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Autor: Rasmussen, B. Højlund

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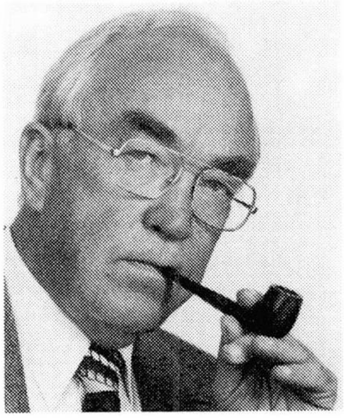
Design Assumptions and Influence on Design of Bridges

Hypothèses de projet et influence sur la construction des ponts

Entwurfs-Voraussetzungen und Einfluβ auf dem Brückenbau

B. Højlund RASMUSSEN
Dr.techn., Partner
B. Højlund Rasmussen, Consult.
Copenhagen, Denmark



B. Højlund Rasmussen, born in 1918, trained at the Technical University of Denmark, where he obtained his civil engineering degree in 1941 and his doctoral degree in 1957. After some years on the staff of the Structural Research Laboratory of the Technical University of Denmark, he established his own consulting firm, which has now been designing bridges, mainly in Denmark for more than 25 years.

SUMMARY
The article discusses decisive factors in connection with the planning of a major bridge over navigated waters and describes the design procedure found most suitable by Danish Engineers.

RÉSUMÉ
L'article traite des facteurs décisifs dans la conception et le projet d'un pont à grande circulation enjambant une voie navigable et donne une description de processus de projet ayant été trouvé le mieux approprié par des ingénieurs danois.

ZUSAMMENFASSUNG
Dieser Artikel erläutert die in Zusammenhang mit der Planung einer Groβbrücke über schiffbare Gewässer entscheidenden aufkommenden Faktoren und beschreibt das Bauverfahren, das von dänischen Ingenieuren für das am meisten geeignete,gehalten wurde.

1. DESIGN ASSUMPTIONS

Let us assume that a bridge over water can be divided into n members that are so important that a collapse of one of them would break the connection. Let us, initially, also assume that these members are the bridge piers and that we know the following characteristic quantities:

C_i: The collision force that is just sufficient to produce failure or inadmissibly big deformations.

If the pier is not rotationally symmetrical about a vertical axis, this force will depend on the angle with the bridge line at which the colliding ship hits the pier

We will define C_i as the maximum force which the pier can resist when hit centrally at right angles to the bridge line.

N_i: The number of ships passing each year which are able to exert a collision force $\geq C_i$ on the pier.

Important contributions to evaluation of the collision force which a ship can exert on a pier have been made by Minorsky [1], W. von Olnhausen [2], Woisin & Gerlach [3], Frandsen & Langsø [4], and Saul & Svensson [5].

Readers are also referred to Theme C, and need here only be reminded that this occurs as a consequence of energy exchanges during which the contact pressure between pier and ship wholly or partially stops the ship.

The maximum value and duration of the contact pressure thus depend on the weight, speed and "hardness" of the ship and the design of the bridge, and the values mentioned should, in principle, be found by means of a dynamic analysis.

Such an analysis will also provide information about the forces that will be transmitted to the superstructure during collision with a pier.

We will, however, imagine that all N ships navigating the waters crossed by the bridge can be characterized by a capacity C, which indicates the contact pressure that occurs when a ship sailing at its normal speed hits a stationary pier at its centre line.

We can then produce a curve N(C), showing how many ships with a capacity $\geq$ C pass the bridge each year (fig. 1).

On this curve we can read N_i, which naturally decreases with increasing C_i.

The curve in fig. 1 can be produced on the basis of information on the ship traffic in the years before construction of the bridge and forecasts for the development of traffic. Here we will imagine that it represents a probable situation in the middle of the anticipated lifetime of the bridge.

