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THE PROBABILITY OF COMPARTMENT AND WING COMPARTMENT FLOODING IN THE CASE OF SIDE DAMAGE
— NEW FORMULAS FOR PRACTICAL APPLICATION —

by

Walter Abicht

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A new mathematical model for the distribution of side damages with respect to damage location, damage length, and damage penetration is presented. Its correspondence with the results of damage statistics is shown. For the probability that a compartment or wing compartment will be flooded, formulas are set up which are strictly based on the assumed distribution functions. It is recommended to introduce these formulas in a revised subdivision regulation applicable to all types of sea-going merchant ships. The importance of such a revision is demonstrated by a presentation of inaccuracies and shortcomings resulting from the calculation methods prescribed in the actual probabilistic subdivision rules for passenger and dry cargo vessels.

INTRODUCTION

Thirty years after Wendel [1] introduced the survival probability as a criterion for the effectiveness of watertight subdivision, two international subdivision rules based on the probabilistic concept exist: Equivalent Regulations on Subdivision and Stability of Passenger Ships (IMO-Resolution A.265) and the Regulations on Subdivision and Damage Stability of Dry Cargo Ships (IMO-MSC 57/WP 13). Both regulations are based on the assumption of the occurrence of a side damage. On account of the randomness of location and dimensions of the side damage, these quantities are presented by their distribution functions. Bottom damages and stem damages are not considered because of the rather high effectiveness of the double bottom in the case of grounding and of the collision bulkhead in the case of ramming.

The method of subdividing ships by aiming at a certain minimum survival probability is less rigid than the conventional method of arranging transverse bulkheads in accordance with a given factor of subdivision. This is a big advantage especially for dry cargo ships. By a proper arrangement of transverse and longitudinal bulkheads – if necessary, in combination with a horizontal subdivision – comparatively spacious cargo holds are possible without reducing the degree of survivability.

It is to be expected that in the near future the aforementioned probabilistic subdivision rules for passenger ships and dry cargo ships will be revised and integrated in one regulation. Furthermore, this regulation will presumably replace the antiquated subdivision requirements of SOLAS 1974 and other damage stability rules which aré still based on the concept of a one-, two- or three-compartment standard. On this occasion, the errors and shortcomings which are to be found in both existing probabilistic regulations should be eliminated. This especially applies to the formulas for the calculation of the probability of compartment and wing compartment floodings. After a short demonstration of their weak points new formulas without such flaws and suited for practical application in a revised subdivision rule will be presented.

DETERMINATION OF THE PROBABILITY OF FLOODING IN THE ACTUAL RULES

The equations by which the probability of flooding must be calculated for passenger and dry cargo vessels are based on the same damage statistics. Nevertheless, the formulas to be applied are different.

In the equivalent subdivision rules for passenger ships [2], the product $a \cdot p$ represents the probability that a compartment (and only the compartment under consideration) will be flooded. Factor a accounts for the location of the compartment within the ship's length, factor p is a basic probability of flooding for a compartment of given length. The probabilities a and p must be calculated by the formulas given in the rules.

Unfortunately, these formulas are not quite correct. This can be easily demonstrated by an example: For a compartment extending over the entire ship length, the flooding probability necessarily is exactly $a \cdot p = 1$. But the result obtained from the formulas is only $a \cdot p = 0.986$ (for $L_S \leq 200$m).

In case of a wing compartment, the flooding probability must be calculated by multiplying the product $a \cdot p$ by a third factor r. The formula for r is even more unacceptable. This becomes evident if, for instance, the distance b of the longitudinal bulkhead from the shell is very short. For $b \to 0$ the reduction factor r should converge to $r \to 0$. The values we get, however, are – depending on the length of the wing compartment – between r = 0.016 and r = 0.800 (for revised version of the r-formula as published in the IMO-paper STAB XII/8, Annex II).

The aforementioned inaccuracies may lead to results which are completely wrong. This mainly applies to ships being able to survive floodings of two or more adjacent spaces. Here, contributions to the survival probability must be determined by subtracting relatively high probability values. It is a well known fact that the difference between two big numbers can only be correctly calculated if these numbers are absolutely exact. For this reason, the formulas for the probability calculations must strictly correspond with the distribution functions assumed for location and extent of damage. The distribution functions themselves must be in accordance with the results of damage statistics; here, and only here, approximations are unavoidable and can – because the survival probability must be seen as a criterion – be accepted. But after these functions are settled, no further approximations should be made and all calculations must follow with absolute accuracy the assumed distribution law. This principle, too much neglected in both of the existing rules, should be consequently observed in a revised regulation.

