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SUBDIVISION OF RO-RO SHIPS FOR ENHANCED SAFETY IN THE DAMAGED CONDITION*)

SUMMARY

The paper shows that ro-ro ships can be as safe in the damaged condition as other ship types without restricting their design features, i.e. with no transverse and/or horizontal subdivision within the cargo space liable to damage, if there are provisions for reserve buoyancy above the vehicle deck - the first deck above the deepest waterline. For this purpose these ships should embody a double hull over the entire length of the cargo region of the ship, terminated at the second deck above the waterline and, in addition, double decks - at least the first deck above the waterline - preferably inclined upwards in the longitudinal direction. The double hull and double decks should be sufficiently densely subdivided by watertight bulkheads into watertight compartments. They should be preferably cross-connected and of a breadth less than B/5. Cargo spaces below the double decks should be provided with efficient air escapes for removing air cushions from the undersides of the decks. A deck (or decks), if any, below the first deck above the waterline and also this deck should be designed as open to the passage of flooding water, i.e. incorporating efficient down-flooding arrangements.

Introduction

Ro-ro ships are considered by the maritime profession and travelling public as the most unsafe ships in operation and this is not surprising when one considers their very low values of indices of subdivision, usually far below the required values. This comes from the fact that these ships were badly designed with little or no concern of damage stability. The large open vehicle decks of ro-ro vessels make them particularly sensitive to presence of water on such decks which may appear there due to collision damage or other accidental operational reasons like fire fighting, intake of water due to the bow door left open (as in the case of the Herald of Free Enterprise), or leakage of water through the aft gate deprived of weathertightness as it was most likely in the case of the Jan Heweliusz, a Polish ferry which capsized in January 1993 during extremely heavy weather, causing the death to 55 passengers and crew members, with only nine persons rescued. These two disasters clearly illustrate the potentially devastating influence of an open deck on the damage stability of a ro-ro vessel. In the absence of transverse subdivision, even a very small amount of water on such a deck can lead to rapid heeling and loss of stability usually associated with a large loss of life. This paper aims to show how significant improvements could be made to the survivability of existing and future ro-ro ships without impairing their present successful operational features.

Current subdivision arrangement of ro-ro ships

For some forty years cargo ships and passenger ferries intended primarily for the carriage of roll-on/roll-off cargo have had no transverse watertight bulkheads within cargo space. Until 1 February 1992 there were no subdivision requirements for cargo ro-ro ships. That is why ballast tanks on such ships were frequently applied due to psychological reasons rather than due to subdivision considerations. They could save the ship only in cases of a minor damage in one of those tanks. Car - passenger ferries (of ro-ro type) are subject to subdivision and damage stability requirements contained in the 1974 SOLAS Convention. Space below the bulkhead deck on such ferries is usually densely subdivided by transverse bulkheads extending from side to side. In such a case, wing tanks are not applied and many of the compartments below the bulkhead deck are neither used for the carriage of cargo nor for other purposes. On the remaining ro-ro passenger ships, compartments with breadth not less than B/5 are applied below the bulkhead deck. The compartments are relatively short and cross-connected to avoid asymmetrical flooding. This type of subdivision arrangement is shown in Fig. 1. The above described solutions however do not provide sufficient safety for passenger ro-ro ships in case of collision. On the contrary, these solutions appear to be extremely dangerous as they do not secure a ferry against rapid capsize in the case of sea water accidentally entering the bulkhead deck. A good evidence of this was the tragic capsizing of the European Gateway in 1982 and the Herald

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of Free Enterprise in 1987, to mention only two recent well known disasters. The two ships had the same type of subdivision, derived from the SOLAS Convention, where the ship due to low freeboard, is densely subdivided with transverse bulkheads below the bulkhead deck in order to get one compartment standard and with no reserve buoyancy above it.