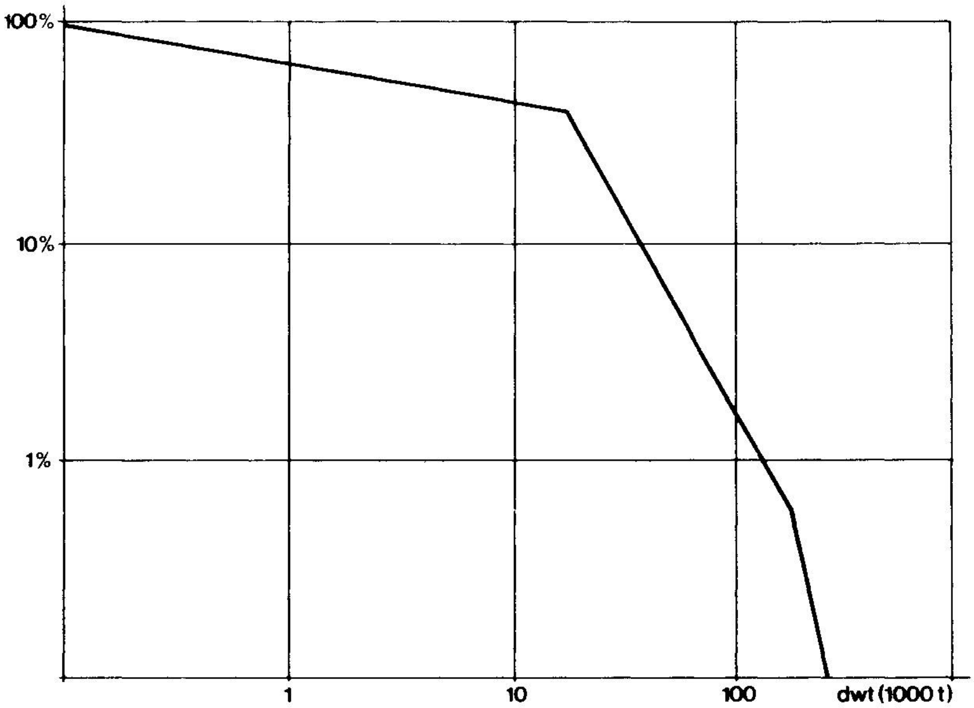


Fig. 1 Distribution of ship sizes in the Storebælt. The distribution has been forcasted to the year 1990. Example on use: 1.5% of all pasing ships are bigger than 100,000 dwt. (From [4]).

Studies of the conditions in Storebælt showed that related values of N_i and C_i lay close to a straight line when depicted on double logarithmic paper, Ↄ:

$$\log. N_i \sim \log. a_i - b_i \log. C_i \text{ or}$$

$$N_i \sim a_i C_i^{-b_i} \quad (1)$$

The curve produced from (1) may possibly be replaced by several curve segments to approximate better the observations and expectations, but in the following we will assume that the constants a_i and b_i in (1) are known in the area in question and that they give a reasonable evaluation N_i for the pier under consideration.

The uncertain factors relating to the determination of a_i and b_i are at any rate far smaller than those involved in the evaluation of the next concept.

p_i: The probability of one of the N_i ships colliding with the element and exerting a collision force $\geq C_i$.

It is obvious that $p_i = 0$ if the pier in question stands in such shallow water that the ship under consideration draws too much water to reach it.

However, if there is a theoretical possibility of contact between the ship and the pier, then there will be some probability of this occurring.

In order to find the magnitude of this probability a probability model must be established which takes into account the distance of the element from the prescribed channels, prevailing wind, current and other navigation conditions.

The model employed in the case of the Storebælt Bridge was formulated by the firm, Cap-consult A/S, Copenhagen, and assumes that a given fraction of the ships passing the bridge will be out of control. The probability of this is called the causation probability p_c and, is evaluated by T. Macduff [6] and Y. Fujii [7], at 2×10^{-4}. This causation probability covers both human and mechanical failure. In the case of the Storebælt navigation channel the causation probability was evaluated at 0.4×10^{-4} to suit the special conditions applying in this waterway.

By estimating how the ships will move after getting out of control (see fig. 2) it is possible to calculate for each pier a geometrical probability of collision with one of them.