Being aware of some of the weak points of the passenger ship rules, it was tried to improve the formulas for the probability calculation when the probabilistic subdivision rules for dry cargo ships were formulated [3]. For the probability of compartment flooding new formulas were established. Factor a, evaluating the influence of the location of a compartment on the flooding probability, is now included in the formula for p_i. For a compartment length being equal to ship's length, the correct result $p_i = 1$ is obtained. On closer examination, however, the revised p_i-formulas are found to have new and even more severe shortcomings. As a result of discontinuities of the probability density function, on which the p_i-formulas are based, we get completely different flooding probabilities p_i for a compartment located at the after or fore end of the ship and the same compartment moved a little bit in the midship direction [4].

Example:
A compartment of 0.12 L in length is shifted from the outmost forward end a little towards the midship section. According to the formulas to be applied the probability of flooding decreases from $p_i = 0.102$ to $p_i = 0.060$. It is obvious that such a big difference is unrealistic and that there is a need for a correction.

The method of determining the flooding probability of wing spaces is for dry cargo ships the same as for passenger ships: the flooding probability p_i of a compartment of the same location and the same length must be multiplied by a reduction factor r. The formulas for r were partly, but not substantially revised. Generally, the critical comments on the r-formulas are also applicable to the rules for dry cargo ships. As an example, for b = 0 we get r = 0.1 instead of r = 0.

DISTRIBUTION DENSITIES AND DISTRIBUTION FUNCTIONS

In order to eliminate the shortcomings of the formulas in the actual rules, it is advisable to start from the foundations, namely the results of damage statistics and their mathematical presentation by distribution densities and distribution functions.

For side damages, the most important results of an analysis of the IMO damage cards are [5], [6], [7]:

- damage locations are distributed over the total ship's length. They are a little more frequent in the forward half of the ship than in the aft part.
- the distribution density curve for the ratio damage length to ship's length (= non-dimensional damage length) starts with a steep upward slope. After having reached its peak, the curve descends gradually. Damage lengths of more than 0.25 of ship's length are extremely seldom and may be neglected. The median of the damage length is somewhere between 5.55 percent and 6.68 percent of ship's length [5], [6].
- the distribution density of the ratio damage penetration to ship's breadth (= non-dimensional damage penetration) strongly depends on the dimensionless damage length. The peak of the curve is located at a penetration depth just above zero for the shortest damage lengths and moves to a penetration depth of about 0.4 of ship's breadth for the longest damage lengths. The median of the damage penetration is – growing with damage length – between a little above zero and 37.5 percent of ship's breadth.

For the damage data, the following symbols are used:

x : damage location (= distance between forward end of damage and the aft end of the ship)
y : damage length (= longitudinal extent of damage)
t : damage penetration (= transverse extent of damage)

or in dimensionless writing:

$\xi \equiv x/L \qquad \eta \equiv y/L \qquad \tau \equiv t/B$

In a system of ξ-η-coordinates each side damage which may occur is represented by a point within an triangular area. This triangle is right-angled [4]. It would be an isosceles triangle if – as in the existing subdivision rules – the center of damage is taken as damage location. The latter definition, however, would complicate some of the following calculations, and it would be a definition of damage location being different from that for bottom and stem damages [8]. So , in this paper, x or ξ respectively is defined as written above.

For a graphic representation of the distribution of a three-dimensional random quantity like the side damage with the parameters ξ, η, and τ, at least two diagrams are needed.

In Fig. 1, a curved surface is plotted, the run of which corresponds with the statistical findings on the distributions of damage locations and damage lengths. It represents the distribution or probability density of side damages if the third parameter, the damage penetration τ, is ignored. In order to get a simple analytic expression for the density function $p(\xi,\eta)$, the curved surface is replaced by an inclined plane. According to what is said in the preceding chapter, such an approximation is acceptable.

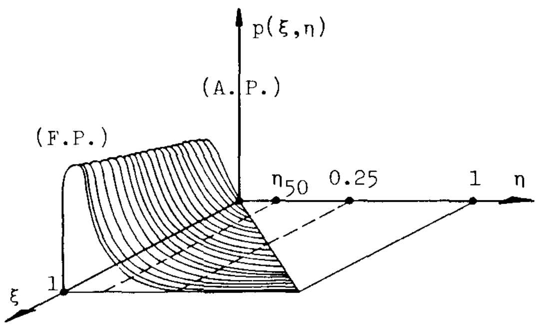

Fig. 1. Distribution density $p(\xi,\eta)$ of the two - dimensional side damage according to damage statistics

