EFFECT OF WATERTIGHT SUBDIVISION ON DAMAGE STABILITY OF RO-RO FERRIES

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SUMMARY

Effect of various subdivision arrangements of ro-ro vessels on damage stability is discussed. The arrangements included single and double sides both below and above the car deck, with and without a double buoyant car deck, and with or without a watertight tween deck below the car deck. This gave as many as 16 various arrangements for each compartment length. The double sides both above and below the car deck are of the same width b = 0.1B. The double bottom, when not flooded, worsens damage stability. The car deck and tween decks should be 'openwork', to be transparent for water and air. Otherwise, the ship can capsize at the very initial stages of flooding. Double sides and a double car deck together improve considerably damage stability, both in terms of maximum arm and range. A new characteristic was introduced, termed the critical deck height. Flooding a deck above the critical height leads to a rapid capsizing of the ship.

NOMENCLATURE

BP =	base plane
b =	breadth of double sides
GM =	metacentric height
GZ =	righting lever
h_0 =	GM_0 – initial metacentric height of the intact ship
i_x =	transverse moment of inertia of the free surface of floodwater
K =	volumetric stiffness of the ship
l =	length of compartment
r_C =	differential metacentric radius
r_w =	metacentric radius of floodwater
T =	draught of the intact ship
V =	volume displacement
v =	volume of floodwater
z_w =	height of the centre of gravity of floodwater above the BP
ΔJ =	increment of the transverse moment of inertia of the undamaged waterplane due to sinkage

1. INTRODUCTION

The study will be performed using as generic ship a Polish ferry, still in operation, whose main particulars are as follows:

Overall length (L_{OA})	= 169.9 m,
length between perpendiculars (L_{pp})	= 159 m,
breath (B)	= 28 m,
depth (H)	= 8.65 m,
design draught (T)	= 6.2 m,
height of double bottom (h_b)	= B/20 = 1.40 m,
height of CG above BP (KG)	= 13.90 m,
metacentric height (GM)	= 1.66 m,
trim (t)	= −0.73 m,
block coefficient (c_B)	= 0.683.

A minimum height of the double bottom for the above ship according to PRS equals h_b = 1.12 m.

A side view of the ship, built in 1995, is shown in Figure 1. The ship has the old type of subdivision, confined to space below the bulkhead deck (car deck)), densely subdivided by transverse bulkheads. Most of these compartments are void, not used for the carriage of any cargo or supplies. Above the car deck, there is no reserved buoyancy. This type of subdivision was common until end of the 1990s. Nowadays, space below the car deck is frequently utilised for ro-ro cargo, in the form of a long lower hold (LLH), stretching for about half of the ship length. It has double sides, subdivided by transverse bulkheads, but no transverse bulkheads in cargo space, see examples in references [1, 2].

For illustration of the damaged stability, flooding a transverse compartment located amidships, of various subdivision arrangements, with two lengths: l = 16 m and l = 25 m will be examined.

2. DAMAGE ABOVE THE CAR DECK

For reference purposes, we will examine first the ship damaged *above* the bulkhead deck only, with two versions: with a single side above the deck, and with double sides of width b = 0,1B, as in Figure 2. For the sake of simplification, we will assume that in the case of double sides the effect of flooding the wing tanks can be ignored.

The GZ-curves for the two cases are shown in Figure 3. The initial run of the two curves, up to the deck edge immersion, is common. In both cases, the damage stability in categories of the maximum righting arms is satisfactory. In the first case, GZ_{max} reaches a value of 0.30 m, while in the second case, a value of 0.41 m. However, range of stability in the first case is unsatisfactory, below 20°. As we can see, the double sides markedly improve stability: location of the maximum increases from 12° up to 17°, whereas range of stability from 17° to 36°. The improvement could be yet larger, if stability at the initial range (up to the angle of deck edge immersion) would be better, i.e. the metacentric height GM and freeboard F were bigger. A trim of the intact ship decreases freeboard at the aft to F = 2.085 m, which reduces the angle of deck edge immersion to ϕ_D = 8.5°.