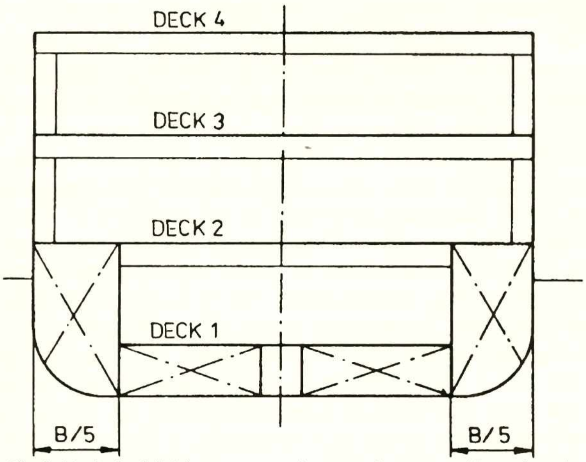


Fig. 1. A typical subdivision arrangement on some large ro-ro ships, extremely dangerous, influenced by the SOLAS Convention.

As the compartments are then very short, probability of flooding more than one compartment is therefore high, resulting in very low probabilities of surviving for such ships and thus objectively confirming their bad performance in case of collision. In addition, the dense subdivision causes the machinery space to be divided into smaller watertight compartments and this in turn opens up an area for human error. A good example of this illusory subdivision was demonstrated by the sinking of the European Gateway [1]. The ship received a small damage below the bulkhead deck but between the bulkheads of the machinery space of the ship. Instead of surviving this potentially safe standard case of damage, she sank very quickly (within some twenty minutes) as all watertight doors within that part of the ship were left open, leading to the flooding of four compartments instead of one. The crew undertook desperate action to close the doors but tragically failed to do so. The new probabilistic rules [2] which entered into force in February 1992 require the same level of safety for all dry cargo ships irrespective of their type. Thus new ro-ro ships will have to be equally safe (have the same indices of subdivisions) as the remaining dry cargo ships. The indices of subdivision for existing ro-ro ships are very low, if not marginal, frequently not exceeding a value of 0.1 whilst for other dry cargo ships this index value is above 0.5. There is no possibility whatsoever of increasing the indices of subdivision so markedly within the presently applied concept of ro-ro ship subdivision, except through a considerable increase in freeboard or by the application of removable transverse bulkheads in holds intended for ro-ro cargo. Such solutions are clearly contradictory to the basic operational features of ro-ro ships and should be applied only in the last resort.

Provision of double hull and deep-sinkage-after-flooding ability

A feasible and efficient remedy for the poor safety of ro-ro ships is application of the idea of deep sinkage after flooding, presented in detail in [3], and briefly summarized here. It comes simply from the fact that the damage stability of the ro-ro ship with the bulkhead deck immersed, which is a typical case, increases the deeper the ship sinks. This startling observation is not difficult to explain. An increase in damage draught for any constant damage displacement allows the centre of buoyancy to move closer to the centre of gravity thereby improving stability. Moreover, experiments have shown that in ships with the much deeper draught associated with the final stage of flooding any roll motion in waves almost completely disappears so that only heave motion remains. It is therefore very unlikely such a vessel to be capsized by wave action when it is floating deeply immersed in a near upright position. In the light of the above remarks an increase in the number of bulkheads below the vehicle deck is found to reduce damage stability dramatically. This situation is opposite to that for conventional ships and is confirmed by model tests [4]. It is evident from the foregoing that the primary safety feature of a ro-ro vessel should be a mandatory double skin extending from the inner bottom to the second deck above the waterline (the upper deck). The wing compartments so formed should be transversely subdivided throughout and incorporate modest flare if possible. Apart from this the number of transverse bulkheads should be limited to the forward and aft peak bulkheads and those required to adequately subdivide the non - vehicular spaces such as the machinery spaces. The strength of these bulkheads should of course be adequate for the pressure loads imposed by the deep draught in a damaged condition. No further transverse bulkheads should be provided, as their function is replaced by the wing compartments. This type of subdivision arrangement is shown in Fig. 2. The breadth of the wing tanks is preferably equal B/10, half as large as in the previous case. As such ro-ro vessels are capable, as a rule, of surviving a major flooding at least in a partial loading condition, there is no need for increasing height of the double bottom. On the contrary, from the standpoint of damage stability, the minimum height is preferable.