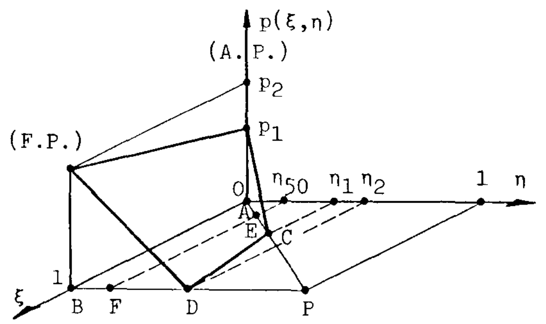

Fig. 2. Linearized distribution density $p(\xi,\eta)$ for practical probability calculations

From Fig. 2, showing this plane, follows:

$$p(\xi,\eta) = p_2\left[\left(1 - \frac{p_1}{p_2}\right)\xi - \frac{\eta}{\eta_2} + \frac{p_1}{p_2}\right] \quad (1)$$

The constants η_1, η_2, p_1, and p_2 are defined in Fig. 2. The function is only applicable to pairs of ξ-η-values located within the area ABCD of the ξ-η-plane; beyond this range, the probability density is equal to zero.

According to the statistical results, realistic values for the p_1/p_2 - ratio and for η_2 are [4]:

$$p_1/p_2 = 0.75 \qquad \eta_2 = 0.25$$

With these values we obtain $\eta_1 = 0.20$. The absolute values for p_1 and p_2, and the median damage length η_{50} follow from two definite double integrals:

$$\iint_{ABCD} p(\xi,\eta)\, d\xi\, d\eta = 1 \quad (2)$$

and

$$\iint_{ABEF} p(\xi,\eta)\, d\xi\, d\eta = 0.5 \quad (3)$$

The probabilities 1 or 0.5 respectively, as a result of the double integration of the probability density $p(\xi,\eta)$, must be attained for the following reasons:

1. Location ξ and length η of the assumed side damage cannot be predicted. The probability, however, that a side damage will occur and that its parameters ξ and η lie within the area ABCD, is known: it is exactly 1.

2. By definition, half of the side damages are less than η_{50} in length. Accordingly, the probability of the occurrence of such a damage, the ξ-η-values of which are located within the area ABEF, is 0.5.

After having solved the integrals, we get:

$$p_1 = \frac{90}{11} \qquad p_2 = \frac{120}{11} \qquad \eta_{50} = 0.06268$$

A median damage length of $\eta_{50} = 0.06268$ is between the values published in [5] and [6]. The present versions of the probabilistic subdivision rules are based on a median of 0.06683. This value was taken in 1973, just before the first oil crisis. At that time, there was a clear tendency of growing speed of ships, and consequently, a growing average extent of damage was expected for the future. In the opinion of the author, this effect was overestimated. A median of $\eta_{50} = 0.06268$ seems to be more realistic. So, there is no need for revising the above numerical values for p_1, p_2, η_1, and η_2. With these values, the final function for the two-dimensional probability density $p(\xi,\eta)$ is:

$$p(\xi,\eta) = \frac{30}{11}\left(\xi - 16\eta + 3\right) \quad (4)$$

In order to give a further proof of the quality of this function, its marginal densities $p(\xi)$ and $p(\eta)$ are compared with the distribution densities $p(\xi)$ and $p(\eta)$ resulting from the statistics [4], [7]. As can be seen in Fig. 3 and Fig. 4, the curves representing the marginal densities are in good accordance with the histograms of the statistical analysis.

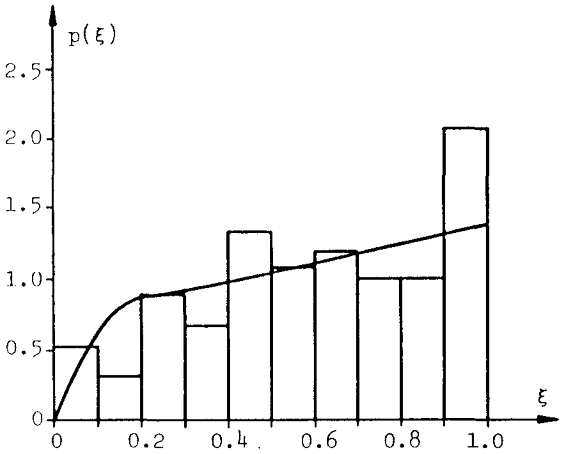

Fig. 3. Marginal density $p(\xi)$ of the linear distribution density $p(\xi,\eta)$ and histogram of damage locations according to statistical analysis