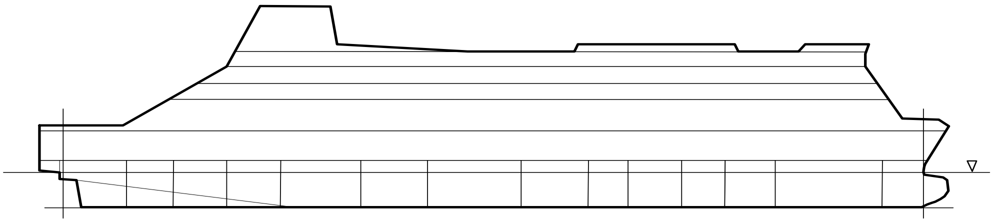

Figure 1. Watertight subdivision of the investigated ro-pax

For damages stretching from below the car deck upwards without a limit, it can be expected that the GZ-curve will be smaller than that shown in Figure 3. It is worth emphasizing that stability of full ships, as bulk carriers or pontoons, of the same proportions is worse than stability of fine ships, as ferries. This refers both to intact and damage stability.

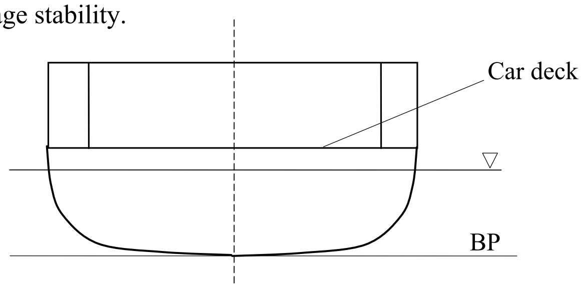

Figure 2. Ship with double sides on the car deck

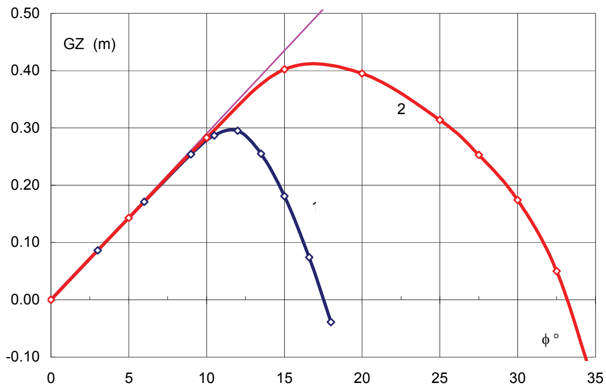

Figure 3. GZ-curves for the ship damaged *above* the car deck; 1 – single sides, 2 – double sides

3. CONFIGURATIONS INVESTIGATED

There will be a number of configurations investigated, such as single sides and double sides *below* the car deck, single sides and double sides *above* the car deck, with and without a buoyant car deck, and with or without a watertight deck below the bulkhead deck. This gives as many as 16 various arrangements for each compartment length. The length of compartment refers to a compartment below the car deck. It is assumed that above the bulkhead deck, the space is open, stretching almost over the entire ship length. The double sides both above and below the car deck are of the same width b = 0.1B. The height (thickness) of the double car deck h_d = 2 m. Hence, the underside of the double deck is at a height 6.65 m from the BP, i.e. in a distance of 0.45 m above the deepest waterplane. Normally, deck girders on ferries have a height of the order of 1.5 m, which increases with the ship beam. Hence, space needed for a buoyant deck already exists. It is sufficient to close it from the underside to get a buoyant deck, providing enormous reserved buoyancy in a close vicinity of the waterplane.

The first four configurations are shown below.

