SCHRIFTENREIHE SCHIFFBAU

LESEPROBE

© Technische Universität Hamburg-Harburg
Schriftenreihe Schiffbau
Schwarzenbergstraße 95c
D-21073 Hamburg

http://www.tuhh.de/vss
Subdivision of Ships

By Kurt Wendel, Member

A very large number of merchant ships have sufficient protection against damages in the bottom and on the ship ends only. Many attempts have been undertaken to develop a protection—suitable in efficiency and expense—also for the ship sides. Corresponding rules for passenger ships can be found in the International Convention of Safety of Ships at Sea, and the new Freeboard Convention also includes regulations for the subdivision of larger cargo ships. But hitherto a theory was missing which would allow the evaluation of the efficiency of subdivisions. Such a theory is discussed in this paper. It will be shown how subdivisions by transverse or longitudinal bulkheads or by combined systems can be evaluated as to quantity. By this method it should be possible to make small ships safe against foundering when small, but frequent damages of the shell are to be expected; damages that would founder these ships as they are presently designed. The influence of the permeability for the survival of damages is mentioned herein also.

In the last decade subdivision of ships into watertight sections has been fostered especially in the United States and by the Society. Very good representations of the respective state in this field of ship design are to be found in Principles of Naval Architecture [1] by J. F. Macmillan and J. P. Comstock, and by J. B. Robertson [2]. These authors also give a survey on the historical development of the watertight subdivision of ships. Finally, Comstock and Robertson have treated the problem in a rather extensive paper [3], and recently Robertson in a study which has not been published [4].

Since 1960, contributions from Germany have also been given to the problem and attention to it has been shown by experts of the United States and other countries.

First, something will be said about the development of the method which was and is still used to place transverse bulkheads. This is necessary in order to describe the controversy which has been prevalent since the introduction of the first International Convention.

Then it will be shown shortly how to evaluate subdivision quantitatively. The mode of valuation based on approaches being considered today as a part of mathematical statistics was published by the author in a paper in 1960, and an improved and supplemented one in 1961, both in German. Some supplements of the theory originating from other authors will be discussed subsequently.

Then some results of extensive damage statistics will be given. From these results also succeeds the quantitative valuation of subdivision of the hull by means of longitudinal bulkheads. A series of examples will demonstrate what safety from sinking after damages can be attained by placing longitudinal bulkheads over a more or less extended part of the length.

In the first publication on our subject, draft, permeability, intact stability, and trim have been put up as constant initial quantities when calculating the probability of surviving a damage. This fact, no doubt, will prove right for many ships, but not for all—particularly in the case of permeability changes for freighters from voyage to voyage. The numerical value of permeability is often known, but very inaccurately, and for one or the other compartment it can have values which vary between nearly zero and one. Examples will serve to verify how the variability of permeability affects safety from damages.

It seems that many results related here and by other authors make it advisable to change fundamentally the regulations for subdivision prescribed by the International Convention [5]. Yet it has to be pointed out that in the first plan the author wants to show modes how to obtain a maximum in safety by means of skillful shaping of the ship design. For that purpose the types of novel ships which were built in the last decade or are under construc-
tion at present (car-ferries, car-transporters, container-ships of all kinds, open ships, special ships for bulk cargo) provide opportunities. But many proposals also can be useful for larger or smaller ships of the usual freighter type for general cargo.

Finally, on the basis of Lloyd's statistics, it will be verified whether the total losses of the world merchant fleet have rising or falling tendencies.

**Development of the Methods to Subdivide Ships**

Around 80 years ago development began with the length rule. The longer the ship was the more watertight bulkheads had to be placed. This rule, which today is still valid for the mass of freighters, does not satisfy logically. True, watertight bulkheads are demanded. The prescriptions of the classification societies, however, do not contain any rules on the volume of compartments enclosed by bulkheads. Obviously, such compartments must not exceed certain volumes if the ship shall keep safe after the compartment is flooded. Therefore, smaller freighters with lengths up to 100 m (330 ft) are still destined to sink if a hole of only a few square inches is torn somewhere on the greatest part of the length. But, since the number of bulkheads increases with the length of the ship and, therefore, the compartments become relatively smaller and smaller, the length rule gives a certain safety to larger ships, no doubt. It is difficult to judge the safety in a special case, however. Some compartments may be flooded without sinking the ship. That may even happen for each compartment of a very large ship.