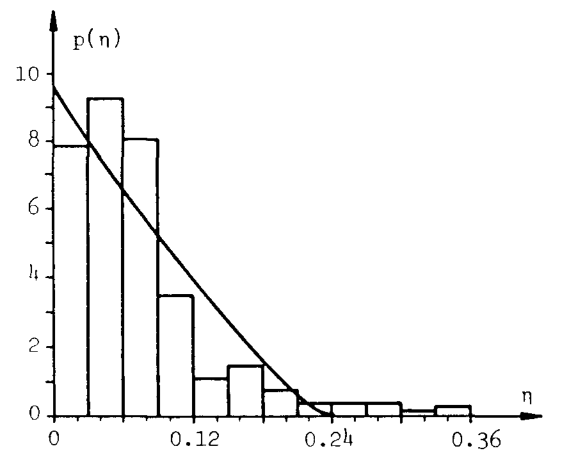

Fig. 4. Marginal density $p(\eta)$ of the linear distribution density $p(\xi,\eta)$ and histogram of damage lengths according to statistical analysis

A diagram showing the distribution of the penetration depths of side damages is given in [7]. It is presented in Fig. 5 and demonstrates the influence of the damage length: the smaller η is, the higher the probability P_τ that a given penetration τ will not be exceeded.

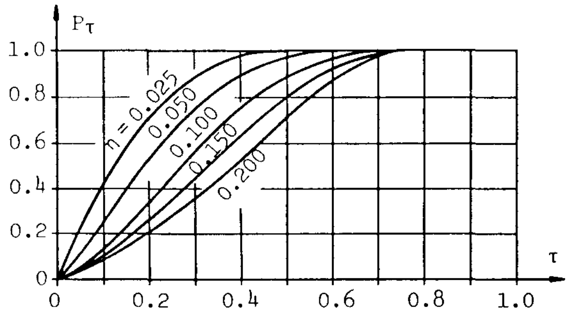

Fig. 5. Distribution functions of damage penetration τ according to damage statistics

The curves in Fig. 5 are directly elaborated from the IMO damage cards. For a translation into a mathematical formula, a function must be found, the graph of which is a family of curves running in the same way as in Fig. 5.

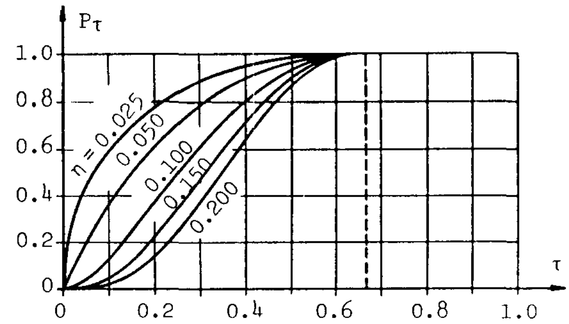

Fig. 6. Distribution functions of damage penetration τ for practical probability calculations

A function meeting this requirement quite well, is

$$P_\tau(\eta,\tau) = (1.5\tau)^{20\eta} \cdot e^{20\eta(1-1.5\tau)} \qquad (5)$$

Its family of curves is plotted in Fig. 6. For damage lengths $\eta < 0.25$ and damage penetrations $\tau \leq 2/3$, the differences between the distribution functions in Fig. 5 and Fig. 6 are rather small. Beyond these limits, the formula is not applicable. According to the assumption that a damage penetration of $\tau = 2/3$ will not be exceeded, the probability P_τ of the event of a penetration depth being smaller than a given numerical value τ_1, is for $2/3 \leq \tau_1 \leq 1$ always exactly $P_\tau = 1$. A further formula, namely for $\eta > 0.25$, is not needed because $\eta = 0.25$ is assumed to be the upper limit of the longitudinal damage extent (Fig. 2).

The statistical informations given by the presented functions $p(\xi,\eta)$ and $P_\tau(\eta,\tau)$, are sufficient to derive formulas for the probability of flooding for compartments and wing compartments. Using a model for the reality, the above functions are considered to be the true functions. In order to avoid the errors of the actual probabilistic subdivision rules, the following calculations are strictly based on these functions. They are carried out correctly without applying approximate terms.

NEW FORMULAS FOR THE SPACE FLOODING PROBABILITY

A general calculation of the flooding probability p_i for side spaces includes the special case of a breadth being equal to ship's breadth ($b = B$). Therefore, in principle, separate formulas for compartments and wing compartments are not necessary.