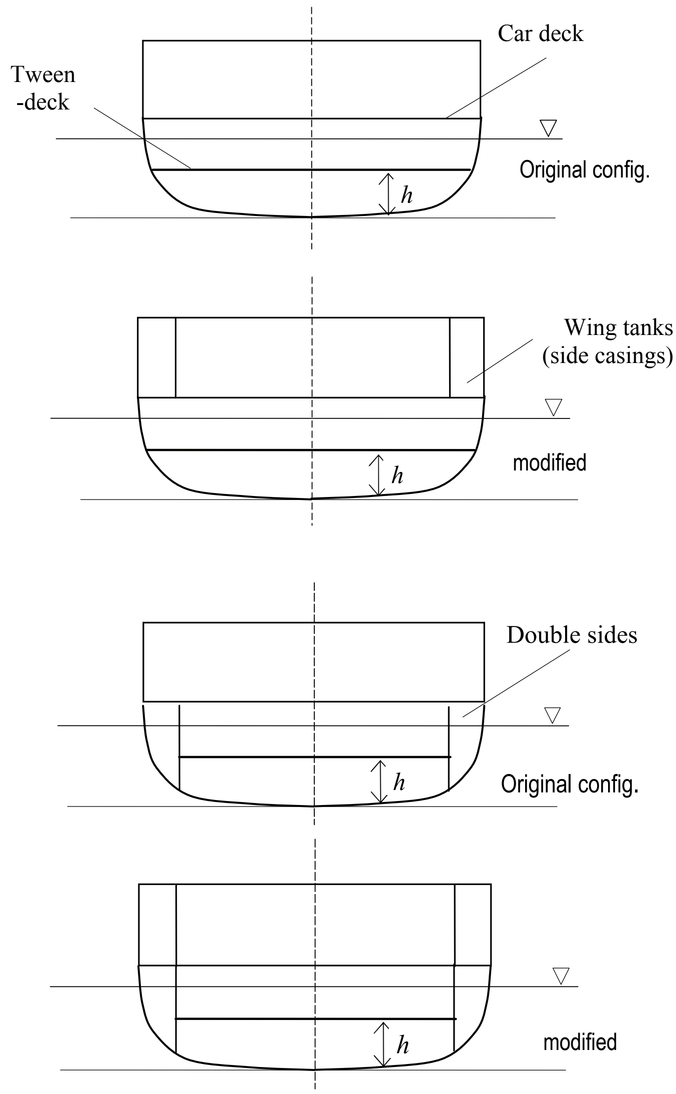

Figure 4. Configurations investigated

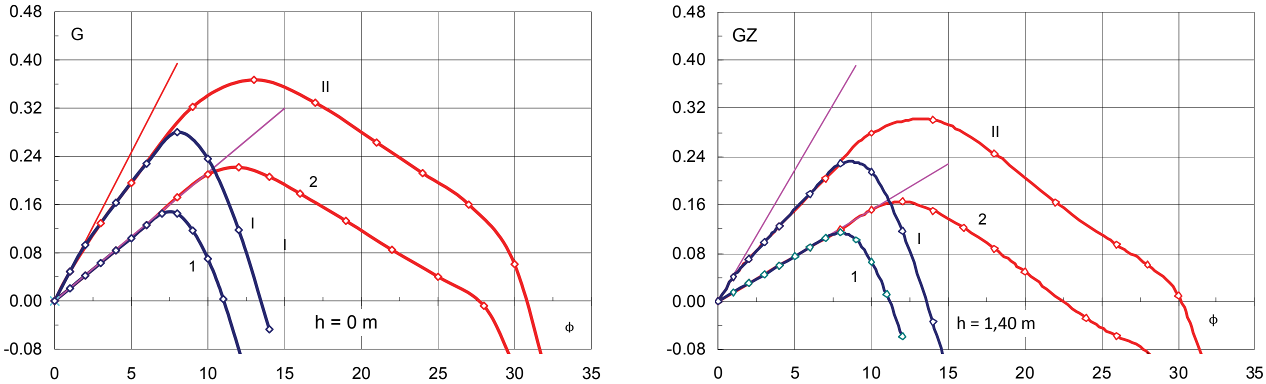

Figure 5. Effect of various configurations on *GZ*-curves for the ship in Figure 4 top (l = 16 m), with single sides below the car deck

If there is a tween deck below the car deck, the damage Generally, the tween deck is located at a height h above the BP. If h = h_b = 1.40 m, then the compartment is flooded above the double bottom, (that is to say, without the double bottom). If h = 0, it means that flooding includes the double bottom, which is supposed to be empty before the commencement of flooding. In all flooding cases the damage opening is assumed to be short. Hence, for the sake of simplicity the effect of asymmetrical flooding is ignored.