In order to limit the effects of flooding, the wing

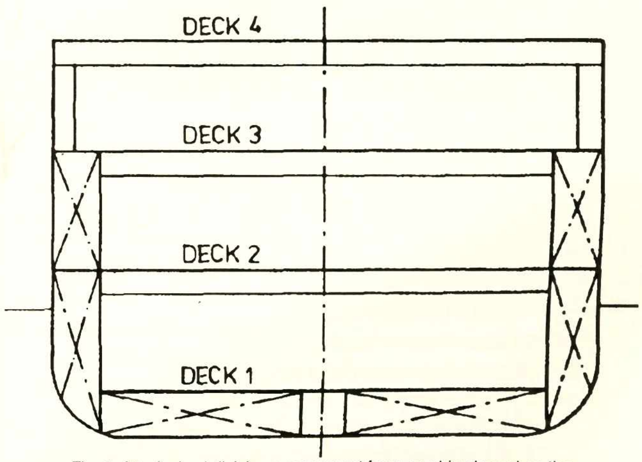


Fig. 2. A typical subdivision arrangement for ro-ro ships based on the deep-sinkage-after-flooding concept.

compartments should be relatively short, identically subdivided on both sides, and cross-connected to prevent asymmetric flooding which is always detrimental to a ship in a damaged condition. In the case of passenger ro-ro vessels, the current SOLAS regulations require that lower wing compartments should have a breadth of not less than B/5 and no wing tanks above the bulkhead deck, as shown in Fig. 1. If one assumes that major flooding of inboard spaces represents the loss of a ro-ro ship then it would be necessary to require for ship safety the wing compartments below the car deck to be as wide as possible to minimise the risk of such a possibility. However, that is not the case and therefore there is no need to impose such broad wing compartments in this position. To withstand major flooding, it is most important for a ro-ro ship to ensure positive stability at the final stage of the event when the bulkhead deck is immersed. It has been shown that this is quite practicable and requires only that narrow wing compartments be fitted below and above the vehicle deck, as shown in Fig. 2, to ensure both stability and sufficient reserve of buoyancy. Such is the purpose for providing these wing compartments.

Intermediate Stages of Flooding

Thus far, stability during the intermediate stages of flooding has not attracted the attention it deserves. Work done to date supports the intuitive notion that the intermediate conditions are usually not a problem, if the final condition is acceptable, provided the angle of heel is not so large as to cause cargo shift and the flooded water can freely spread over the entire compartment. The deck edge then remains above the waterline all the time during transient flooding [5]. The same applies also to ro-ro vessels with the double skin arrangement provided that the decks are made transparent for the flooding water which is crucial for the safety of these ships. Thus, if there are efficient down- or cross- flooding arrangements, it is entirely sufficient as far as damage stability is concerned to check only the maximum angle of equilibrium during flooding, and focus attention on the safety of the ship in the final stage of flooding. Hence, the above theoretical development considerably simplifies damage stability assessments. Owing to physical reasons, stability during the intermediate stages of flooding should be analysed for the freely floating ship longitudinally balanced at each angle of heel, using the added mass method. There are usually marked differences between the GZ-curves calculated for the free trim condition and for fixed trim particularly if the deck edge is immersed and the ship has large longitudinal asymmetry. However in the case of horizontal subdivision without efficient down-flooding arrangements, it should be assumed that after the immersion of the edge of the watertight deck the level of water above such a deck coincides with the level of water outside. This covers the case of a small hole below and a very large one above the horizontal subdivision, a typical damage when the striking ship has a bulbous bow associated with a large flare - see the case of the European Gateway [1]. The current regulations [2] overlook entirely this problem. This is the reason why naval architects consider horizontal subdivision, particularly on ro-ro ships, as beneficial to their safety. Unfortunately, this is not the case and it is now high time to tell this loudly and clearly in an attempt to divert the way things are developing.