Before dealing with the side space, we first will have a look at a compartment. Its forward end may be located at $\xi = \xi_L$, its length may be $\Delta\xi$. In Fig. 7, showing the graph of the assumed density function $p(\xi,\eta)$, those side damages causing a flooding of this compartment – and only of this compartment –, are represented by pairs of ξ-η-values falling into the triangular area MNO. We must differentiate between two cases:

- compartment length $\Delta\xi \leq \zeta/16$ (point O of the triangle MNO below line CD)
- compartment length $\Delta\xi \geq \zeta/16$ (point O of the triangle MNO above line CD)

where $\zeta \equiv 3 + \xi_L$.

b) WING COMPARTMENTS OF $\Delta\xi \leq \zeta/16$ IN LENGTH

The flooding probability p_i of a wing compartment depends on a further parameter, namely on its dimensionless breadth b/B. The knowledge of the distribution function P_τ (η,τ) enables us to derive a formula for p_i for side spaces being smaller than b/B = 2/3. The flooding probability of side spaces of b/B > 2/3 is – because damage penetrations of τ > 2/3 are excluded – the same like that of a compartment with b/B = 1.

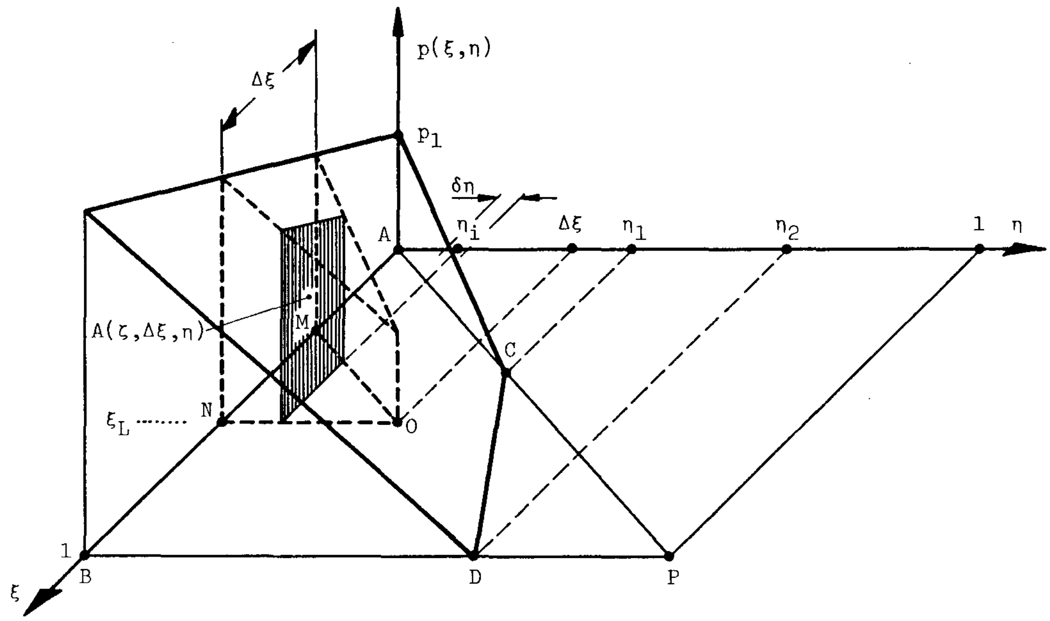

Fig. 7. Probability of flooding to a compartment of $\Delta\xi \leq \zeta/16$ by a side damage of given length η_i

a) COMPARTMENTS OF $\Delta\xi \leq \zeta/16$ IN LENGTH

The example given in Fig. 7 is a compartment of this type. The flooding probability p_i for this compartment is obtained by an integration of the probability density p (ξ,η) within the limits of the triangle MNO. This can be done in two steps: determination of the sectional areas A ($\zeta,\Delta\xi,\eta$) of the prism in direction parallel to the p-ξ-plane, and integration of A ($\zeta,\Delta\xi,\eta$) with respect to η.

For A ($\zeta,\Delta\xi,\eta$) we get

$$A(\zeta,\Delta\xi,\eta) = \frac{30}{11}\zeta\,\Delta\xi - \frac{15}{11}\Delta\xi^2 - \frac{30}{11}\left(\zeta + 15\,\Delta\xi\right)\eta + \frac{465}{11}\eta^2 \qquad (6)$$

Its definite integral with respect to η from 0 to $\Delta\xi$ is

$$p_i = \int_0^{\Delta\xi} A(\zeta,\Delta\xi,\eta)\,d\eta = \frac{5}{11}\Delta\xi^2\left(3\,\zeta - 17\,\Delta\xi\right) \qquad (7)$$