How stability varies depending on configuration, is shown in the following figures. Figure 5 and Figure 6 show the effect of the double bottom, compartment length, double sides and a double buoyant car deck for a ship with *single* sides below the car deck. Figure 5 refers to a compartment with length 16 m, while Figure 6 – with length 25 m. The same effect for a ship with *double* sides below the car deck shows Figure 7 and Figure 8. Graphs on the left-hand side in all these figures refer to flooding cases including the double bottom, while on the right-hand side, excluding bottom. As can be seen, in all cases flooding a compartment without the double bottom makes worse the stability. When length of the compartment increases, deterioration of stability is even higher. Therefore, height of the double bottom should be kept minimum allowable by the rules. In this case, it could be reduced from 1.40 m to 1.12 m, i.e. by 0.28 m, if possible due to other reasons.

Curves 1 in Figure 5 to Figure 8 refer to a compartment with no wing tanks on the car deck and with a single bulkhead deck, i.e. to the original configuration with single or double sides below the car deck. Curves 2 show the effect of adding wing tanks (side casings) on the car deck. As can be seen, this effect is substantial, particularly for the ship with double sides below the car deck and when the double bottom is flooded. Wing tanks increase the maximum arm, its location, and particularly the range of stability.

Curves I in these figures refer to a compartment with a double deck but with no wing tanks above it. In other words, curves I show the effect of adding solely a double deck. As can be seen the double deck increases markedly the metacentric height and the maximum righting arm, but not so much the range of stability. In all cases the metacentric height increases above the value for the intact ship. This can be easily explained. When the double deck is partially submerged, the waterplane moment of inertia is virtually the same as for the intact ship, whereas the centre of buoyancy is markedly shifted up. For example, for a longer compartment without flooding the double bottom (h_b = 1.40 m) the metacentric height increases from a value 0.5 m up to as much as 2.98 m! (Figure 6 right). Flooding the double bottom (Figure 6 left) increases the metacentric height

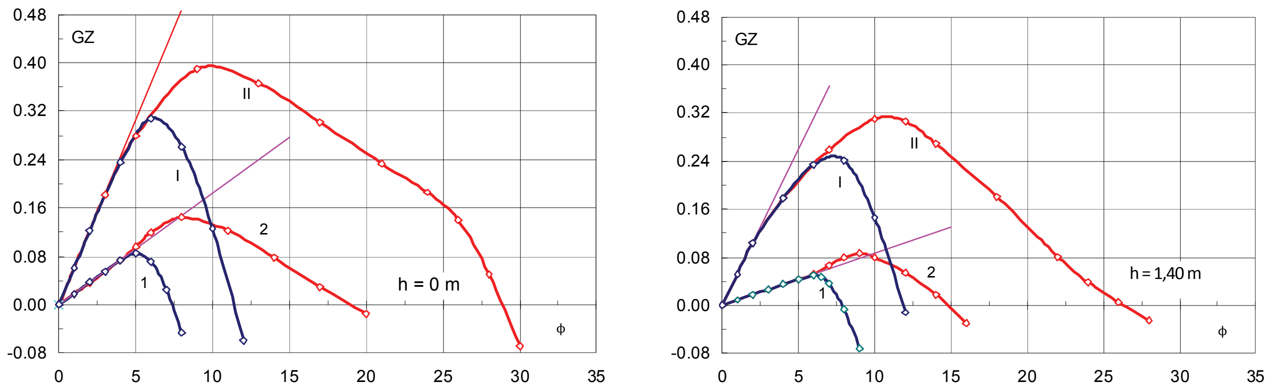

Figure 6. Effect of various configurations on *GZ*-curves for the ship in Figure 4 top (l = 25 m), with single sides below the car deck

