamax h ⁻¹	Capesize h ⁻¹
Side shell failure	B4	1,14E-07	4,70E-09	4,31E-08	1,25E-08	2,67E-08	2,74E-08
Hull envelope failure due to degradation of strength	B4.3	1,57E-09	0	7,84E-10	0	0	7,84E-10
Side shell failure	B4.3.2.1	7,84E-10	0	7,84E-10	0	0	0
Sustained external forces	B4.3.2.2	7,84E-10	0	0	0	0	7,84E-10
Collision	B4.4.1.7	2,04E-08	6,72E-09	1,02E-08	1,57E-09	1,57E-09	7,84E-10
	B4 Tot	1,38E-07	1,10E-08	5,49E-08	1,41E-08	2,82E-08	2,98E-08

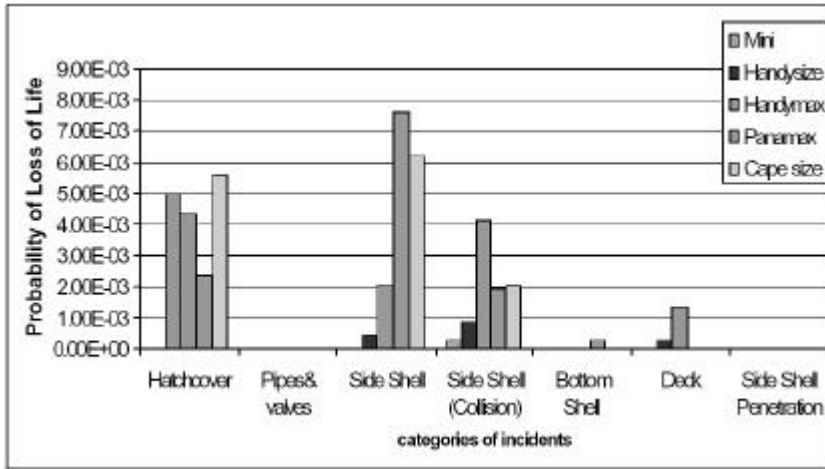


Fig. 5: Probability of Loss of Life per BC Classes [7]

Side shell failure (B4)		
Size	ENF	BP Index
Mini	9,620E-05	1,881E-01
Handysize	4,810E-04	3,196E-01
Handymax	1,240E-04	3,763E-01
Panamax	2,470E-04	4,370E-01
Capesize	2,610E-04	4,242E-01

Table 3: Events criticality [7]

4.2 Identification of hazards relevant to DS

On the basis of the above reports we have compiled the following list of hazards whose consequences seem to be affected from the adoption of the double-skin concept:

Dents on side shell structure during loading/unloading

The lack of framing in the internal cargo hold shell makes less likely this damage. Also, the consequences are less critical, given the existence of the outside skin.

Extreme dynamic seawater pressure to the outside side shell (without counter-pressure by cargo)

Due to the double skin, the ambient seawater pressure is not counterbalanced by the pressure exerted by the cargo in the holds. If the side ballast tanks are empty (in the loaded condition) there will be neither counter pressure from ballast water on the outside shell, hence the risk of damage is increased unless the side structure is built to a higher specification.

Extreme dynamic pressure to the inside side shell (without counter-pressure by ambient seawater)

The pressure exerted by cargo to the internal side shell (longitudinal bulkhead), especially when the cargo hold

is assumed flooded and there is a mixture of cargo and seawater in the hold, is not counterbalanced by the ambient seawater pressure. This is more severe if the side ballast tanks are empty (in the loaded condition). The extreme scenario is when a hold with cargo is flooded while the space between the skins remains empty (at least to the one side). For this condition there is no specific rule to be followed at this moment and hence a first principles approach is required in order to ensure that the side structure has sufficient strength

for such a case.

Rapid corrosion of structural members

The existence of side ballast tanks is a new feature for the double-skin vessels. Given the high probability of experiencing rapid corrosion in these spaces, the requirement for coating is an essential one. Furthermore, the difficulty of access to these spaces, due to the very limited width, should be addressed as it influences the level of risk. To obtain quantitative information about this we have carried out a search in Lloyd's Register's incident database which is reported in Section 5.

Excessive hull girder bending moment/shearing force

The existence of the double skin should change the critical shearing force/bending moment, compared to the single-skin structure. However, in view of the strengthening of the hull girder lengthwise, it might be assumed that this effect will be positive and hence not a critical one compared to a comparable single-skin vessel.

Chemical damage due to corrosive cargo

The corrosion effect of the cargo on the side shell of the cargo hold has a different consequence if compared to the more critical corrosion of the external skin of the single-hull vessels.

Damage to external hull due to collision

The consequence may be flooding of the ballast space only, or, for deeper penetration, flooding also of cargo hold(s). The severity of consequences can be assumed to be reduced compared to a SS design, although this is coupled of course with the width that is allowed between the two skins. Survivability due to asymmetric flooding is a new feature that needs to be assessed.

Fatigue due to use of higher tensile steels in order to obtain a lighter structure

During the structural weight optimization of a DS vessel, one of the objectives is to reduce steel weight to levels comparable to a SS. This could lead to the more extensive use of higher tensile steels and this in turn could raise the level of risk due to fatigue. Also the reduced plate thickness could make the structure more vulnerable against corrosion due to inadequate coating

procedures and requirements. For this we have also carried out a search in LR's database, reported also in Section 5.

Strength of transverse bulkheads between holds in static and dynamic loads, given the existence of the double skin

As the hold width is less than the breadth for a double-skin vessel, the application of UR S19 should be slightly modified. In Section 6 we have performed a comparison of safety margins in terms of bending, between an existing single-skin and an existing double-skin vessel, on the basis of UR S19. As expected, the double skin is not leading to a higher risk.

Strength of inner bottom

As pointed out in [5], if the double-bottom is lowered in order to compensate for the loss of space for cargo, the thickness should be increased. However this can be covered by the rule which applies for a single-skin vessel.

Floatability after asymmetric flooding

This involves either the occurrence of asymmetric flooding through the outer hull, with no penetration of the inner hull, or the occurrence of flooding due to "deep" penetration extending inwards of the inner shell structure. Reg. 4 of Chapter XII of SOLAS must be rephrased, to account for the above two cases which are not applicable to bulk-carriers of single-skin construction. We have carried out a detailed study on these issues, reported in Section 7.

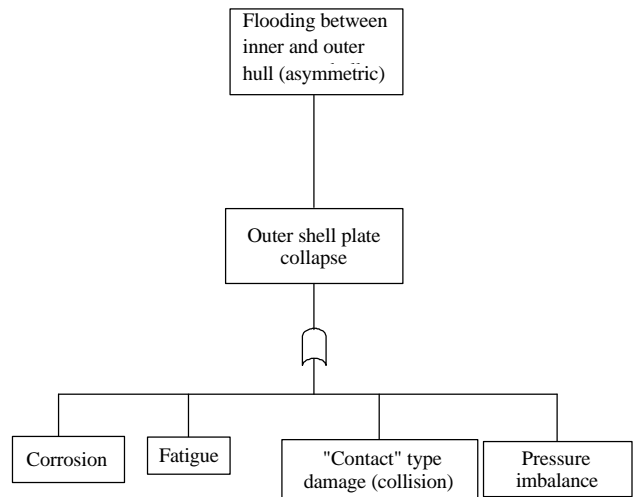


Fig 6: Asymmetric flooding

General lack of design criteria, class and statutory requirements for DS bulk carriers

Notwithstanding the fact that the structural integrity of standard DS bulk carrier designs is assessed from first principles (FE modelling), the lack of specific class and statutory requirements for the design, construction and operation of DS bulk carriers might be the source of additional (extremely remote or remote) risks with major structural failure consequences. This lack of criteria