From Fig. 7 it is easy to see: the probability δp_i that the compartment under consideration will be flooded by a side damage of given length η_i (exactly: $\eta_i - \delta\eta/2 < \eta < \eta_i + \delta\eta/2$), equals the volume of a "slice" located parallel to the p-ξ-plane at $\eta = \eta_i$ and having a thickness of $\delta\eta$:

$$\delta p_i = A(\zeta,\Delta\xi,\eta_i)\cdot\delta\eta$$

The individual distribution function P_τ to be applied if $\eta = \eta_i$, is:

$$P_\tau = (1.5\,\tau)^{20\eta_i}\cdot e^{20\eta_i(1-1.5\tau)}$$

By substituting b/B for τ, we get the probability that in the case of a damage length $\eta \approx \eta_i$, the damage penetration τ will be smaller than b/B:

$$P_\tau = (1.5\,b/B)^{20\eta_i}\cdot e^{20\eta_i(1-1.5\,b/B)}$$

The product of the above probabilities, $\delta p_i \cdot P_\tau$, represents the probability that the flooding will be caused by a side damage with a longitudinal extent of $\eta \approx \eta_i$ and a transverse extent of τ < b/B. If these products are evaluated for all damage lengths

– from the smallest just above zero up to a length being equal to the compartment length $\Delta\xi$ – and then summed up, the result is just the probability p_i we are looking for: the probability of a flooding to the compartment under consideration – and only to this compartment – by a side damage with a penetration depth not exceeding a given numerical value. This probability is identical with the flooding probability p_i of a wing compartment with a dimensionless breadth b/B. From

$$p_i = \int_0^{\Delta\xi} A\ (\eta_i) \cdot P_\tau\ (\eta_i)\ \cdot d\eta_i$$

follows, after substitution of the analytical expressions for A and P_τ, the final formula for practical application:

$$p_i = \frac{15\ \Delta\xi\ (\ 2\zeta - \Delta\xi\ )}{11\,c} - \frac{30\ (\ \zeta + 15\ \Delta\xi\ )}{11\,c^2} + \frac{930 - 930e^{-c\Delta\xi} + 30c(\ \zeta - 16\ \Delta\xi\ )e^{-c\,\Delta\xi}}{11\ c^3} \qquad (8)$$

where $c \equiv 30\ b/B - 20\ \ln\ (\ 1.5\ b/B\ ) - 20$.

As mentioned at the beginning, the limits to be observed are:

$\Delta\xi \leq \zeta/16$ and $b/B \leq 2/3$.

If $b/B = 2/3$, the above formula gives us the flooding probability for a compartment of $\Delta\xi \leq \zeta/16$. In order to demonstrate this, we must write – to avoid a negative denominator (for $b/B = 2/3$ we get $c = 0$) –

$$e^{-c\Delta\xi} = 1 - c\Delta\xi + 1/2\ c^2\Delta\xi^2 - 1/6\ c^3\Delta\xi^3 +-....$$

By introducing this series for the exponential function exp $(-c\Delta\xi)$, we get for p_i the same result as presented in subparagraph a) for compartments of $\Delta\xi \leq \zeta/16$.

c) COMPARTMENTS OF $\Delta\xi \geq \zeta/16$ IN LENGTH

For compartments being more than $\zeta/16$ in length, the triangular area MNO in the ξ-η-plane extends beyond the ABCD-region where side damages are assumed to occur. As demonstrated in Fig. 8, the prism with the base MNGR, the volume of which equals the flooding probability p_i of the compartment considered, has sectional areas of different shape. For damage lengths $\eta \leq \eta_G$, we get a trapezoidal cut surface; its area A_1 is:

$$A_1(\ \zeta,\Delta\xi,\eta\ ) = \frac{30}{11}\ \zeta\,\Delta\xi\ - \frac{15}{11}\ \Delta\xi^2\ - \frac{30}{11}(\ \zeta + 15\Delta\xi\ )\,\eta\ + \frac{465}{11}\ \eta^2 \qquad (9)$$

For damage lengths $\eta_G \leq \eta \leq \eta_R$, the cut surface becomes triangular, and its area A_2 is:

$$A_2(\ \zeta,\eta\ ) = \frac{15}{11}\ \zeta^2 - \frac{480}{11}\ \zeta\,\eta + \frac{3840}{11}\ \eta^2 \qquad (10)$$