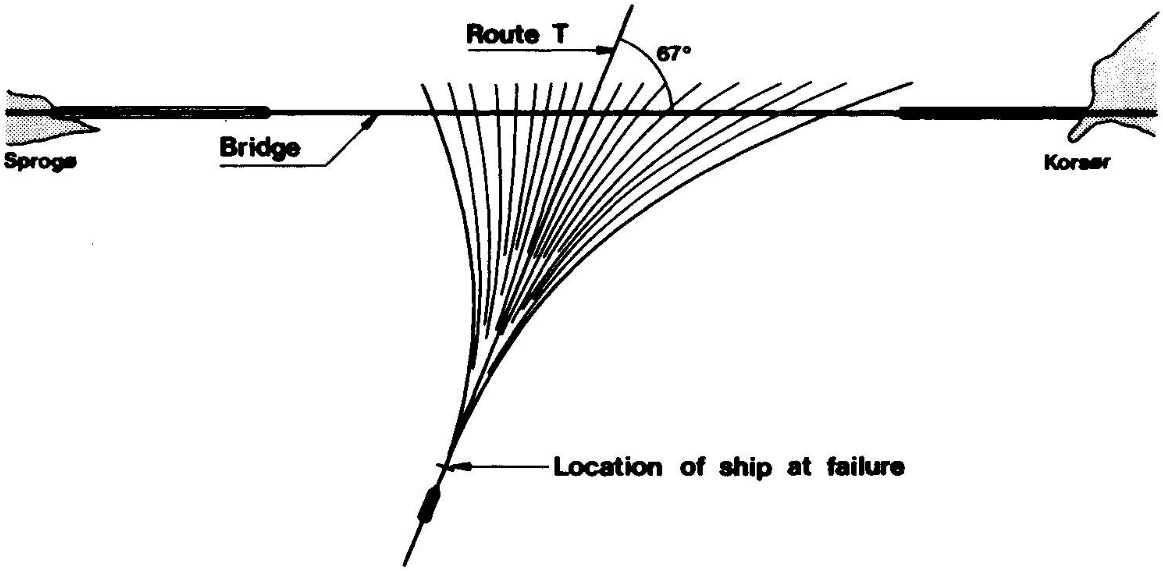


Fig. 2 Ships out of control: estimate of possible courses towards the bridge. (From [4]).

If, in our estimate of the movement of the ships having regard to wind and current, we can also incorporate an evaluation of their speed as a function of the distance from the point at which they got out of control, and if we know the reduction of the impact force that takes place when the collision is not central, we can, finally, calculate a resultant geometrical probability $p_{G,i}$ of the impact force exceeding the capacity of the pier in the direction in question.

Similarly, by evaluating the possible collision situations, we can obtain an idea of the resistance $C_{i,1}$ which the pier should have to forces $\neq$ the bridge line in relation to C_i for the probability of collapsing being equally big in all directions.

This leads to a value $p_i = p_C \cdot p_{G,i} \cdot N_i$, or, cf. (1):

$$p_i = k_i \cdot C_i^{-b_i}, \quad k_i = p_C \cdot p_{G,i} \cdot a_i \tag{2}$$

If we design the bridge so that

$$C_i \geq C_{i,max} \quad i = 1,2, \ldots, n \tag{3}$$

where $C_{i,max}$ is the biggest collision force to which pier no. i can be imagined to be subjected, the probability of an interruption of the crossing will be 0.

In many cases, this will result in prohibitive production costs.

The client will then have a natural possibility of accepting a certain risk of interruption of the connection.

By introducing two new concepts:

L: The anticipated lifetime of the bridge : the number of years after which it is estimated to be obsolete.

r: The risk of interruption of the bridge in the period L, which the client will accept.

We can formulate the following new design criterion:

$$\sum_{1}^{n} p_i \leq \frac{r}{L} \tag{4}$$

For the sake of clarity, we have so far only considered the bridge piers, but theoretically we can deal with the superstructure in the same manner provided we know the forces that are necessary to break the ships' masts and smoke stacks and to penetrate their deck superstructure or the uppermost part of their hulls, together with the height of these parts over daily water levels.

We can then include the bridge superstructure in the members considered, regarding C_i in this case as the maximum horizontal force which a bridge girder can resist.

This, however, calls for a new curve like fig. 1 for the superstructure.

The design criterion (4) was employed in the case of the Storebælt Bridge, and the result thereof for the high-level bridge over the east channel is shown in fig. 3.

However, the criterion (4) gives no direct information on the most economical distribution of the capacities C_i, although there will be an intuitive feeling that p_i should be small for those members where a failure would result in exceptionally heavy costs and inconvenience.