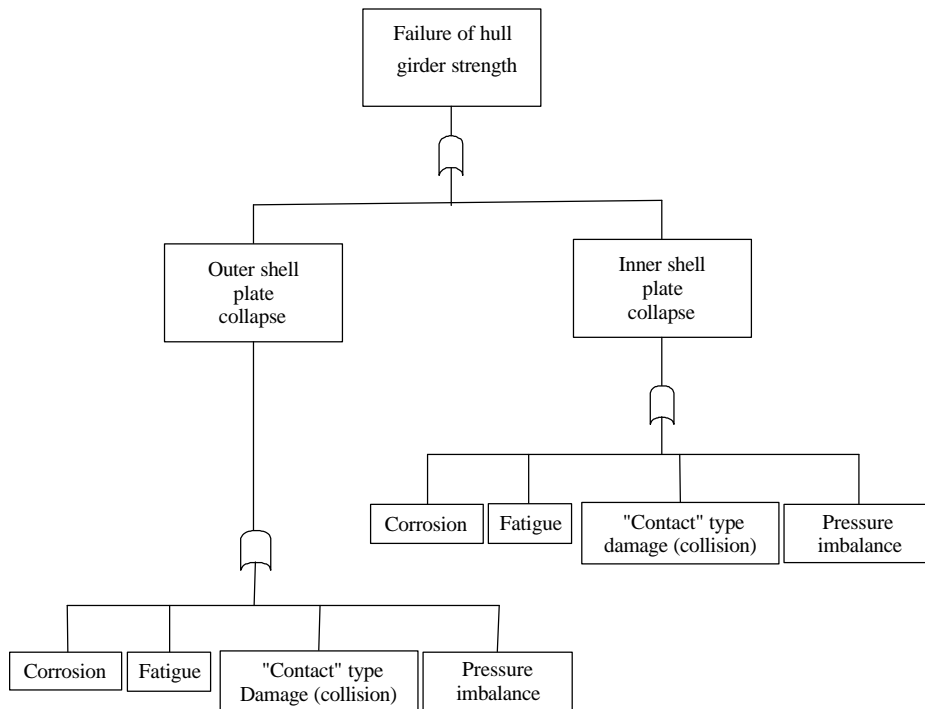


Fig. 7: Hull girder collapse

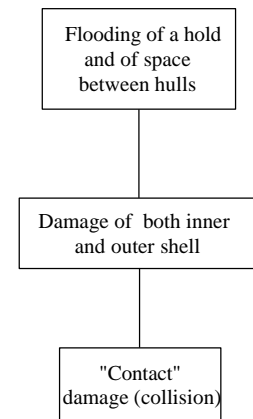


Fig. 8: "Deep" penetration due to collision.

cannot be considered as a typical hazard i.e. a potential threat to vessel integrity. Nonetheless it can have a major effect and it should be taken into account in the process of risk quantification.

Below are shown qualitative fault trees for the three main scenarios, i.e. a) flooding of the space between the two hulls, b) flooding of a hold as well as of the space between the hulls, and c) failure of hull girder strength, are presented in Figs 6 to 8 (scenarios of side-shell structure collapse are only examined).

5. STATISTICS OF “WASTAGE” AND “NON-CONTACT” INCIDENTS

Quantitative data on corrosion and fatigue are difficult to obtain from first principles and for this reason we have requested a search into Lloyd’s Register’s (LR) database for occurrences of “wastage” and “non-contact” incidents and defects for LR registered bulk-carrier vessels. Generally, the “wastage” records may be considered as owed to corrosion, while the “non-contact” cases include those due to fatigue as a subset and therefore the two may not be considered as completely identical groups. The records of “incidents” and the records of “defects” are differentiated in the sense that from the same incident one or more defects may result. The defects may be considered as representing the damages that have been realised.

Table 4: Bulk-carrier classification

Bulk carrier	DWT (ton)
Mini	Less than 10,000
Handysize	10,000-34,999
Handymax	35,000 – 49,999
Panamax	50,000 – 79,999
Capesize	80,000 +

The study period is the 10 years from 01-Jan-1990 to 31-Dec-1999. We have divided the fleet of bulk-carriers into 5 groups according to their size, so that a more detailed picture about the correlation of size and defect tendency can be obtained. These five groups, from the smallest to the biggest, are shown in the Table 4 next.

5.1 Damage locations

For identification of defect distribution the study was concerned only with the cargo carrying length between the collision bulkhead and the engine room bulkhead. Furthermore, for the purpose of identification and presentation of affected structure within the cargo carrying length, the following locations were set under investigation:

- Upper Deck (not between hatches)
- Top Side Tank (including plating and internals)
- Side Tank (including plating and internals)
- Hopper Side Tank (including plating and internals)

A similar search for incidents and defects was also carried out for single skinned bulk carriers. The only differentiation between the searches in the double-skin (DS) and the single-skin (SS) group is that for the DS we collect data for the side tanks with the internals while for the SS we consider only the side shell structure.

For each of the five bulk-carrier categories, the database was interrogated sequentially for the DS and the SS vessel populations. Each interrogation was run twice, firstly for collecting data on “wastage” and then for “non-contacts”. The collective results are summarised in Figs. 9 and 10. However it must be noted that in the above analysis the real age of the single-skin and double-skin ships is not clarified. For this reason we have requested an additional more restrictive search into LR’s database for the Handymax category. With regard to the data on the Handymax vessels, which refer to specific age groups, the following observations and conclusions are appropriate:

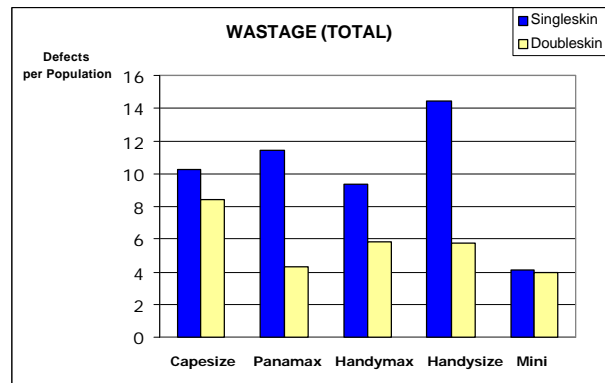
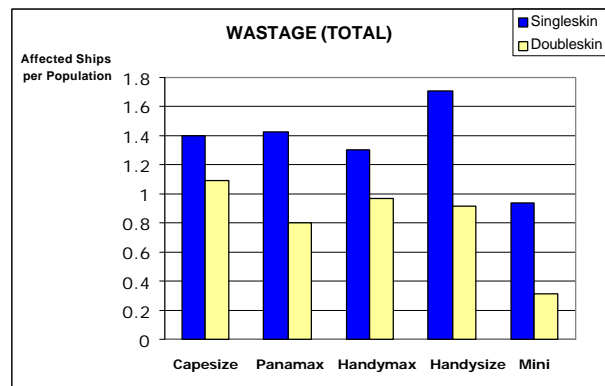