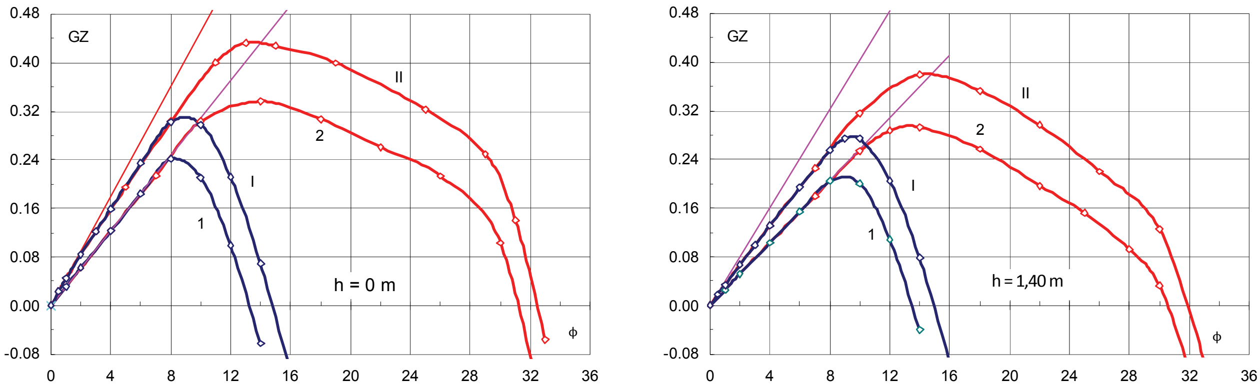

Figure 7. Effect of various configurations on GZ-curves for ship in Figure 4 bottom (l = 16 m), with double sides below the car deck

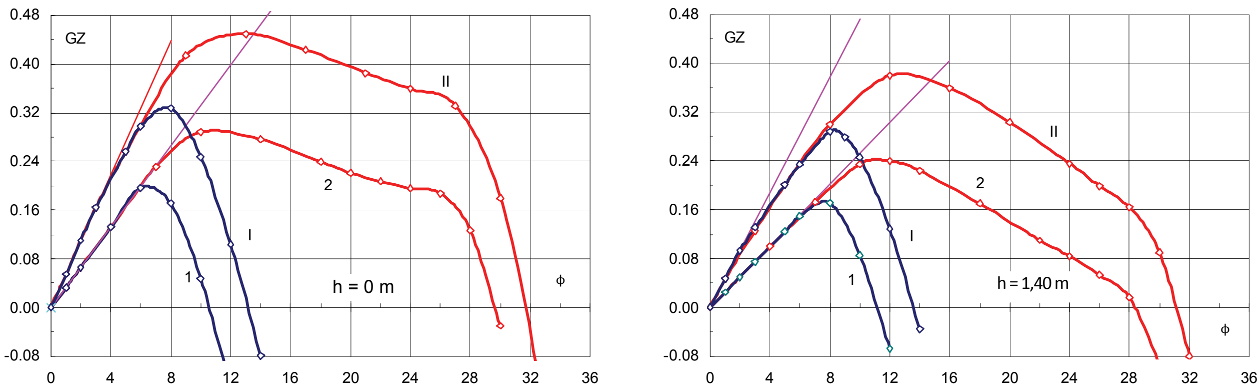

Figure 8. Effect of various configurations on GZ-curves for ship in Figure 4 bottom (l = 25 m), with double sides below the car deck

yet more by 0.50 m, reaching a value of 3.48 m.
It is amazing that the double deck for a longer compartment yields GZ-curves whose maximum values are *higher* than for a shorter compartment!

Curves II in Figure 5 to Figure 8 refer to a compartment both with wing tanks on the car deck and with a double deck. In other words, these curves show the effect of adding a double deck along with wing tanks on the car deck. As can be seen, the two effects are particularly strong, when a flooded compartment has double sides below the car deck. Note that in such a case the maximum value of the righting arm can exceed a value 0.41 m, i.e. be higher than for the ship damaged only above the car deck (Figure 3).