Perforated Vehicle Decks

An important point in all ro-ro vessels concerns the watertight integrity of the main and other vehicle deck,i.e. the presence of horizontal subdivision. From the previous discussion it should be clear that any deck, including the vehicle deck which may suffer flooding from whatever source, should be non-watertight. Furthermore, such decks should be designed to allow both water and air to pass freely through them. How this should be accomplished in practice is an interesting challenge for the designer. The drainage systems must be capable of allowing very large quantities of water to drain directly into the lower cargo spaces without access to machinery or other critical spaces, which must be effectively sealed from the cargo spaces at all times. This has the effect of maximizing the damage metacentric height by both eliminating isolated free water surfaces and lowering the centre of gravity.

Watertight vehicle decks or tweendecks cannot be recommended for the following reasons:

- Decks below the vehicle deck are not usually designed to withstand the pressure forces that would be imposed by serious flooding either above or below them.
- When flooding occurs above such a deck, a large free water surface is formed which immediately reduces the vessel's metacentric height, usually causing a large angle of heel or capsizing.
- These decks can trap during sinkage large quantities of air beneath them, maintaining an additional free surface effect, which would be eliminated if the compartment were free to fill completely. In addition, these air cushions contribute to the creation of an additional heeling moment of significant value as they are formed usually at the outmost areas beneath the decks close to the side opposite to damage. As a result, these air cushions are extremely dangerous and lead to the capsizing of the ship, otherwise safe, before reaching the final stage of flooding.
- Watertight ramps and decks are more expensive than their non-watertight counterparts. In view of these points, there seems to be no good reason to retain the concepts of either horizontal or vertical watertight subdivision applied to internal vehicle spaces. In particular, retaining the vehicle deck as a bulkhead deck is particularly dangerous and should be abandoned as a design objective.

There are two further reasons why the bulkhead deck within the cargo space should be made transparent to the flooded water. Such a deck virtually eliminates the accumulation of the flooded water above this deck due to the action of waves which is found to be dangerous as it leads eventually to the capsizing of the ship [6,7]. Due to a very similar reason the watertight deck is also detrimental to stability during the intermediate stages of flooding which is rarely analysed during designing and overlooked by the current regulations.

The idea of deep sinkage was implemented at the Gdańsk Shipyard, Poland by designing a passenger-cargo ro-ro vessel of 12 000 DWT and with the overall length of 183 m, based on the double hull arrangement, as shown in Fig. 2. The bulkhead deck was designed, however, as watertight and thus it was only partly fulfilling the necessary requirements for a really safe ro-ro vessel. To make this deck open to the passage of water appeared to be too challenging for the designers.

Provision of buoyant decks

It is rather difficult to achieve deep sinkage after flooding on real ro-ro ships due to the large longitudinal unbalance between the aft part containing the big machinery room and the forepeak. As a result, the ship assumes after flooding an extremely large trim by the bow which is not as beneficial to damaged ship safety as deep sinkage at even keel. It is worth considering, therefore, fitting additionally the ship with a buoyant deck or decks, at least the bulkhead deck, transversely and longitudinally subdivided by watertight bulkheads - see Fig. 3. As previously, cargo spaces should be provided with efficient air escapes (vents) placed at the sides, close to the top of cargo spaces, to eliminate detrimental air cushions which may occur during flooding. The breadth of the double sides is definitely less than B/5; they should be subdivided into wing tanks by transverse bulkheads and preferably be cross-connected. The height of the double decks is preferably not greater than the depth of deck girders for relevant single decks. The double bottom should be preferably of the minimum height required by the classification rules.