Fig. 9: Wastage incidents and defects

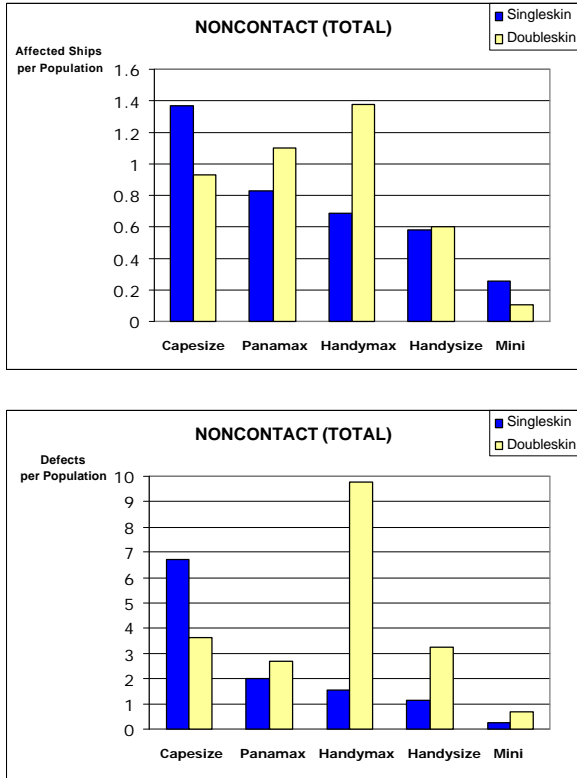


Fig. 10: Non-contact incidents and defects

The query in LR’s database for ships built between 1985 and 1990 produced 74 for the single-skin category and only 3 double-skin. In the period 1990-1995 the population was consisted of 13 single-skins and none double-skin. Finally the 1995 – 2000 search produced 13 single-skins and 4 double-skins. As it is obvious, the population of double-skin vessels is clearly inadequate for performing a sound statistical analysis from which useful conclusions could be drawn. With these reservations in mind, from the general records that have been made available the following tendencies can be deduced:

Deck

In terms of wastage, the SS group seems to be more vulnerable (except for the Capesizes where the picture is more balanced, with the number of DS incidents/defects even slightly exceeding that of SS), this however is likely to be reflecting the younger age of the DS fleet. In terms of the “non-contact” cases, the trend appears reversed and (with the exception of capsize vessels again) the DS vessels appear to have more problems.

Topside Tank

The wastage is consistently higher in the DS group for all sizes. Again the trend is reversed for the non-contacts, with the exception of Capesize vessels.

Side Tank for DS versus Side Shell for SS

The records on wastage are excessive for the SS in the larger sizes (Panamax and Capesize) while the records are more balanced in the smaller categories. In terms of non-contacts, the DS appear more vulnerable in all sizes.

Hopper Tank

More defects due to wastage are recorded for the DS. Wastage incidents appear excessive for the DS in the Handymax and Panamax categories. In terms of non-contacts, the DS Handymax type appears very vulnerable.

The overall picture

In terms of wastage, the SS presents excessive incidents and defects (once more, however, it must be stressed that this result is probably biased due to the probable higher average age of the SS group). On the other hand, the DS presents more incidents and defects of the “non-contact” type, especially in the category of Handymax.

6. STRENGTH OF TRANSVERSE BULKHEAD

Our objective was to assess the strength of the transverse bulkheads separating the holds under static and dynamic loads, given the existence of the double side-structure. To this end we applied the requirements of UR S19 for a double-skin bulk carrier and we compared the safety margins against those of a single-skin vessel.

6.1 The UR S19 requirement

The bending capacity of the corrugated transverse bulkhead, according to the requirement S19 paragraph S19.4.2, should satisfy the following relationship:

$$\frac{M}{0.5Z_{le} \sigma_{a,le} + Z_m \sigma_{a,m}} \times 10^3 \leq 1.0 \quad (1)$$

The formula for calculating the bending capacity of the corrugated bulkhead, (1), assumes that one half pitch of the corrugation maybe modelled as a beam, which is clamped at one end and hinged at the other and is subjected to a load at its mid-span. The numerator is the applied bending moment and the denominator is the ultimate bending moment, which the above beam may support.

The ultimate load, P_{ul} , which this beam may support, is calculated as follows:

$$P_{ul} = \frac{M_{le} + 2M_m}{l/2} \quad (2)$$

where, M_{le} is the plastic moment of the cross section at the clamped, and M_m is the plastic moment of the cross section at the mid-span

The plastic moment of a beam cross-section is equal to $M_{pl} = Z s_0$.

Equation (2) may be solved as follows

$$\frac{P_{ul} l}{8} = 0.5 M_{le} + M_m \quad (3)$$

Thus the ultimate bending moment that the beam may support is given by (3).

The applied bending moment is calculated as $M = \frac{F l}{8}$, as given is paragraph 3.1 of S19. The force acting on the corrugation is calculated based on the loading of the holds.

6.2 Application

The bending capacity of the two bulk-carriers described in Table 5 was calculated according to IACS UR S19:

	single side skin	double side skin
L_{oa} , m	224.950	288.94
L_{bp} , m	216.000	274.80
B , m	32.240	44.500
D , m	19.100	23.000
DWT, MT	72700	151000
Number of holds	7	9

Table 5: The dimensions of the two vessels.

	single side skin	double side skin
V , m^3	7185	17832
l_c , m	24.9	27.7

Table 6: Dimensions of first hold.

	single skin	double skin
a , m	1	1.6
c , m	1.0978	1.4861
S_1 , m	1.57	2.1
δ , °	58.5	70.34
t_w , mm	16.5	28
t_f , mm	16.5	32.5

Table 7: Dimensions of bulkheads

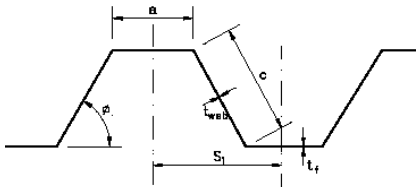


Fig. 11: Bulkhead configuration

(3)

	single side skin	double side skin
D , m	19.1	23.0
V , m^3	7185	17832
SG , t/m^3	1.993	1.6
d_f , m	19.1	23.0
d_1 , m	11.5005	19.0782
h_f , m	13.62	16.501
h_1 , m	6.02051	12.5792

Table 8: Bending capacity of bulkheads for the two vessels.

	Single skin	double skin
M , $kN*m$	2237.2	4995.79
Z_{le} , cm^3	9275.82	46497.7
$\sigma_{a,le}$, N/mm^2	320	240
Z_m , cm^3	10667.2	50966.9
$\sigma_{a,m}$, N/mm^2	320	240
bending capacity	0.45679 < 1	0.28048 < 1

Table 9: Calculation of pressure head

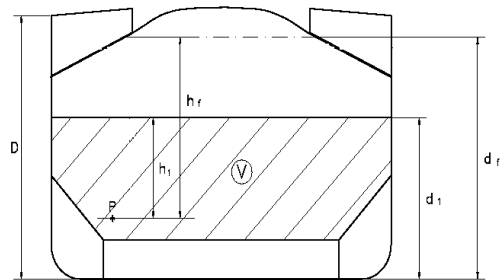


Fig. 12: Definitions for calculation of pressure head

The dimensions of the first hold are shown in Table 6. The dimensions of the corrugated bulkhead between holds No.1 and 2 for both vessels are given in Table 7 and Fig. 11. The alternate loading condition was applied for both vessels. The pressure head was calculated according to the vessel's plans (Table 8 and Fig. 12). Finally, the bending capacity of the corrugated transverse bulkhead is shown in Table 9.

6.3 Discussion

Our experience from the application of S19 indicates that the formula for calculating the bending capacity of the corrugated transverse bulkhead is based on principles which are not dependent on whether the vessel is single- or double-skinned. The only aspect that is influenced by

the configuration of the vessel is the calculation of the pressure in the flooded hold. In particular, instead of the vessel's breadth amidships, the breadth of the hold should be considered in the calculation of the pressure head, d_1 , according to paragraph S19.2.3.1. According to the requirement S19, the corrugated transverse bulkhead of the double side skin bulk carrier has sufficient bending capacity, as shown in the previous section. Finally the comparison between the two vessels shows that in the case of the double side skin bulk carrier the bulkhead has more bending capacity than the single side skin. This may be attributed to the stiffer construction of the bulkhead as shown in the table presenting the dimensions of the corrugations.