For a consistent economic optimization, we need to know:

P_i (C): A curve giving a price for member no. i as a function of the capacity of this member in a given interval about C_i.

SUSPENSION BRIDGE				CABLE-STAYED BRIDGE			
PIER No.	WATER DEPTH M	SHIP SIZE DWT	SHIP IMPACT MN	PIER No.	WATER DEPTH M	SHIP SIZE DWT	SHIP IMPACT MN
1,2,3	6	4.000	60	1,2,3, 4,5	6-7	4.000	60
4,5	7	10.000	100	6,7	8	10.000	100
6,7, 8,9	8-9	60.000	240	8,9	8-9	60.000	240
				10,12, 13,15	12-25	110.000	320
11,14, 20,23	15-25	250.000	430	16,17, 18,19, 21,22	15-35	250.000	430
				24	13	110.000	320
25,26, 27	8-10	60.000	240	25,26, 27	8-10	60.000	240
28,29, 30	5-6	10.000	100	28,29, 30	5-6	10.000	100
31,32, 33,34	2-5	4.000	60	31,32, 33,34	2-5	4.000	60

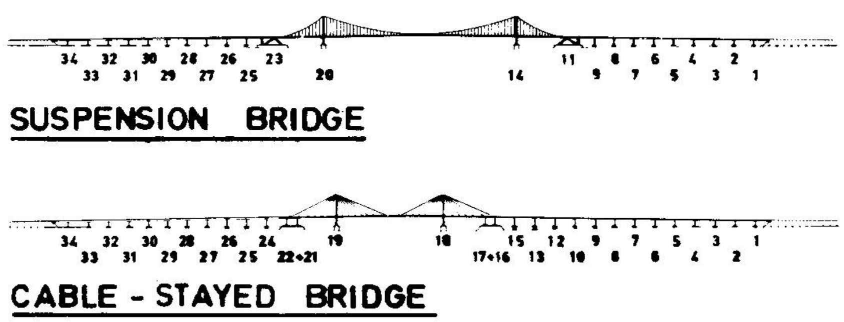


Fig. 3 Ship impact forces specified for the piers of the eastern high level part of the Storebælt Bridge.

U_i: The costs resulting from failure of member no. i. These comprise:

1) The cost of re-establishing member no. i together with the other members destroyed through the failure of member no. i.

2) The cost of establishing and operating an emergency connection during the repair period.

3) The costs resulting from loss of human life, disablement and the destruction of material assets in connection with the collapse.

4) The national economic loss through reduction of the capacity of the connection during the repair period.

The evaluation of U_i will be very uncertain and, especially as regards points 3) and 4), will be based on rather arbitrary assumptions.

We can now calculate:

R_i: The expected cost of repairing member no. i on account of ship collisions in the course of the period L.

$$R_i = p_i \cdot L \cdot U_i \tag{5}$$

and the expected gross price of the bridge in its lifetime will then be

$$\overline{P} = \sum_1^n (P_i + R_i) \tag{6}$$

In order to investigate whether maintaining the design criterion (4), variations ΔC_i in the capacity of the individual members will have a favourable influence on the effective price of the bridge, we can calculate:

$$\overline{P} + \Delta\overline{P} = \sum_1^n \left(P_i + R_i + \left(\frac{dP_i}{dC_i} + L\, U_i \frac{dp_i}{dC_i}\right) \Delta C_i\right) \tag{7}$$

and seek a minimum value for this subject to the condition (cf. (4)):

$$\sum_1^n (p_i + \Delta p_i) \leqq \frac{r}{L} \tag{8}$$

Under reference to (2), we have, in a certain area of C_i:

$$\frac{dp_i}{dC_i} \sim -b_i \cdot k_i \cdot C_i^{-(1+b_i)} = -\frac{p_i b_i}{C_i} \tag{9}$$

hence,

$$\Delta C_i \sim - \frac{C_i}{b_i} \frac{\Delta p_i}{p_i} \tag{10}$$

By means of (5), (9) and (10), we can rewrite (7) as

$$\overline{P} + \Delta\overline{P} = \sum_1^n (P_i + p_i\, LU_i - (\frac{dP_i}{dC_i} - \frac{p_i b_i}{C_i} LU_i) \frac{C_i}{b_i p_i} \Delta p_i)$$