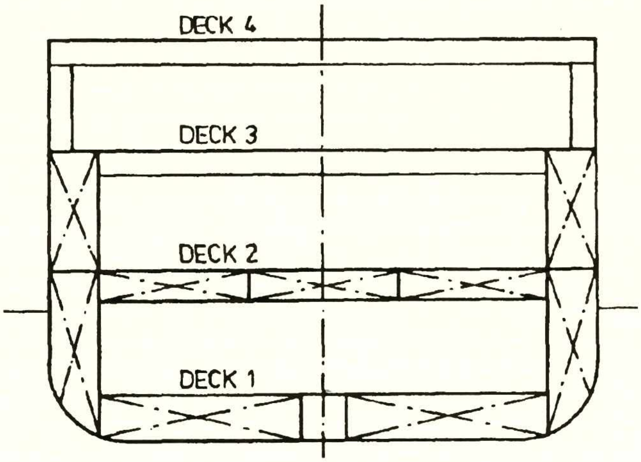


Fig. 3. Subdivision of a ro-ro ship based on the extended double shell concept.

The bulkhead deck and a deck below, if any, should be designed as permeable (transparent) for the flooded water to ensure free flooding, i.e. uniform spread of water over the whole compartment during intermediate stages of flooding. With the provision of buoyant decks, sinkage after flooding is obviously reduced and, in the extreme, can be as small as to keep the bulkhead deck emerged.

Ro-ro ships, in general, have deep deck girders because of the large unsupported deck spans. In view of the problem of cargo handling, cargo stowage is usually restricted to spaces below the flanges of these girders. There is opportunity, therefore, of sealing off the space upwards from the flanges of the deck girders to the deck plating into a buoyant chamber that can provide additional buoyancy and, depending on its location, height and extent, be of some advantage in terms of damage survivability.

The problem of location of this buoyant deck is a fairly involved exercise. However, it can be shown that for such a buoyant deck with a displacement of ν the stability coefficient will be increased, if the buoyant deck is located at a height H_{deck} satisfying the relation

$$H_{deck} > T_{dam} + \frac{\Delta J}{\Delta V} - \frac{\Delta i}{\Delta V}$$

where

T_{dam} – draft of the ship in the damaged condition without the buoyant deck;

ΔJ, Δi – change in the moments of inertia of the undamaged waterplane and the free surface of the water due to change in displacement of $\Delta V = \nu$ caused by fitting the buoyant deck.

Because $\Delta i \approx 0$ if the vehicle deck remains submerged and $\Delta J / \Delta V$ is positive then it is practically impossible to satisfy the above inequality unless there is a large reduction in the free surface moment of inertia due to the partial emergence of the buoyant deck. Unless this inequality can be satisfied, a buoyant vehicle deck will have a nearly neutral effect on initial stability in the flooded condition and consequently on the ship safety. Even though effective increase in freeboard, due to the provision of the buoyant deck, increases stability at large angles of heel, it is rather unlikely that this will be of much practical benefit in ship survival except situations when the angles of flooding are very small.

However, it is not difficult to design for significant reductions in the free surface moment of inertia. This is because in the majority of damage cases there will be a trim by the bow due to the comparatively large machinery space. In an appropriate combination of a buoyant vehicle deck and wing spaces, a situation may be reached that for a large number of damage cases the next higher deck comes into contact with the flooded water. If this higher deck is also made buoyant in the forward part of the ship, a significant gain in the index A value may be obtained and also an advantage from utilization of spaces which are usually non-productive anyway from the cargo carriage point of view. Another possibility is to use a buoyant vehicle deck which is slightly inclined upwards in the longitudinal direction so that after damage the entire deck continues to remain above water in spite of the vessel's trim by the bow.

Moreover, active consideration might be given to designing the forward upper part of a ro-ro cargo ship as a rectangular box, like in an aircraft carrier [8], to improve matters further in cases of deep sinkage after flooding.

The effect of a buoyant bulkhead deck is relatively modest in the cases where the deck is chosen with no concern regarding the reduction of free surface. It can be of the order of a 5% increase in index A values [9]. The improvement, obviously, may be considerably greater, if multiple buoyant decks are used, as may be feasible in some ro-ro vessels, or when the vehicle deck is inclined and remains above water in the majority of damage scenarios.

Advantages of the Novel Subdivision Arrangement

The benefits of subdivision arrangement based on the extended double shell concept are twofold:

- from the design and operation standpoints:

- It is possible to obtain high indices of subdivision for ro-ro ships required by the new subdivision regulations, without impairing their successful operational features, based on non-subdivided horizontal cargo spaces.