Considering the efficiency of the structures that comply with UR S19 requirements, it is considered that the bending capacity of the corrugated bulkhead is a measure of its strength that incorporates a well established safety factor. The results of finite element analysis that we carried out have shown that, for the regulations' pressure level, the bulkhead has sufficient residual strength.

The fact that the bending capacity approaches one half proves that plastification at the lower end and mid-span of the corrugation is at an early stage and far away from forming a plastic hinge. This is also seen in the finite element results. Further, it has been shown that even at a pressure level 25% higher than the pressure mentioned in UR S19, the lower end and mid-span of the centrestmost corrugation are still in the elastic region.

The maximum stress at the lower stool is 330 MPa (compare with 315MPa), a mere 5% increase. Also, the stresses at the longitudinal girders are 339Mpa,

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 Fringe: Default, Step1, Total Time, Stress, Components - At SECTION_POINT_1 (VONM)
 Deform: Default, Step1, Total Time, Displacements

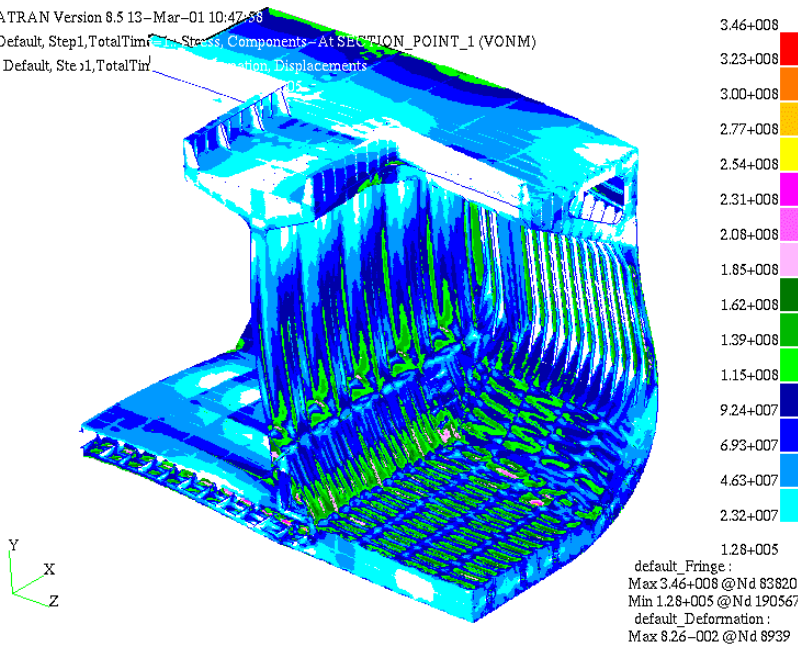


Fig. 13: Finite element analysis for cargo holds 1 & 2.

compared to 329MPa (Fig. 13), giving a 3% increase. Once again, it is shown that the corrugations are well designed to fulfill the UR S19 requirements, but other areas may be liable to dangerously large stresses. Taking into account that for the previously presented example the safety margin is considerably larger for the double-skinned bulk carrier, it is concluded that the double-skin design will not affect the structure in a negative way.

7. SURVIVABILITY AFTER ASYMMETRIC FLOODING

In order to assess in quantitative terms the survivability due to asymmetric flooding and also due to "deep" hull penetration we have compared the damage stability of a single-skin vessel with that of two double-skin variants of this vessel: In the first the distance between the two skins is 1.0 m, with the double skin "running" along the full length of cargo space. In the second variant the double-skin covers only the two cargo holds nearest to the bow. Furthermore, in this case the distance between the two skins was assumed to be 1.5 m. This is an unusual, extreme value for bulk-carriers but we have considered it in order to maximise the negative effect due to one-sided flooding of the space between the two skins.

The bulk carrier that we have taken as a basis of the investigation had the following characteristics:

L_{BP} =216.0 m, B =32.4 m, D =19.1 m, T =13.896 m,
 KG =9.21 m
 Δ =83,828.11 tons, DWT =72,700tons.

The cargo space was comprised of 7 cargo holds. The condition *short voyage full load departure* was examined, assuming that the ship is carrying a cargo with density 1,993 kg/m³ in the holds No 1, 3, 5 and 7. Therefore the cargo holds No 2, 4 and 6 were assumed empty.

According to Reg. 4 of Chapter XII of SOLAS, bulk carriers with a length over 150 m carrying cargo with density over 1,000 kg/m³ and built on or after the 1st of July 1999 should, when sailing in summer load line, survive the flooding of any cargo hold in all loading conditions and also remain afloat in a satisfactory condition of equilibrium as defined in the Annex to resolution A.320 (IX). Bulk-carriers with length over 150 m and carrying cargo with density higher than 1,780 kg/m³ should be able to withstand the flooding of the forward cargo hold in all loading conditions and also maintain a

satisfactory condition of equilibrium as specified in the Annex to resolution A.320 (IX).

All possible combinations of flooding were considered for the single-skin vessel as well as for its two double-skin alternatives, involving the two most forward cargo holds and their surrounding spaces. In all examined cases we have assumed that the quantity of cargo remains the same. The reduced width of the cargo tanks for the double-skin vessels results, for the same cargo per hold, in a higher KG. Then we have examined if damage stability is deteriorated significantly in the case of a double-skin construction. The general conclusion of this study is that double-skinned vessels continue to satisfy the requirements therefore we have no indication that additional technical requirements are essential for the doubled-skin vessels.

8. COST BENEFIT ANALYSIS FOR DOUBLE-SKIN BULK-CARRIERS

8.1 Criteria and results

The cost-benefit analysis that is discussed below is based on the following criteria:

Gross Cost for Averting Fatalities (Gross-CAF):

The additional cost of implementing the risk control option (RCO), in this case the double skin, divided by the anticipated reduction of the number of fatalities per ship:

$$\text{GrossCAF} = \frac{\dot{A}\text{Cost}}{\dot{A}\text{Risk}}$$

Net Cost for Averting Fatalities (Net-CAF):

Like the above, but taking into account the economic benefit accruing from the implementation of the RCO.

$$\text{NetCAF} = \text{GrossCAF} - \frac{\dot{A}\text{Economicbenefits}}{\dot{A}\text{Risk}}$$

Quantitative and detailed information about the cost of adopting a double skin-construction in a new bulk-carrier design and the cost of converting an existing single-skin into double skin were identified from the following sources:

- The IACS study of bulk carrier formal safety assessment [2].
- The work of BIMCO with Danish Consultants in the context of the current international FSA study [8].

Cost-benefit analysis referring to the adoption of double-skin for cargo hold No 1 only is presented also in the Korean FSA study.

It should be noted that the classification of bulk carriers in the IACS and the international RINA ledstudies are

different, as the IACS study follows on this the Japanese submission to IMO (MSC 74/Inf.x) (compare Table 4 with Table 10 below). We have carried out a comparative assessment of data in the two studies with main aim to contrast the finally obtained Gross and NetCAF related with the adoption of the double-skin. The results are presented in Tables 11 to 19. However it must be taken into account that the data in the Tables refer to the classification adopted by each group.

Table 10: The classification of bulk-carriers in the IACS study

<i>Bulk carrier size</i>	<i>DWT (ton)</i>
(Mini)	10,000 – 22,999
Small-Handy	
Handymax	23,000 – 54,999
Panamax	55,000 – 79,999
Capesize	80,000 +
(VL)	

Table 11: Cost of double skin for materials, work and accompanying costs (in US\$).