4. TWEEN DECKS

We could see from the foregoing discussion that stability of the ship without flooding the double bottom is always worse than in the case when flooding includes the double bottom. The height of the double bottom cannot go beyond a certain value. However, there are decks below the car deck (bulkhead deck), termed tween decks, which can play a similar role as the inner bottom. It can be generally shown that if only space above the tween deck is flooded, than stability of the ship is worse than in the case without it. That is to say, the greater the deck height h above the BP is (see Figure 4), the worse stability, and the faster capsizing of the ship.

If the presence of the tween deck is neglected, which frequently happens in calculations, the ship can be stable in the final stage of flooding, though it can capsize during the process of flooding, if the deck is above a certain critical height h_{crit}. The situation is deteriorated, when the flood water flows down to the bottom, not necessarily through down-flooding arrangements, and creates an additional free surface.

If for some reasons water got to the car deck, as it was in the case of the *Herald of Free Enterprise* or *Estonia*, the ship would capsize within minutes. For each ship and compartment a critical deck height h_{crit} can be defined. Flooding a deck above h_{crit}, leads to a rapid capsizing of the ship. It is, therefore, important that decks below the car deck are made transparent for air and water to avoid the creation of air cushions and free surfaces. The same should also apply to the car deck, where water can occur due to firefighting. Two first ships with openwork decks were built at end of the 1990s by Gdansk Shipyard [1].

It can be strictly proved that the coefficient of stiffness K for the ship with floodwater during the process of flooding reaches maximum at the final stage, when flooding is completed. Hence, the critical deck height determines the condition K = 0, i.e. when the stiffness vanishes at the final flooding. For a compartment located at the midships, K is given by the equation:

$$K = K_0 + v(T + ½\Delta T + r_C - z_w) - i_x, \tag{1}$$

valid for any volume of floodwater, where $K_0 = Vh_0$ is the intact ship stiffness, v is volume of floodwater, T is draught of the intact ship, ΔT is the increase of draught due to floodwater, r_C is the differential metacentric radius, z_w is height of the centre of gravity of floodwater above the BP, and i_x is the transverse moment of inertia of the free surface of floodwater. Except K_0 and T, other quantities are instantaneous, corresponding to the current volume of floodwater v, varying from zero to the final volume of floodwater, when flooding is completed. K is a monotonic function of v, reaching a maximum at the final stage of flooding.

Considering that $r_C = \Delta J/v$, where ΔJ is the increment of the transverse moment of inertia of the undamaged waterplane, equation (1) can be written, as follows:

$$K = K_0 + v(T + ½\Delta T - z_w) + \Delta J - i_x. \tag{2}$$

Usually, at the very beginning of flooding the stiffness K < 0 is negative, when the compartment is long enough, which entails heel of the ship, even when flooded compartment is symmetric. Further flooding causes the ship heel, reaching a maximum value of the order of several degrees, just prior to coming by the floodwater to the opposite side, provided that at the final stage of flooding the stiffness K > 0 is positive.

Further flooding reduces the heel. The ship comes back to an upright position, when the stiffness K = 0 vanishes. From this moment the stiffness increases with floodwater, reaching a maximum value at the final stage of flooding, when level of floodwater inside the compartment coincides with the level of water outside. Vanishing of the stiffness at the final stage of flooding determines the critical deck height h_{crit}; flooding a deck at this height will end up with capsizing of the ship at the end of flooding or earlier. The more the deck height h exceeds the critical height h_{crit}, the sooner capsizing of the ship happens. If the elevation of the critical value is large enough, capsizing can occur soon after commencing of flooding.

Equation (1) can be expressed in terms of the metacentric height, if subdivided by the volume displacement of the ship V:

$$GM = h_0 + (v/V)(T + ½\Delta T + r_C - z_w - r_w), \tag{3}$$

where $h_0 \equiv GM_0$ and V are correspondingly the initial metacentric height and volume displacement of the intact ship, whereas r_w is the metacentric radius of floodwater. The expression in parentheses represents the difference between the differential metacentre of the waterplane and the metacentre of the centre of gravity of floodwater.