- from the technical standpoint:

- The cargo space is not reduced. The double decks make use of the space on the underside of single decks, contained between the huge deck girders, useless for cargo anyway. Confinement of this space by relatively thin watertight shell plating, replacing the thick flanges of deck girders, converts this inefficient space into a double buoyant deck of a considerable volume, reducing the trim by the bow after flooding.
- The weight of the ship is only marginally increased thus nearly the same deadweight is maintained.
- Overall ship and deck strength is improved.
- Smooth sides make cargo handling and insulation works easier.

In result, it can be expected that the overall labour consumption and thus the cost of ship production may be fairly reduced.

Numerical examples

To see how this concept works, a ro-ro ship designed at the Gdańsk Shipyard was examined whose main particulars were as follows:

subdivision/overall length	177.50/183.00m
length between perpendiculars	171.30 m
moulded breadth	28.70 m
depth to main/upper deck	8.90/15.23 m
depth to weather deck	21.20/23.10 m
design/scantling draught (T)	6.80/7.40 m
supply/water ballast tanks	1880/9500 m^3
ship's deadweight at scantling draught	12400 t
breadth of wing tanks	2.80 m
KG for full load condition at T=7.40 m	13.65 m
KG for partial load condition at T=6.11 m	13.67 m

permeability μ 0.80
required subdivision index R value 0.545

EXAMPLE 1: The ship with the subdivision arrangement as in Fig. 2, with no cross-flooding, deck No. 3 (upper deck) watertight (which is not realistic in this case). For such a ship the attained subdivision index value is much below the required one and equals:

A=0.513

EXAMPLE 2: The ship as above but with cross-flooding. The index value is then:

A=0.581

As it can be seen, cross-flooding caused here a significant increase in the index value. That, if assumed as the rule cross-flooding, is always beneficial for the ship safety, and therefore, it should be applied whenever possible.

EXAMPLE 3: The ship as in Example 2 but with Deck 3 treated as non-watertight which is in compliance with the actual design. The attained index value is now much lower and equals:

A=0.512

which should obviously be expected. It is then quite sensible to make the upper deck watertight, if possible. Moreover, as the ship has typically a large bow trim after flooding and thus small angles of flooding, active consideration might be given to a deck or decks made buoyant at the forward end, to increase the height to openings above the damage waterline, thereby improving stability.

EXAMPLE 4: The ship as in Example 3 but with Deck 2 as pontoon, creating a buoyant double deck of depth 1600 mm as shown in Fig. 3. The attained index value is now:

A=-0.519

that is only marginally higher than in the previous case. This is because the buoyant deck as it is , due to the bow trim, in the majority of damage scenarios still remains under water on the majority of its length, thus insignificantly contributing to the reduction of the free surface effect.

This example provides a good lesson: not every buoyant deck can be expected to contribute significantly to ship safety. To do so, the whole subdivision arrangement must be carefully chosen so that the buoyant deck could remain above water in prevailing cases of flooding.

However, it is not difficult to do so. Keeping the remaining subdivision unchanged, there are two immediate possibilities: - a slight increase of the height of Deck 2 maintaining the underside structure of the deck with the original depth which is equivalent to an increase of the pontoon depth by the same value; - and/or a slight inclination upwards in the longitudinal direction of the topside of the deck. The application of medium speed engines for ship propulsion provides another possibility. If such engines are located in the wing compartments, then the lower cargo hold can be significantly extended abaft thus largely reducing the trim by the bow after flooding.

EXAMPLE 5: The ship as in Example 4 but with the ship's depth to Deck 2 increased by 0.2 m from 8.9 to 9.1 m. The depth of the pontoon is simultaneously increased from 1600 to 1800 mm, keeping the underside structure of the deck at the previous height. The attained index is now:

A=0.556

which is higher than the required value R=0.545. It is worth noting the incredible increase of the index due to the increase of the depth to Deck 2 by only 0.2 m. This example shows how sensitive is ship safety to some parameters of subdivision arrangement containing a buoyant deck and that is why it is so easy to be disappointed with it, if it is not properly chosen. The most important of all is to keep as far as practicable the buoyant deck dry (to remain above water) in the majority of damage cases.