	IACS	BIMCO + Danish Consultants
CAPE SIZE		
<i>Newbuilding</i>	435,633*	895,970 - 1,983,485
<i>10 year old</i>	1,516,003	2,717,537 – 5,747,423
<i>15 year old</i>	(416,493 for holds 1 & 2)	2,641,353 – 5,674,274
PANAMAX		
<i>Newbuilding</i>	228,031*	402,833 – 876,433
<i>10 year old</i>	778,243	1,721,259 – 3,618,862
<i>15 year old</i>	(250,427)	1,591,966 – 3,401,487
HANDYMAX		
<i>Newbuilding</i>	149,924*	364,474 – 803,389
<i>10 year old</i>	512,898	1,188,051 – 2,463,081
<i>15 year old</i>	(219,656)	1,123,643 – 2,377,990
SMALL HANDY		
<i>Newbuilding</i>	74,774*	
<i>10 year old</i>	254,570	
<i>15 year old</i>	(130,477)	

* These values are based on the cost of steel only (\$800/t) therefore they represent clearly an underestimation.

Table 12: Additional steel for double skin (in tons)		
	IACS	BIMCO + Danish Consult.
CAPEXSIZE		
<i>Newbuilding</i>	545	490
<i>10 year old</i>	(131)	823
<i>15 year old</i>	for holds 1&2)	783
PANAMAX		
<i>Newbuilding</i>	285 (86)	205
<i>10 year old</i>		823
<i>15 year old</i>		783
HANDYMAX		
<i>Newbuilding</i>	188 (77)	195
<i>10 year old</i>		543
<i>15 year old</i>		534
SMALL HANDY		
<i>Newbuilding</i>	94 (47)	
<i>10 year old</i>		
<i>15 year old</i>		

Table 13: Additional cost due to loss of earnings and extra repair/maintenance (in US\$/year). In the brackets is shown the contribution of repair and maintenance to the cost.		
	IACS	BIMCO + Danish Consultants
CAPEXSIZE		
<i>Newbuilding</i>		46,116 – 47,358 [2636]
<i>10 year old</i>	59,533	110,242 – 113,303
<i>15 year old</i>	(14,263 for holds 1 & 2)	108,432 – 111,440
PANAMAX		
<i>Newbuilding</i>		30,216 – 31,028 [1796]
<i>10 year old</i>	65,033	91,594 – 94,106
<i>15 year old</i>	(19,681)	86,295 – 88,654
HANDYMAX		
<i>Newbuilding</i>		25,259 – 25,936 [1554]
<i>10 year old</i>	30,195	76,879 – 79,001
<i>15 year old</i>	(12,402)	77,334 – 79,470
SMALL HANDY		
<i>Newbuilding</i>		
<i>10 year old</i>	18,856	
<i>15 year old</i>	(9,428)	

Table 14: Total additional cost in US\$ (in the brackets is given the cost if assumed that for newbuildings there is no loss of earnings).		
	IACS ⁽¹⁾	BIMCO + Danish Consultants ⁽²⁾
CAPEXSIZE		
<i>Newbuilding</i>	435,633	2,042,205 [961,870 – 2,049,385]
<i>10 year old</i>	2,408,998 (630,438 ⁽¹⁾ for holds 1 & 2)	5,173,599
<i>15 year old</i>	2,111,333 (559,123)	4,731,398
PANAMAX		
<i>Newbuilding</i>	228,031	1,047,784 [447,733 – 921,333]
<i>10 year old</i>	1,753,738 (545,642)	3,517,930
<i>15 year old</i>	1,428,573 (343,676)	3,032,852
HANDYMAX		
<i>Newbuilding</i>	149,924	922,722 [403,324 – 842,239]
<i>10 year old</i>	965,823 (271,897)	2,524,797
<i>15 year old</i>	814,848 (224,757)	2,215,301
SMALL HANDY		
<i>Newbuilding</i>	74,774	
<i>10 year old</i>	537,410 (271,897)	
<i>15 year old</i>	443,130 (224,757)	

(1): In the IACS study the service life is 25 years.
(2): In the international RINA-led study the calculation is based on a 5% interest rate while the service life (newbuilding) is assumed to be 22.2 years for the Handymax, 22.5 for the Panamax and 21.2 for the Capesize. The displayed cost is based on the average of min and max value.

Table 15: Difference in potential loss of life (ÄPLL) due to the double skin.

	IACS	BIMCO + Danish Cons.
CAPESIZE		
<i>Newbuilding</i>	1.72 E-02	3.29 E-03
<i>10 year old</i>	1.65 E-02 (1.05 E-02 for holds 1&2)	4.94 E-03
<i>15 year old</i>	1.50 E-02 (1.05 E-02)	4.94 E-03
PANAMAX		
<i>Newbuilding</i>	4.25 E-03	3.83 E-03
<i>10 year old</i>	4.25 E-03 (2.84 E-03)	5.75 E-03
<i>15 year old</i>	2.48 E-03 (1.77 E-03)	5.75 E-03
HANDYMAX		
<i>Newbuilding</i>	4.93 E-03	4.44 E-04
<i>10 year old</i>	4.93 E-03 (2.06 E-03)	6.66 E-04
<i>15 year old</i>	3.67 E-03 (1.72 E-03)	6.66 E-04
SMALL HANDY		
<i>Newbuilding</i>	7.71 E-03	
<i>10 year old</i>	7.71 E-03 (6.85 E-03)	
<i>15 year old</i>	4.28 E-03 (4.28 E-03)	

Table 17: Assumed benefit following implementation of the double-skin, in US\$ (in brackets is shown the benefit in terms of steel recycle value).

	IACS	BIMCO + Danish Consultants
CAPESIZE		
<i>Newbuilding</i>	115,000	7,107,078 [72,550]
<i>10 year old</i>	95,000 (78,000 for holds 1&2)	4,199,711 [85,738]
<i>15 year old</i>	68,000 (58,000)	2,435,398 [86,878]
PANAMAX		
<i>Newbuilding</i>	115,000	3,947,587 [30,334]
<i>10 year old</i>	95,000 (78,000)	2,445,874 [62,102]
<i>15 year old</i>	68,000 (58,000)	1,439,410 [62,787]
HANDYMAX		
<i>Newbuilding</i>	115,000	2,429,136 [28,924]
<i>10 year old</i>	95,000 (78,000)	1,473,464 [48,400]
<i>15 year old</i>	68,000 60,000	839,956 [48,391]
SMALL HANDY		
<i>Newbuilding</i>	115,000	
<i>10 year old</i>	95,000 (78,000)	
<i>15 year old</i>	68,000 (58,000)	

Table 16: Assumed number of averted fatalities per ship, ÅRisk

	IACS	BIMCO + Danish Cons.
CAPESIZE		
<i>Newbuilding</i>	0.43 ⁽¹⁾	6.98 E-02
<i>10 year old</i>	0.379 ⁽²⁾ (0.241 for holds 1&2 ²)	5.53 E-02
<i>15 year old</i>	0.327 ⁽³⁾ (0.229 ⁽³⁾)	3.06 E-02
PANAMAX		
<i>Newbuilding</i>	0.106 ⁽¹⁾	8.62 E-02
<i>10 year old</i>	0.098 ⁽²⁾ (0.065 ⁽²⁾)	7.19 E-02
<i>15 year old</i>	0.054 ⁽³⁾ (0.039 ⁽³⁾)	4.31 E-02
HANDYMAX		
<i>Newbuilding</i>	0.123 ⁽¹⁾	9.86 E-03
<i>10 year old</i>	0.113 ⁽²⁾ (0.047 ⁽²⁾)	8.13 E-03
<i>15 year old</i>	0.080 ⁽³⁾ (0.038 ⁽³⁾)	4.80 E-03
SMALL HANDY		
<i>Newbuilding</i>	0.193 ⁽¹⁾	
<i>10 year old</i>	0.177 ⁽²⁾ (0.158 ⁽²⁾)	
<i>15 year old</i>	0.093 ⁽³⁾ (0.093 ⁽³⁾)	

Remaining years of service: (1) 25, (2) 15 × 1.53=23, (3) 10 × 2.18=21.8. The coefficients 1.53 and 2.18 reflect that the risk is higher for older vessels. These coefficients were derived from the distribution of fatalities according to age.