From the sum of the two definite integrals

$$\int_0^{\eta_G} A_1(\ \zeta,\Delta\xi,\eta\ )\ d\eta \quad \text{and} \quad \int_{\eta_G}^{\eta_R} A_2(\ \zeta,\eta\ )\ d\eta$$

follows the formula for the flooding probability p_i for compartments exceeding a length of $\zeta/16$:

$$p_i = \frac{\Delta\xi \cdot \zeta\ (\ \zeta - \Delta\xi\ )}{11} + \frac{\Delta\xi^3}{33} - \frac{\zeta^3}{528} \qquad (11)$$

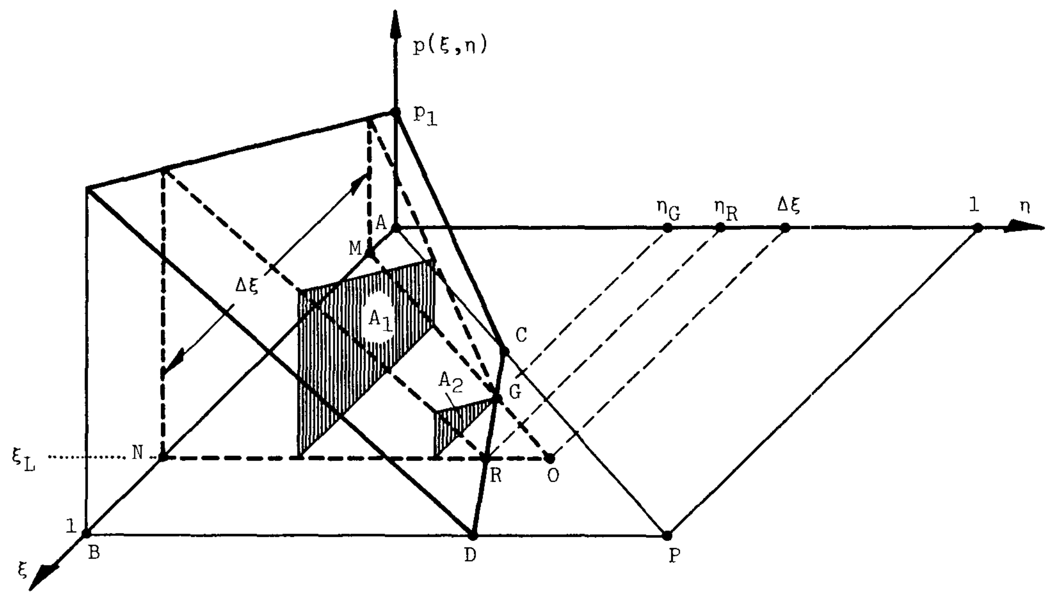

Fig. 8. Probability of flooding to a compartment of $\Delta\xi \geq \zeta/16$ by a side damage with $\eta_i \leq \eta_G$ and with $\eta_G \leq \eta_i \leq \eta_R$

d) WING COMPARTMENTS OF $\Delta\xi \geq \zeta/16$ IN LENGTH

The flooding probability p_i can be calculated in the same way as described in subparagraph b). The only difference is that it must be observed whether the damage length under consideration does or does not exceed η_G (Fig. 8). According to the assumed limitation of the damage penetration to $\tau = 2/3$, the resultant formula for p_i is only applicable to wing compartments which are smaller than $b/B = 2/3$. For side spaces of a depth of more than 2/3 of the ship's breadth, the formula for compartments of $\Delta\xi \geq \zeta/16$ must be applied for the calculation of the flooding probability p_i (subparagraph c). If $b/B \leq 2/3$, the steps of determining p_i are:

Probability of flooding by a side damage of $\eta \approx \eta_i$ and any depth τ:

$$0 < \eta_i \leq \eta_G: \qquad \delta p_i = A_1(\zeta, \Delta\xi, \eta_i) \cdot \delta\eta$$

$$\eta_G \leq \eta_i \leq \eta_R: \qquad \delta p_i = A_2(\zeta, \eta_i) \cdot \delta\eta$$

Probability of flooding by a side damage of $\eta \approx \eta_i$ and $\tau < b/B$:

The above probabilities δp_i must be multiplied by $P_\tau(\eta_i)$, where

$$P_\tau(\eta_i) = \left(1.5\ b/B\right)^{20\eta_i} \cdot e^{20\eta_i(1 - 1.5\ b/B)}$$
$$= e^{-c\eta_i}$$

Probability of flooding by a side damage of $\tau < b/B$ and any length:

$$p_i = \int_0^{\eta_G} A_1(\eta_i) \cdot P_\tau(\eta_i) \cdot d\eta_i + \int_{\eta_G}^{\eta_R} A_2(\eta_i) \cdot P_\tau(\eta_i) \cdot d\eta_i$$