Around the turn of the century the mathematical estimation of the floodable length was started: in the beginning approximately, later by more accurate mathematical methods. Then, it was agreed at international conventions: subdivision is to be the safer the longer the ships are and the more they are designed to carry passengers. Thereby, the conventions make use of the so-called subdivision factor $F$. By multiplying the floodable length with this factor it is reduced to the permissible length of the compartments. Thus, two-compartment standards ($F = 0.5$) and eventually three-compartment standards ($F = 0.33$) result. The lengths in such cases depend on the service the ship is intended for, i.e., whether it is primarily a passenger ship or, though arranged for a number of passengers, serves primarily to carry freight.

It is noteworthy that by the use of these factors permissible lengths result that do not lead to ships of which just one compartment or just two or three adjacent compartments can be flooded. As a rule, intermediate values result for the permissible lengths. Thus ships, which, according to the calculation, carry 1.5 or 2.6 compartments, may be flooded without sinking.

Since 1948 there are also regulations in the International Convention demanding rather subtle inquiries on damage stability. Such inquiries may prompt the result that the permissible length of the compartments be further reduced, except in the case of a ship given an intact, unusually large stability.

Thus, a rather complicated opus of regulations has originated and is comprehended in all its details only by a small group of experts.

**The Controversy**

There were many votes that were not convinced by the factor method. Is it correct to place bulkheads closer than required according to the floodable length? The factorial system implies this method in nearly all cases, for the one-compartment standard ($1 \geq F > 0.5$) as well as the two-compartment standard ($0.5 \geq F > 0.33$) or the three-compartment standard ($0.33 \geq F$).

The transition towards greater safety could also be performed otherwise, e.g., by beginning in the forebody and subdividing the ship partly by the two-compartment standard, proceeding step by step towards safer subdivision. This was, in fact, the prevailing view in the days before the first international conventions—in the nineties in England and Germany. Regulations basing hereupon were issued from the German "SeebueroGensenschaft SBG" around 1900. In England, legal regulations were not adhered to, but a number of committees worked out proposals somewhat similar to those of Germany. It was considered disadvantageous that the increase in safety was done by steps, i.e., the transition to the two-compartment standard for a part of the ship and finally for the whole ship. The steps appeared at certain ship lengths similar to the length rule of the classification societies. This was different with the factorial system. According to Macmillan and Comstock, the International Conference decided that safety increases continuously with a continuously decreasing factor. The International Conventions of 1929, 1948, and 1960 were based on this principle.

The fact that there are more unsafe points on the ship when the number of bulkheads is high militates against the factorial system. For the one-compartment standard ($1 \geq F > 0.5$) the ship can be sunk readily by slight damage, since damaging one bulkhead means flooding of two compartments. Some authors have treated this part of the problem in detail, also by simple calculation: Hovgaard [1, p. 177], Abell [6], and later Varges [7]. They proceed from a defined damage length and then conclude, e.g., at a length of the damage, and the length of a compartment, $l$, the probability of surviving a damage that only opens this single compartment is equal to $(l - y)/l$. The more $y$ is compared with $l$, the less the probability will be, obviously. Thus, greater damage lengths require greater lengths of the compartments. This fact again leads to greater freeboards. The authors point out that if $y = l$, the probability thus calculated equals zero, of course. From such considerations it was concluded advisable not to make compartments too short. A minimum length of compartments was then prescribed in the conventions.

$^3$Hovgaard and Abell have expressed this differently. Abell, e.g., speaks of "odds on for loss of vessel," and that is, at a defined length of the damage, the ratio of the unsafe part of a compartment to the safe residuary part, $y/(l - y)$. At $y = l$, the "odds on for loss" are infinite.
The following was, and still is, claimed today in favor of the factorial system: For the calculation of the floodable lengths, uncertain assumptions concerning the permeability of the compartments must be made. Furthermore, a residual freeboard of 3 in. and a residual metacentric height of 2 in. of the damaged ship are sufficient according to the convention. The argument is that, even for favorable cases when no bulkhead is damaged, a one-compartment ship can only be considered safe, therefore, if the subdivision factor falls very much short of 1.

The controversy: The factorial system, or transition by steps to a higher compartment standard, has not been clarified until now in a satisfactory manner. The factorial system was maintained. In 1960 it was agreed that for a certain range where factors between 0.5 and 0.65 result, the factor here be 0.5, i.e., a two-compartment standard is to be carried out. In this way greater safety is attained. Continuity in the progress of the subdivision factor is partly removed, however, and, as may well be said, the whole method, too, is made dubious, even in its application to rules.