Table 18: GrossCAF in US\$ million/averted fatality (in the brackets is the GrossCAF assuming that for newbuildings there is no loss of earnings).		
	IACS	BIMCO + Danish Consultants
CAPESIZE		
<i>Newbuilding</i>	1.01	29.27 [6.87 – 14.64]
<i>10 year old</i>	6.36 (2.61 for holds 1&2)	93.56
<i>15 year old</i>	6.46 (2.44)	154.57
PANAMAX		
<i>Newbuilding</i>	2.14	12.15 [3.20 – 6.58]
<i>10 year old</i>	17.92 (8.35)	48.96
<i>15 year old</i>	26.37 (11.55)	70.35
HANDYMAX		
<i>Newbuilding</i>	1.22	93.59 [2.88 – 6.02]
<i>10 year old</i>	8.51 (8.55)	310.64
<i>15 year old</i>	10.18 (9.17)	461.85
SMALL HANDY		
<i>Newbuilding</i>	0.39	
<i>10 year old</i>	3.03 (1.72)	
<i>15 year old</i>	4.74 (2.40)	

Table 19: NetCAF (US\$ million/averted fatality)		
	IACS	BIMCO + Danish Cons.
CAPESIZE		
<i>Newbuilding</i>	0.75	-72.58
<i>10 year old</i>	6.11 (2.29 for holds 1&2)	17.61
<i>15 year old</i>	6.26 (2.19)	75.02
PANAMAX		
<i>Newbuilding</i>	1.06	-33.63
<i>10 year old</i>	16.94 (7.15)	14.92
<i>15 year old</i>	25.11 (10.02)	36.96
HANDYMAX		
<i>Newbuilding</i>	0.28	-152.78
<i>10 year old</i>	7.67 (6.90)	129.35
<i>15 year old</i>	9.32 (7.59)	286.73
SMALL HANDY		
<i>Newbuilding</i>	-0.21	
<i>10 year old</i>	2.49 (1.23)	
<i>15 year old</i>	4.01 (1.77)	

8.2 Discussion

1. In the IACS study is assumed that the additional cost associated with the adoption of the double-skin is only the cost of steel. Furthermore the operational cost for the 10 year old and the 15 year old bulk carriers is calculated uniformly for a 10 year period. However, in the IACS column of Table 12 we have determined the operational cost assuming 15 years remaining period of service for the 10-year-old vessels. The international RINA led study differentiates the service life-time of a newbuilding according to type, assuming 22.2 years for a new Handymax (and accordingly for the 10 and 15-year-old), 22.5 for the Panamax and 21.2 for the Capesize. Furthermore, it is assumed that the ship will have an extended life-time after the introduction of the double skin, as follows: 2.5 years for the newbuilding, 1 year for the 10-year-old and 0.5 years for the 15-year-old. This is logical, however the assumed values for the accruing benefit due to longer life-span may be too high as other factors are also influential. Indicatively, the assumed benefit for a new Panamax has been taken as 5.6 million US\$, for a 10-year-old as 1.9 million US\$ and for a 15 year old as 0.75 million US\$.

2. The IACS study is based on a search into the LMIS database covering the period 1978-1998. From there were extracted 98 serious incidents with flooding due to side-shell failure for bulk-carriers over 20,000 DWT, of which 62 were total losses. The corresponding human loss was 572 people. For a 20-year period we have 73,600 bulk-carriers × years, therefore the *PLL* according to this data is:

$$PLL = \frac{572}{73600} = 7.8E - 03$$

To be noted that the probability of side-shell failure should be influenced also by the introduction of the Enhanced Survey Programme (ESP) introduced as an IACS Unified Requirement on the 1st of July 1993, and also the introduction of SOLAS XII. According to the IACS study, the introduction of ESP should reduce the *PLL* according to the following formula $\dot{A}PLL = (1 - r_{ESP})(1 - r_{SOLASXII})PLL$, where r_{ESP} , $r_{SOLASXII}$ are respectively relative reductions in probability of side-shell failure after the introduction of ESP and after the introduction of SOLAS XII. In the IACS study the values of r_{ESP} , $r_{SOLASXII}$ were respectively 0.19 and 0.22 resulting in a new *PLL* for side shell failure $4.9E - 03$. The values for the probabilities r_{ESP} , $r_{SOLASXII}$ are derived by examining the casualty rate before and after the introduction of the corresponding new requirements. Of course these calculations are quite subjective as the reduction of the casualty rate is influenced by several factors. According to the same study, the *PLL* for all types of accident for the same period was $1.7E - 02$, while the

PLL for scenarios involving water ingress was $1.15E-02$.

3. In the international RINA led study the number of ship years for the period 1978 – 2000, on the basis of LRS and MCA’s data, is 145624 (Mini 23890, Handysize 77705, Handymax 15961, Panamax 14822, Capesize 13246). The corresponding number of fatalities (for all bulk-carrier types) was 1758 (Mini 152, Handysize + Handymax 927, Panamax 233 and Capesize 446). The PLL for all types of accident was $1.21 E-02$ while the PLL for side shell failure was $2.48 E-03$ which is considerably lower than the IACS figure.
4. In the international RINA led study [8] the assumption is that, for newbuildings, the introduction of the double-skin leads to a 40% PLL reduction while for the existing the corresponding percentage is 50% higher (i.e. 60%). It seems that expert judgement was used for deriving these values although the initial intention of MCA was not to use this approach. As it is obvious, unless the benefit in terms of PLL is calculated with reasonable accuracy, the end results of the whole method can be questioned. In the international RINA led study the assumed PLL for single skin bulk-carriers is $9.58E-03$. The PLL values in the international RINA led study do not differentiate on the basis of bulk-carrier age while this is catered for in the IACS study. It does not appear logical the PLL value for newbuildings to be as for older vessels.
5. In the international RINA led study is assumed a cost for loss of cargo space even for the newbuildings. Generally, it is essential when we compare the double skin with a single skin design to express clearly what is kept constant. Taking into account only the additional cost for repair and maintenance (see Table 17) would have lowered the total cost and thus the GCAF very significantly. This is reflected in Table 18.
6. The distance between the two skins is a parameter which, in general, can influence the cost-benefit assessment. This distance affects mainly the remaining capacity of cargo holds, and thus the implementation cost (obviously larger distance leads to higher implementation cost), and the level of risk reduction (here the trend is opposite, the larger the distance the smaller the risk of fatalities). Some quantitative information about this can be found in the Korean FSA study mentioned earlier. However, the distance between the skins is the kind of parameter that needs to be considered once the introduction of the double skin has been decided. In the international RINA led study is assumed a distance between the skins of 1.0 m for the Handymax and the Panamax, and 1.2 m for the Capesize.

8.3 Concluding remarks on the cost-effectiveness of the double skin

In Table 20 below are provided ICAF values which are considered as acceptable for some other industries, on the basis of a recent submission to IMO by Norway [9]. A GrossCAF of 3 million US\$ has been used as an empirical limit of cost-effectiveness for an RCO in the IACS study. However here seems more logical to use as criterion the NetCAF because the benefits are very significant and they are worthy to be taken into account.