Equation (3) can be written in an identical form, resulting from equation (2):

$$GM = h_0 + (v/V)(T + ½\Delta T - z_w) + (\Delta J - i_x)/V. \tag{4}$$

In the case of a rectangular cargo hold, the above equation can be somewhat simplified for the final flooding, since then $½\Delta T - z_w = -½(T + h)$. Therefore, $T + ½\Delta T - z_w = ½(T - h)$. Equation (4) reduces then to

$$GM = h_0 + ½(v/V)(T - h) + (\Delta J - i_x)/V. \tag{5}$$

Given length of the compartment and breadth of the double sides, equation (5) defines the critical deck height, i.e. a height of the deck, whose flooding at the final stage reduces GM = 0 to zero.

The critical height depends chiefly on the metacentric height of the intact ship, and on moment of inertia of the free surface of floodwater in the compartment. The latter in turn depends on the length and breadth of the compartment. For a deck at height h = T, v = 0, equation (5) reduces to $i_x = Vh_0$, which determines the admissible length for such a compartment.

Given deck height and breadth of double sides, equation (5) defines a floodable length of the compartment, whose flooding at the final stage reduces GM = 0 to zero, or brings down the deck to the level of water outside. The critical deck height or the floodable length can be easily found from equation (5) with the help of „Goal seek" in Excel. For the ship investigated, with the intact GM = 1.66 m, the floodable length is given in Table .

Table 1. Floodable length as function of breath b of double sides and deck height h

b = 0 m		b = 2,8 m	
h	l_f	h	l_f
0	46,12	1,4	57,33
1,4	32,44	2,497	67,55
3	23,88	3	58,89
4	20,57	4	46,34
5	18,21	5	38,07
6,2	16,20	6,2	31,64

As can be seen, the double sides increase considerably the floodable length l_f, in this case, when b = 0,1B more than twice. Secondly, the floodable length decreases monotonically with deck height, to a minimum value for h = T. Hence, the height of the double bottom should be minimal, whereas tween decks should be made openwork. For single sides (b = 0), the floodable length results from vanishing the metacentric height GM = 0. For a ship with double sides, vanishing of GM is possible, when h > 2.497 m. When h < 2.497 m, the floodable length results from vanishing the freeboard, while stability is positive, i.e. GM > 0. The ship sinks then in an upright position. The floodable length in such a case has a maximum, when both freeboard and GM vanish. For a ship with double sides the floodable length increases markedly, making the ship almost unsinkable.

The paper focused on flooding a midships compartment. To account for flooding end compartments, causing trim of the ship after flooding, detrimental for damage stability, the car deck should have a sheer in the form of a segmented (broken) line, with knuckles some ⅓ of deck length from the ends, to increase height of the car deck at the ends [1], and keep it dry after flooding.

Two first ropax vessels ever built in the world with a double car deck were built at the Shipyard Nova in Szczecin in 2001, described in [2]. They incorporated the features discussed above. The double deck appeared to be very effective on these ships.

5. CONCLUSION

Based on the results of the carried out work, the following conclusions can be drawn:

- For the intact ship the angle of immersion of the car deck edge ϕ_D should be at least 10°
- The double bottom worsens damage stability, therefore it should be of minimum height, allowable by the regulations
- The car deck and tween decks below should be openwork, to be transparent for water and air. Otherwise, the ship can capsize at the initial stages of flooding, irrespective of stability at the final stage
- Stability at the final flooding is reliable, if there is no room for the creation of multi free surfaces and air cushions, i.e. when tween decks below the car deck are openwork
- During a symmetric flooding, the maximum heel ϕ_{max}, due to a negative metacentric height at the initial stages of flooding, does not exceed 10°. At this situation the water is almost touching the opposite side
- The ship will not capsize during flooding, if at the final stage the metacentric height GM is positive. This theorem does not hold, if there is room for multi free surfaces
- Double sides and a double car deck together improve damage stability considerably, both in terms of maximum arm and range. The double deck on its own shows a decent effect on the range of stability.

6. REFERENCES

1. PAWŁOWSKI M. *Subdivision of RO/RO Ships for Enhanced Safety in the Damaged Condition*, Marine Technology, Vol. 36, No. 4, Fall 1999, pp. 194–202
2. *Best Ships of 2001,* pp. 46-47