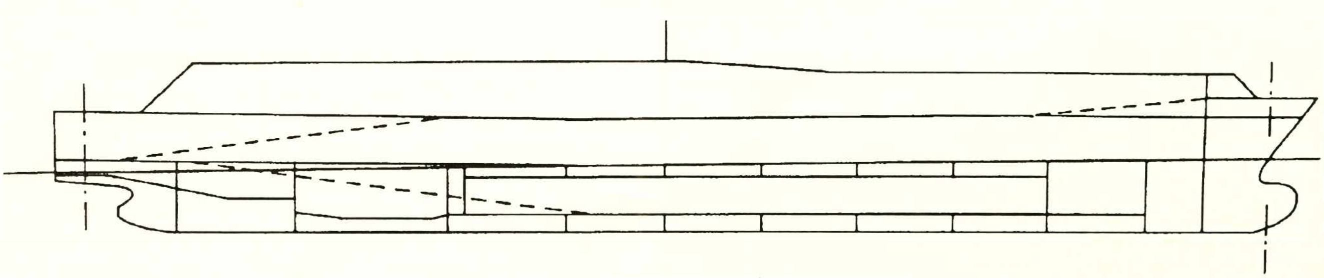
EXAMPLE 6: The ship as in Example 5 but with Deck 2 inclined upwards in the longitudinal direction by 1 m at the foremost end of this deck, as shown in Fig. 4. The attained index value is now:

A = 0.621

and it is thus drastically higher than in the previous case. Such a result should obviously be expected in the light of the previous remarks. From the examination of some of the most representative cases of flooding for the previous case study, it followed that the depth of the flooded water at the forward end of Deck 2 did not exceed a value of 1 m. This is why the free surface effect could be reduced now in the case of the 1 m sheer of Deck 2 to nearly nothing in most cases of damage, thus markedly increasing the index value.

The rise of Deck 2 by 1 metre at its foremost end is not much. Examining Fig. 4, one can hardly believe that this deck is inclined at all. All other decks above Deck 2, must have obviously, the same sheer, to keep them parallel to one another.

In all the examples, Deck 2 was treated as open for the passage of water and air, to eliminate the many adverse effects, discussed above and not accounted for in the current regulations. Owing to that reason, horizontal subdivision due to Deck 2 was simply ignored, and this was for the benefit of the ship.



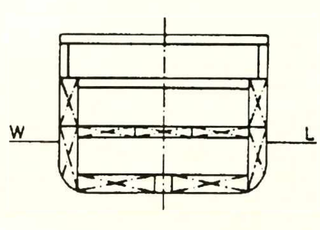


Fig. 4. Example of a large ro-ro ship subdivision based on the extended double shell concept.

Conclusions

The probabilistic subdivision regulations for dry cargo ships [2] provide a framework for the rational assessment of competing ro-ro ship designs from the damage survivability point of view. It is clear from the results above reported that it is possible to achieve a satisfactory subdivision index value for such ships without transverse or horizontal subdivision below the upper deck. Their intended function is replaced by the wing compartments extending from the bottom to the upper deck and cross-connected, and a buoyant deck or decks, open for the passage of water and air below the upper deck, leaving this deck area clear for through transport.

The judicious distribution of reserve buoyancy in the longitudinal, transverse and vertical direction is important in the design of these ships and since there are many different ways of doing this satisfactorily, there is the obvious scope for optimization of the arrangement of such vessels. The performance of these ships in the damaged condition is very sensitive to some particulars of the subdivision arrangement containing a buoyant deck, depending on presence of water on the deck in a flooded condition. It is important to note that the current survivability regulations merely set standards, though imperfectly, and are not prescriptive as regards an actual arrangement. The designer, therefore, retains the opportunity to meet the range of design objectives. Subdivision arrangement based on double hull and double deck seems to be particularly efficient and beneficial for these ships.

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