The data of the IACS and the international RINA led study, although they produce quite different figures in quantitative terms, they both show that the introduction of the double skin is cost-effective for all newbuildings of any bulkcarrier type. On the other hand, for existing ships the conversion to double-skin depends on ship’s age and type. The data of the international RINA led study suggest, that for the 10 yrs old ships the introduction of double skin is still a cost effective measure. Finally, according to the IACS study, if the double skin is applied only to the two forward holds the measure can be cost effective, especially for the very large (Capesize) and the very small (small Handy) vessels.

Organisation	Subject	ICAF	Source
US Federal Highway Administration	Road Transport	\$2.5m (£1.6m)	FHWA (1994)
UK Department of Transport	Road Transport	£1.0m (1998, updated with GDP per capita)	DETR (1998)
UK Health and Safety Executive	Industrial Safety	As above or higher	HSE (1999)
Railtrack (UK Rail Infrastructure Controller)	Overground Railways	As above to £2.65m	Railtrack (1998)
London Underground Ltd	Underground Railways	£2m	Rose (1994)
EU	Road Transport	ECU 1m (£0.667m)	Evans (1998)
Norway	All Hazards	NOK 10m (£0.8m)	Norway (1996)

Table 20: Acceptable CAF level (gross) in various industries [9].

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APPENDIX

We have examined only cases of flooding concerning the two most forward cargo holds and their surrounding spaces. The considered loading of the reference single-skin vessel is illustrated in Fig. 4. In Table 21 can be seen the main hydrostatic characteristics of this ship while Table 22 details its cargo volume capacity. The corresponding loading condition for the two double-skin vessels is summarised in Tables 3 and 4. In all examined cases we have assumed that the quantity of cargo remains the same. The reduced width of the cargo tanks for the double-skin vessels results, for the same cargo per hold, in a higher KG.

We have examined if damage stability is deteriorated significantly in the case of a conversion to double-skin. The results obtained are summarised in Tables 23 to 25 where the following notation has been applied:

Hold1, Hold2: No 1 and No 2 cargo holds.
 db1.s, db2.s: No 1 and No 2 double-bottom water ballast tanks, starboard.
 ts1.s, ts2.s: No 1 and No 2 top-side water ballast tanks, starboard.
 dh1.s, dh2.s: No 1 and No 2 side water ballast tanks, starboard.
 dh1.p, dh2.p: No 1 and No 2 side water ballast tanks, port.

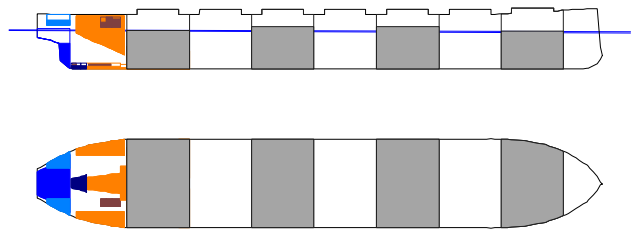


Fig. 14: Loading condition of reference single-skin vessel

Draught F.P	13,616 m
Draught MIDSHIP	13,947 m
Draught A.P.	14,279 m
Trim by stern	0,660 m
Heel	stbd 0,07 deg
Displacement	83828,11 tons
LCF from A.P.	107,214 m
LCB from A.P.	114,132 m
LCG from A.P.	113,321 m
KMT	13,447 m
KG (solid)	9,179 m
GM (solid)	4,268 m
Free surface correction	0,031 m
GM (actual)	4,237 m
KG (actual)	9,210 m

Table 21: Hydrostatic characteristics

Compartment	Volume (m ³)
Hold 1.c	11203,10
Hold 2.c	12449,36
Hold 3.c	12381,86
Hold 4.c	12382,02
Hold 5.c	12444,19
Hold 6.c	12445,33
Hold 7.c	11823,46

Table 22: Cargo hold capacity

Table 23: Flooding scenarios for the single-skin vessel

	Compartments	LCF	GM (Fluid)	Heel (deg)	T _M (T _{FP} /T _{AP})	trim (deg)	Distance from Margin Line	Criteria
1	dh1.s	106.726f	4.018	0.65stbd	13.998 (13.788/14.207)	0.42aft	(5.266/4.843/7.758)	pass
2	dh2.s	107.094f	4.065	0.78stbd	14 (13.759/14.24)	0.48aft	(5.21/4.803/7.772)	pass
3	dh1.s+ dh2.s	106.795f	4.045	1.46stbd	14.044 (13.932/14.155)	0.22aft	(5.214/4.566/7.524)	pass
4	dh1.s+ 1db.s	107.067f	4.124	1.61stbd	14.081 (14.181/13.981)	0.20fwd	(5.369/4.488/7.259)	pass
5	dh1.s+ 1db.s+ 1ts.s	106.841f	4.127	1.80stbd	14.129 (14.278/13.981)	0.30fwd	(5.345/4.386/7.141)	pass
6	dh1.s+ 1db.s+ hold1	104.257f	4.462	1.79fwd	15.081 (17.85/12.313)	5.53fwd	(7.011/3.448/3.57)	pass
7	dh1.s+ 1db.s+ 1ts.s+ hold1	102.565f	4.247	2.18stbd	15.115 (17.98/12.25)	5.73fwd	(7.022/3.303/3.397)	pass
8	dh2.s+ 2db.s	107.335f	4.238	2.10stbd	14.124 (14.129/14.119)	0.06fwd	(5.168/4.306/7.256)	pass
9	dh2.s+ 2db.s+ hold2	104.558f	4.536	1.95stbd	15.225 (17.387/13.062)	4.32fwd	(6.242/3.256/4.015)	pass
10	dh2.s+ 2db.s+ 2ts.s	106.975f	4.13	2.14stbd	14.126 (14.137/14.126)	0.02fwd	(5.166/4.291/7.243)	pass
11	dh2.s+ 2db.s+ 2ts.s+ hold2	103.248f	4.255	2.43stbd	15.261 (17.501/13.022)	4.47fwd	(6.22/3.084/3.849)	pass
12	dh1.s+ 1db.s+ dh2.s+ 2db.s	107.240f	4.354	3.82stbd	14.302 (14.800/13.805)	0.99fwd	(5.258/3.640/6.389)	pass
13	dh1.s+ 1db.s+ 1ts.s+ dh2.s+ 2db.s+ 2ts.s	106.110f	4.08	4.05stbd	14.319 (14.851/13.787)	1.06fwd	(5.245/3.559/6.312)	pass
14	dh1.s+ 1db.s+ 1ts.s+ hold1+ 2db.s+ 2ts.s	101.240f	4.114	5.23stbd	15.419 (18.951/11.887)	7.03fwd	(6.975/2.134/2.088)	pass
15	dh1.s+ 1db.s+ 1ts.s+ hold1 dh2.s+ 2db.s+ 2ts.s+ hold2	68.085f	2.39	10.95stbd	18.991 (30.478/7.503)	22.56fwd	(10.407/2.963/-9.823)	-
16	dh1.s+ dh1.p+ hold1	103.677f	4.303	0	14.999 (17.543/12.455)	5.09fwd	(7.098/4.035/4.0273)	pass
17	dh2.s+ dh2.p+ hold2	104.326f	4.39	0	15.138 (17.132/13.143)	3.99fwd	(6.410/3.894/4.484)	pass
18	dh1.s+ dh1.p+ 1ts.s+ 1db.s+ hold1	102.857f	4.276	1.44stbd	15.183 (18.239/12.127)	6.11fwd	(7.242/3.448/3.220)	pass
19	dh2.s+ dh2.p+ 2ts.s+ 2db.s+ hold2	103.408f	4.284	1.70stbd	15.314 (17.654/12.9740)	4.68fwd	(6.363/3.24/3.777)	pass

Table 24: Results of flooding for the DS vessel (1.0 m)