$$= \sum_1^n (P_i + \frac{C_i}{b_i} \frac{dP_i}{dC_i} + (LU_i - \frac{C_i}{p_i b_i} \cdot \frac{dP_i}{dC_i})(p_i + \Delta p_i)) \tag{7a}$$

and can now find improved values $p_i + \Delta p_i$ of p_i by seeking the set that gives the least possible value of (7a) while at the same time complying with the criteria (8), supplemented by

$$p_i + \Delta p_i > 0, \; i = 1,2 \;......, n \tag{11}$$

During the design of the Storebælt Bridge, consideration was given to employing (7a) in connection with (11) as design criterion, but this approach was abandoned owning to the considerable uncertainty connected with determination of the quantities U_i, the costs which would result from failure of member no. i.

One could, however, determine the relative values of the quantities U_i with considerably greater certainty, while maintaining the necessary assumptions consistently and uniformly for all members.

A minimum value of (7a) would thereby result in a reasonably good distribution of the costs between the structural members of the bridge, even with an incorrect level for the quantities U_i. This must just be set so low that the adopted design criterion (8) becomes effective.

By putting L = 0 in (7a), i.e. by disregarding the magnitude of any repair costs, one could arrive at the cheapest design that satisfies the design criterion.

It seems like that, in the planning of an offshore structure, one would have a greater possibility of calculating the consequences of a collapse and thus of employing (7a) and (11) as design criterion: however, a discussion of this falls outside the scope of this article and the author´s experience.

It should, of course, be noted that the foregoing only provides information on the necessary capacities of the n members in a specific design of the bridge and that an economic optimization is therefore pointless before one is certain that a different design, for example, with other spans or a different longitudinal profile, more extensive precautions for protection of the piers etc. will not give a better solution.

1.1. Summary of design criteria

When planning a major bridge over navigated waters, certain steps must be taken as outlined below in order take account of the risk of the connection being interrupted due to collisions between the bridge and ships:

1) Procure information on the number of ships that must be expected to pass the bridge each year within a certain time horizon.

2) Arrange the ships in an order that as far as possible gives the largest force C which they can exert on the bridge during a collision, in other words, plot a curve as in fig. 1.

3) On the basis of this curve and information on navigation conditions, wind, current, etc., formulate a model that gives the probability p_i of a ship hitting an important structural member (no. i) in the bridge during a year, thereby imposing a load $\geq C_i$ on the member, where C_i is the force that just causes the member to fail.

4) By means of the model, determine a value $C_{i,1}$ of the components' resistance to forces $\neq$ the bridge line that the probability of failure is equally great in all directions.

5) Decide on the risk r that one is prepared to run of a breakdown of the bridge in its expected lifetime L.

6) Design the bridge so that Σp_i, extended over all members, is smaller than $\frac{r}{L}$

With this approach, and taking account of the costs resulting from an increase in C_i and the costs resulting from failure of the member, one can seek to achieve the desired result as economically as possible.

By designing on the basis of the procedure outlined above, one will have done one's best to achieve a safety level adopted in advance, although it must be admitted that the precision with which this level is reached is hardly likely to be very great.

On the other hand, precise determination of the safety level considered to be desirable is also an extremely difficult matter for the client, who, while wanting this to be as high as possible, has limited means to invest in the construction of the bridge because of necessary considerations to other national tasks.

In a manner of speaking, the concept "the risk of breakdown of the connection within a certain time horizon", puts the client and the technicians working for him on speaking terms, allowing them to negotiate and reach the best possible decision guided by the knowledge existing at any time - which must naturally be constantly widened and deepened.

The most difficult task of all is undoubtedly to judge the probability that one ship out of a number of ships that are theoretically able to collide with the bridge with fatal consequences, is actually doing so, and then to find the means to reduce this probability.

It is to be hoped that the contributions to Theme C will create the possibility of a more reliable solution of these problems.

On the other hand, with the knowledge we already possess, we can determine with reasonable accuracy the consequences of collision with a ship of known size, speed and type.