Valuation of Subdivision

Clearing this controversy seems to be possible only if a valuation of subdivision can be found: i.e., a valuation that takes the reality of the whole ship into consideration. Such a theory, as all theories, must proceed from simplified or restricted suppositions.

Let us assume some problems of practice requiring a valuation if a quantitatively based decision must be passed on the safety of a subdivided but damaged ship.

(a) In favor of a widely subdivided ship with correspondingly great freeboard is the fact that it can survive larger damages than a closely subdivided ship with small freeboard. This is a plausible, nonetheless qualitative, judgment. We would like to know how much safer the ship is with great freeboard and widely placed bulkheads.

(b) We now imagine the two variants to be built and subdivided so that the flooding of two adjacent compartments does not yet sink the ship. How much safer will the ships now be? Is it possible to express the improvement of safety quantitatively? Thereby the question could be answered, too, whether a one-compartment ship with great freeboard and widely spaced bulkheads can be made as safe as a two-compartment ship with small freeboard and very close subdivision.

(c) Does the factorial system bring continuously increasing safety if the subdivision factor decreases continuously?

(d) The Convention for the Safety of Life at Sea demands that ships be subdivided to effect more safety, especially regarding longer ships such as passenger ships. How can the increase of safety be performed as practically as possible and at as little expense as possible?

(e) How much safety is obtained if, as is done today with most of the cargo ships, bulkheads are placed only in accordance with the simple rules of the classification societies and the requirements given by ship operation?

(f) What is the safety of a ship after several damages?

The valuation of the quality of a subdivision can only be the ratio of the quantity of damages that do not sink the ship (or do not greatly endanger it) to the quantity of all damages which may occur. This ratio is called here the “probability of surviving damages.” It can be determined more or less simply and also more or less exactly with the methods of mathematical statistics. Let us suppose that the compartment sizes to be considered as floodable have been determined for a certain draft on the basis of buoyancy proofs and under consideration of sinkage, residual stability, permeability, and change of trim. This supposition is approximately realistic for many ships, e.g., ordinary passenger ships, warships, ferries for the transportation of automobiles, railroad cars, and passengers; also freighters with invariable loading conditions, e.g., tankers, ore carriers, automobile transporters, container ships and similar modern ships, but not for general cargo ships.

To begin with, we shall mention the ship types in the first position. If we further suppose main compartments extending from board to board, damage length and location of damage are to be seen as random variables. By some relatively simple mathematical operations, then, the wanted probability of surviving damages can be determined. The author described this previously [8] for the first time and has given an improved supplement [9]. What is essential in these papers will follow.

A particularly simple example is the estimation of the probability of surviving damages occurring at the ramming of a ship. They extend from stem to aft. The location of all damages is at the stem; the lengths of the damages are different, however. (The characteristic region is one-dimensional.) A statistical collection of such damages yields a distribution of the lengths of the damages approximately as shown in Fig. 1. Let the distance between collision bulkhead and stem be \( l \). The percentage of the damages below the length of \( l \) can then be taken from this distribution; this obviously is the probability of flooding only the compartment in front of the collision bulkhead, and thus, if flooding of this compartment together with the following would lead to the loss of the ship, the probability of surviving damages of the ramming ship.

On a ship hit by grounding or a rammed one which is only subdivided by transverse bulkheads, we make the following considerations. The damage length \( y \) and the location of damage \( x \) are random variables. In Fig. 2 the damage lengths are plotted as ordinates versus their corresponding location of damage \( x \), the latter being the center of the damage. The greatest possible damage has the length of the ship. A damage, e.g., bordering on the stern post, has its location at a distance half the length of the damage from the stern post. For the location of damage “stern” the damage length is equal to zero. We get

---

4The existing calculations based on observations of the damage lengths at ramming ships showed that the arrangement of the collision bulkhead according to the rules of the classification societies yields a rather great probability of surviving damages at these ships.
Fig. 1 Probability of lengths of damage for ramming ships

Fig. 2 Triangular area G containing all possible combinations of damage lengths and locations

a triangular area G into which all imaginable pairs of damage lengths and locations fall (Fig. 2). Each point within the triangle represents a possible damage. The abscissa is the location of damage, the ordinate the damage length.