	Compartments	LCF	GM (Fluid)	Heel (deg)	T _M (T _{FP} /T _{AP})	trim (deg)	Distance from Margin Line	Criteria
1	dh1.s	106.726f	4.018	0.65stbd	13.998 (13.788/14.207)	0.42aft	(5.266/4.843/7.758)	pass
2	dh2.s	107.094f	4.065	0.78stbd	14 (13.759/14.24)	0.48aft	(5.21/4.803/7.772)	pass
3	dh1.s+ dh2.s	106.795f	4.045	1.46stbd	14.044 (13.932/14.155)	0.22aft	(5.214/4.566/7.524)	pass
4	dh1.s+ 1db.s	107.067f	4.124	1.61stbd	14.081 (14.181/13.981)	0.20fwd	(5.369/4.488/7.259)	pass
5	dh1.s+ 1db.s+ 1ts.s	106.841f	4.127	1.80stbd	14.129 (14.278/13.981)	0.30fwd	(5.345/4.386/7.141)	pass
6	dh1.s+ 1db.s+ hold1	104.257f	4.462	1.79fwd	15.081 (17.85/12.313)	5.53fwd	(7.011/3.448/3.57)	pass
7	dh1.s+ 1db.s+ 1ts.s+ hold1	102.565f	4.247	2.18stbd	15.115 (17.98/12.25)	5.73fwd	(7.022/3.303/3.397)	pass
8	dh2.s+ 2db.s	107.335f	4.238	2.10stbd	14.124 (14.129/14.119)	0.06fwd	(5.168/4.306/7.256)	pass
9	dh2.s+ 2db.s+ hold2	104.558f	4.536	1.95stbd	15.225 (17.387/13.062)	4.32fwd	(6.242/3.256/4.015)	pass
10	dh2.s+ 2db.s+ 2ts.s	106.975f	4.13	2.14stbd	14.126 (14.137/14.126)	0.02fwd	(5.166/4.291/7.243)	pass
11	dh2.s+ 2db.s+ 2ts.s+ hold2	103.248f	4.255	2.43stbd	15.261 (17.501/13.022)	4.47fwd	(6.22/3.084/3.849)	pass
12	dh1.s+ 1db.s+ dh2.s+ 2db.s	107.240f	4.354	3.82stbd	14.302 (14.800/13.805)	0.99fwd	(5.258/3.640/6.389)	pass
13	dh1.s+ 1db.s+ 1ts.s+ dh2.s+ 2db.s+ 2ts.s	106.110f	4.08	4.05stbd	14.319 (14.851/13.787)	1.06fwd	(5.245/3.559/6.312)	pass
14	dh1.s+ 1db.s+ 1ts.s+ hold1+ 2db.s+ 2ts.s	101.240f	4.114	5.23stbd	15.419 (18.951/11.887)	7.03fwd	(6.975/2.134/2.088)	pass
15	dh1.s+ 1db.s+ 1ts.s+ hold1 dh2.s+ 2db.s+ 2ts.s+ hold2	68.085f	2.39	10.95stbd	18.991 (30.478/7.503)	22.56fwd	(10.407/2.963/-9.823)	-
16	dh1.s+ dh1.p+ hold1	103.677f	4.303	0	14.999 (17.543/12.455)	5.09fwd	(7.098/4.035/4.0273)	pass
17	dh2.s+ dh2.p+ hold2	104.326f	4.39	0	15.138 (17.132/13.143)	3.99fwd	(6.410/3.894/4.484)	pass
18	dh1.s+ dh1.p+ 1ts.s+ 1db.s+ hold1	102.857f	4.276	1.44stbd	15.183 (18.239/12.127)	6.11fwd	(7.242/3.448/3.220)	pass
19	dh2.s+ dh2.p+ 2ts.s+ 2db.s+ hold2	103.408f	4.284	1.70stbd	15.314 (17.654/12.9740)	4.68fwd	(6.363/3.24/3.777)	pass

Table 25: Flooding for DS vessel with 1.5 m distance.

	Compartments	LCF	GM (Fluid)	Heel (deg)	T _M (T _{FP} /T _{AP})	trim (deg)	Distance from Margin Line	Criteria
1	dh1.s	106.726f	4.018	0.65stbd	13.998 (13.788/14.207)	0.42aft	(5.266/4.843/7.758)	pass
2	dh2.s	107.094f	4.065	0.78stbd	14 (13.759/14.24)	0.48aft	(5.21/4.803/7.772)	pass
3	dh1.s+ dh2.s	106.795f	4.045	1.46stbd	14.044 (13.932/14.155)	0.22aft	(5.214/4.566/7.524)	pass
4	dh1.s+ 1db.s	107.067f	4.124	1.61stbd	14.081 (14.181/13.981)	0.20fwd	(5.369/4.488/7.259)	pass
5	dh1.s+ 1db.s+ 1ts.s	106.841f	4.127	1.80stbd	14.129 (14.278/13.981)	0.30fwd	(5.345/4.386/7.141)	pass
6	dh1.s+ 1db.s+ hold1	104.257f	4.462	1.79fwd	15.081 (17.85/12.313)	5.53fwd	(7.011/3.448/3.57)	pass
7	dh1.s+ 1db.s+ 1ts.s+ hold1	102.565f	4.247	2.18stbd	15.115 (17.98/12.25)	5.73fwd	(7.022/3.303/3.397)	pass
8	dh2.s+ 2db.s	107.335f	4.238	2.10stbd	14.124 (14.129/14.119)	0.06fwd	(5.168/4.306/7.256)	pass
9	dh2.s+ 2db.s+ hold2	104.558f	4.536	1.95stbd	15.225 (17.387/13.062)	4.32fwd	(6.242/3.256/4.015)	pass
10	dh2.s+ 2db.s+ 2ts.s	106.975f	4.13	2.14stbd	14.126 (14.137/14.126)	0.02fwd	(5.166/4.291/7.243)	pass
11	dh2.s+ 2db.s+ 2ts.s+ hold2	103.248f	4.255	2.43stbd	15.261 (17.501/13.022)	4.47fwd	(6.22/3.084/3.849)	pass
12	dh1.s+ 1db.s+ dh2.s+ 2db.s	107.240f	4.354	3.82stbd	14.302 (14.800/13.805)	0.99fwd	(5.258/3.640/6.389)	pass
13	dh1.s+ 1db.s+ 1ts.s+ dh2.s+ 2db.s+ 2ts.s	106.110f	4.08	4.05stbd	14.319 (14.851/13.787)	1.06fwd	(5.245/3.559/6.312)	pass
14	dh1.s+ 1db.s+ 1ts.s+ hold1+ 2db.s+ 2ts.s	101.240f	4.114	5.23stbd	15.419 (18.951/11.887)	7.03fwd	(6.975/2.134/2.088)	pass
15	dh1.s+ 1db.s+ 1ts.s+ hold1 dh2.s+ 2db.s+ 2ts.s+ hold2	68.085f	2.39	10.95stbd	18.991 (30.478/7.503)	22.56fwd	(10.407/2.963/-9.823)	-
16	dh1.s+ dh1.p+ hold1	103.677f	4.303	0	14.999 (17.543/12.455)	5.09fwd	(7.098/4.035/4.0273)	pass
17	dh2.s+ dh2.p+ hold2	104.326f	4.39	0	15.138 (17.132/13.143)	3.99fwd	(6.410/3.894/4.484)	pass
18	dh1.s+ dh1.p+ 1ts.s+ 1db.s+ hold1	102.857f	4.276	1.44stbd	15.183 (18.239/12.127)	6.11fwd	(7.242/3.448/3.220)	pass
19	dh2.s+ dh2.p+ 2ts.s+ 2db.s+ hold2	103.408f	4.284	1.70stbd	15.314 (17.654/12.9740)	4.68fwd	(6.363/3.24/3.777)	pass