In the view of the author, the greatest advantage offered by the design method described lies in the fact that one ensures a structure without isolated, particularly weak points, and that the materials and other resources made available for construction of the bridge are distributed in the most appropriate manner. In other words, an additional investment to take account of the risk of ship collision is utilized as effectively as possible.

1.2 National design rules

Such thorough treatment of ship collision problems as described above would normally be reserved for big and really important bridges, and it is obviously reasonable to establish simplified design rules for, say, small bridges within a national area with uniform wind and weather conditions, and especially, uniform requirements to safety level.

The following section on collision force from the Joint Nordic Load Specifications [8] is an example of such national design rules:

> "Where there is a risk of a ship colliding with a bridge pier, the pier shall be designed for collision. The forces occurring during a collision will depend on the design and size of the vessel, its load and its speed, the collision point and direction of impact, together with the mass and elasticity of the bridge structure. The collision forces shall be assumed to act centrally on the pier level with the water surface, either in the longitudinal or in the transverse direction of the pier.
>
> As design vessel, use can be made of a vessel whose size must be expected to be exceeded in a specific number of passages per annum (e.g. 100 passages/year in an easily navigable channel). When determining the design vessel, account must be taken of the prevailing navigation conditions (wind, current, vision, compulsory pilotage, etc.), and of the risk which it will be reasonable to accept having regard to the design of the bridge, the width of the channel and the intensity of the traffic.

In the comments guidelines are given for evaluating the magnitude of the collision forces assuming that the bridge pier can be regarded as non-yielding and that the whole of the collision energy is absorbed through deformations (damage) in the vessel. This assumption normally applies where the pier is designed to take account of the risk of collision by big ships.

In the case of an elastic bridge pier, which can occur in the case of low collision energy, the collision force can be determined on the basis of the deformation properties of the structure and the ship.

Comments:

- On the basis of the size (tonnage or draught) of the
- design vessel and the permitted speed in the channel,
- the magnitude of the collision force can be estimated by
- means of the following diagram (fig. 4)."

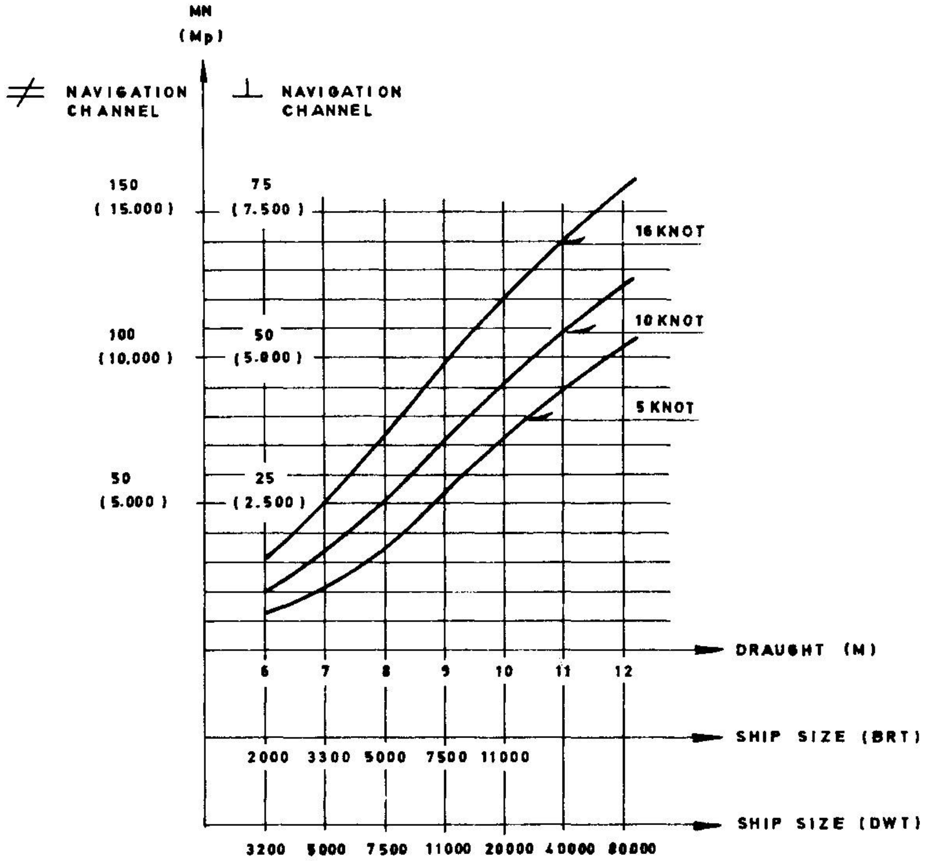


Fig. 4 Magnitude of ship collision force as a function of ship size and speed. (From [8]).