Similar partial areas $G_1$, $G_2$, and so on exist for the compartments. They contain all damages according to length and location opening these compartments. The damages falling into the quadrilateral partial areas above the triangles open corresponding groups of adjacent compartments, e.g., the partial area $G_{455}$, the two compartments 4 and 5, and the partial area $G_{3455}$, the compartments 3, 4, and 5. The partial area at the top contains the damages according to length and location which would open the whole ship.

From observations of damage lengths and locations of damage we draw conclusions as to the distribution density $w(x,y)$ of the damages. Let the function be represented as a three-dimensionally curved surface over the area G. Fig. 3 shows, e.g., a distribution density $w(x,y)$ with damages between length $y_{min}$ and length $y_{max}$ and damages that are more frequently at the forebody than at the afterbody. The volume below this surface represents the quantity of all possible damages.

The volumes above the partial areas $G_1$, $G_2$, ..., $G_{12}$, $G_{22}$, ..., generally $G_i$ represent the quantity of the damages associated with these partial areas. Some of these partial areas are assumed to be “safe,” i.e., the associated compartments or compartment groups may be open towards sea without sinking the ship or greatly endangering it. The total of the volumes over the “safe” partial areas represents that quantity of the damages that do not sink the ship (or endanger it). The ratio of these two quantities, thus the sum of the volumes over the “safe” partial areas, to the total volume over the large triangle $G$, then represents the probability of surviving one damage. The numerical calculation leads to integrations easily done if the distribution function $w(x,y)$ is put up in a simple form $[8 - 12, 22, 24]$.

When the author made these considerations shortly
before the beginning of the 1960 International Conference in London, only very few data on damages were at hand. Data on 63 damage lengths could be taken from an American study. One of the author's assistants collected data on 91 damage lengths and hit-points on the basis of information given by German repair yards. According to these data the author supposed in his first publication that the damage lengths were distributed nearly like one half of a normal distribution and that the stem was damaged more frequently than the midship body, and the midship body more frequently than the aft body.

In a paper of 1961, supplemented and improved in some respects, the author made somewhat simpler suppositions for damage lengths and locations. The distribution of the damage lengths and locations was assumed as in Fig. 4. The function declines linearly from the frequently occurring small damage lengths to the rare great damage lengths and is limited by a maximum damage length \( Y_{\text{max}} \) which also can be set equal to the length of the ship. The declining surface would then extend up to the top of the triangle \( G \). The distribution of the locations of damages over the length of the ship is constant. A somewhat greater frequency of damages at the bow would have no essential influence on the probability of surviving damages. The density function \( w(x,y) \) becomes \( w_1(x)w_2(y) \) if the density function of the damage lengths and density function of the locations of damage are assumed as independent of each other. Results from recent and very extensive damage statistics will follow.

The following calculations were made on the basis of a distribution function \( w_1(x)w_2(y) \) according to Fig. 4:

1. A ship of 125 m length was subdivided into eight compartments. According to the buoyancy proof, the midship compartments can be flooded alone and those at the ends jointly without the residual freeboard and the metacentric height for the flooded condition falling short of certain minimum safety values. The median value for the distribution of damage lengths is \( \gamma_{00} = 6.94 \text{ m} \); \( \gamma_{\text{max}} = 25 \text{ m} \). Fig. 5 shows the partial areas of “safe” damages. The probabilities of the partial areas were plotted, i.e., the volumes of the polyhedrons erected on these areas up to a top surface as drawn in Fig. 4. Their sum is \( W = 0.65 \). This is the probability of surviving a damage under the given suppositions made on damage lengths and locations of damages.

2. For a ship of 200 m in length, eleven compartments, a median damage length of \( \gamma_{00} = 11.10 \text{ m} \), and a maximum damage length of 40 m, the partial areas of “safe” damages are as shown in Fig. 6. The sum of the probabilities of the partial areas, thus the probability \( W = \Sigma W_i \) for surviving a damage, is \( W = 0.96 \) here.

The calculations of \( W \) can be done easily with the aid of curves published in [9] and [12]. Such a curve for the distribution used here according to Fig. 4 is given in Appendix 1.

In Fig. 7 the “safe” partial area is marked with full lines, meaning (a) wide subdivision, (b) close subdivision, (c) cargo ships. The dotted line in (a) and (b) \( \gamma_{\text{max}} \) has been determined from the marginal distribution of the observed damage lengths. In the section “Damage Statistics” \( \gamma_{\text{max}} = 0.2L \) (see Appendix 1).

Subdivision of Ships