The result of the integrations represents the flooding probability p_i for a wing compartment of $\Delta\xi \geq \zeta/16$ and $b/B \leq 2/3$:

$$p_i = \frac{15\ \Delta\xi\ (2\zeta - \Delta\xi)}{11\ c} - \frac{30\ (\zeta + 15\ \Delta\xi)}{11\ c^2} + \frac{930 + 6750\ e^{-\frac{c}{15}(\zeta - \Delta\xi)} - 7680\ e^{-\frac{c\zeta}{16}}}{11\ c^3} \qquad (12)$$

From the definition

$$c \equiv 30\ b/B - 20\ \ln(1.5\ b/B) - 20$$

follows $c = 0$ if $b/B = 2/3$. If we develop the exponential expressions into series, we get for $c = 0$ the same p_i-formula as presented in subparagraph c) for compartments of $\Delta\xi \geq \zeta/16$.

DISCUSSION AND CONCLUDING REMARKS

The formulas derived in the preceding section for the probabilities of compartment and wing compartment floodings offer several advantages. They are applicable in practical subdivision rules and fulfil fundamental requirements such as:

- no discontinuities in the results
- the p_i-formulas for compartments follow from the more general p_i-formulas for wing compartments. According to the assumption that damage penetrations $\tau > 2/3$ do not occur, they are identical with the p_i-formulas achieved for $b/B = 2/3$. This applies to compartment lengths $\Delta\xi < \zeta/16$ as well as $\Delta\xi \geq \zeta/16$.
- for a compartment of $\Delta\xi = 1$ the correct result $p_i = 1$ is obtained
- the correct flooding probability $p_i = 0$ is attained for $\Delta\xi = 0$ as well as for $b/B = 0$
- application of the p_i-formulas for $\Delta\xi \leq \zeta/16$ and $\Delta\xi \geq \zeta/16$ results in identical formulas for $\Delta\xi = \zeta/16$

For the future, an universal probabilistic subdivision regulation, to be applied to all types of seagoing ships, is desirable. In this context, it is recommended to introduce the presented formulas into the new regulation. By such a decision the judgement of the safety of ships could be clearly improved.

Though not subject of this paper, it may be mentioned that another requirement in the present subdivision rules calls for an amendment. The assumption of a damage stability based on a vertical center of gravity which equals the allowable upper limit, is against the probability concept. Efforts, for instance, of attaining a high survivability by giving the ship a great deal of damage stability, do not find expression in the survival probability criterion called "Attained Subdivision Index" because not the actual but unrealistic small minimum stability values must be assumed to exist. Here, a replacement of the highest permissible $\overline{KG}$-value by a mean value or by a distribution of $\overline{KG}$-values should be considered.

Coming back to the flooding probability p_i, it still remains to point out that the method of defining the side damage location by the distance of its forward end from the aft end of the ship, leads to a graphic representation of the survivable side damages which differs from the conventional graph. This is demonstrated by an example in Fig. 9. It shows a ship subdivided by five transverse bulkheads. The following floodings are assumed to be survivable: flooding of the after two adjacent compartments, of the forward two adjacent compartments, or of any of the two inner compartments.

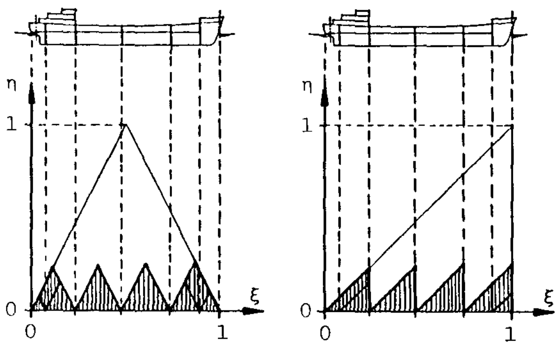

Fig. 9. Triangular hatched areas representing the survivable pairs of ξ-η-values for a transversely subdivided ship. In the left graph ξ indicates the location of the center, in the right graph the location of the forward end of the side damage as well as of the floodable compartment

If the location of a side damage or a compartment is defined by the location of its center, the areas of the survivable pairs of ξ-η-values look like illustrated in the left diagram of Fig. 9. The limiting isosceles triangles change into right-angled triangles if the forward end of damage and watertight space respectively is taken to indicate the position within ship's length. We then get the diagram on the right side of Fig. 9.

In the author's opinion, it should be unproblematic to introduce the new kind of graphic representation. This view is confirmed by practical experience gained from survival probability calculations in the cases of bottom and stem damages. For these types of damages, the proposed definition of location is in use from the beginning.

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