It will be seen that these rules are very similar to those proposed earlier.

We put $N_i \sim 100$ and thereby arrive at a ship of a certain size. From fig.4 we then read C_i, for which the piers are designed.

Since $P_i = p_C \cdot p_{G,i} \cdot N_i$, we accept, cf. (4), a risk $100L \cdot p_C \cdot P_{G,i} \sim 0.4 \cdot p_{G,i}$ of collision with pier no. i disrupting the bridge during its lifetime.

Contributions to Theme F containing examples of national design rules will be of great interest for the preliminary report.

2. INFLUENCE ON DESIGN

In the foregoing attention has been concentrated on establishing rules that will, with reasonable certainty, prevent a bridge over navigated waters from being interrupted on account of ship collision.

The principle effect of these rules is to make the piers often appreciably more expensive.

They must be designed as strong, solid structures without abutments or other slender members that can result in secondary, but catastrophic failure.

They must have ample resistance to loads in all directions, including torsion, which can occur in the event of eccentric impact, and it should be ensured by means of a dynamic analysis that any bearings between piers and superstructure can transmit the forces occurring during a collision.

Simply to be able to resist collisions, the piers get such large dimensions that their carrying capacity in respect of deadload, traffic load, wind, etc., cannot be fully utilized unless suitable bigger spans are introduced than have hitherto been used.

The development can be illustrated by a brief account of the proposals put forward over the years for a bridge crossing the east channel in Storebælt:

A proposal in 1936 from the Danish engineering firms, Christiani & Nielsen, Højgård & Schultz and Kampsax, resulted in the first official project from the Bridge Office of the Danish State Railways which was at that time responsible for all major bridges in Denmark.

In 1948, a broadly composed commission was appointed to investigate the conditions for and the effects of a permanent crossing. In December 1959, this commission presented its report including a proposal, which was an obvious development of the project of the Danish State Railways, envisaging a 2-level lattice girder for road and railway with navigation spans of 300 + 350 + 300 m and approach spans of 135 m.

In 1965-67, an international competition for sketch proposals was held, and following this, the working committee appointed presented a proposal with similar spanning as the 1959 proposal.

In 1970, a Technical Committee was appointed which, in its report from 1972, presented two proposals:

1. A continuation of the lattice girder solution with 5 spans, 280 + 400 + 325 + 400 + 280 m over the navigation channel.

2. A solution with two cable-stayed bridges, 210 + 600 + 210 m in direct extention of each other, forming two separate navigation spans of 600 m.

In 1973, the Board for the State Bridge Storebælt was appointed. In 1978, the Board, assisted by its consultants, prepared two tender projects:

1. A cable-stayed bridge with a navigation span of 780 m, two side spans of 300 m and approach spans of 144 m.

2. A suspension bridge with a navigation span of 1416 m, two side spans of 360 m and approach spans of 144 m.

In all cases, but especially in view of the constantly increasing requirements to resistance collision forces, the proposals in question were optimized with regard to spans, taking due regard to water depths and foundation conditions.

The big spans have the added advantage of reducing the direct risk of a ship colliding with a pier, because there are fewer piers.

In other words, the risk is reduced of environmental damages occurring through a ship with a hazardous cargo springing a leak through a collision.

We have not earlier concerned ourselves with this aspect, concentrating on whether the bridge would be damaged in a collision, and not thinking about the ship.

In this connection, I would finally like to make a few remarks regarding special protective measures for the piers, for example protective islands. With the conditions applying at many of the piers in Storebælt, protective islands proved to be an effective, low-cost method of increasing the capacity C_i, while at the same time reducing the damage to the ship.

However, with the exception of the anchor piers of the east bridge, the idea of using protective islands had to be abandoned for fear that their consistent use would reduce the passage so much that it would have damaged the environment in the Baltic.

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