Ship Collision Problems

Problèmes des collisions maritimes

Probleme der Meeres-Kollisionen

I Great Belt Bridge

II International Enquiry

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SUMMARY

Accidents in which ships collide with piers or other structures constitute a real danger for bridges crossing navigable waters. The problem has been aggravated in the last decades due to increase in ship sizes. The problem was therefore considered carefully in the design of the Great Belt Bridge. Part I of this publication presents the mainlines of the project, the risk models and the risk level considerations, the impact forces, protective islands and load specifications. Part II summarizes the results of an international enquiry on the ship collision problem.

RÉSUMÉ

Les collisions entre navires et pylônes ou autres structures sont un danger réel pour les ponts traversant des voies navigables. Le problème s'est aggravé ces dernières décennies à cause des tonnages croissants des navires. Le problème a été considéré sous tous les aspects dans l'étude du pont du Grand Belt. La partie I de cette publication présente le projet, les modèles de risque et les niveaux de risques considérés, les forces d'impact, les îlots protecteurs et les spécifications de charges. La partie II donne sommairement les résultats d'une enquête internationale sur les problèmes de collision.

ZUSAMMENFASSUNG

Die Kollision von Schiffen mit Pfeilern und anderen Konstruktionen bedeutet eine reale Gefahr für Brücken über Wasserstrassen. Das Problem hat sich in den letzten Jahrzehnten durch die Zunahme der Schiffsgrössen verschärft. Bei der Projektierung der Brücke über den Grossen Belt wurde dieses Problem daher eingehend untersucht. Teil I dieser Publikation behandelt die Hauptmerkmale des Projekts, die Risikomodelle und die Überlegungen zu Risikoniveau, Stosskräften, Schutzinseln und Belastungsvorschriften. Teil II fasst die Resultate einer internationalen Umfrage bezüglich Kollisionsprobleme mit Schiffen zusammen.

PRELIMINARY REMARKS

In 1978 the Danish government decided to postpone the building of the planned Great Belt Bridge, and the preliminary work on the bridge was consequently stopped. [1].

The work on the ship collision problem was almost finished, and it was decided to publish the results of this work. The report entitled: "Investigation into the Ship Collision Problem" appeared in February 1979, [2], and has been received with interest by bridge designers all over the world. As the report was printed in a limited edition, which could not satisfy the demand for copies, the idea of publishing the contents of the report elsewhere was put forward. The present editors, who have taken active part in the work with the ship collision problem and in the editing of the above mentioned report, have accepted the task of adapting the report for publication in IABSE Periodica.

The publication has been divided into:

- Part I, dealing with the impact on the bridge design of the ship collision problem.
- Part II, summarizing the results of an international enquiry on the ship collision problem.
- Part III, References and Appendices.

The contents of the publication corresponds closely to that of the report. A few minor amendments have been made in the text, some new references have been added, and, in order to keep the length of the article within limits, some illustrations have been omitted and the bibliography shortened.

Part I: Great Belt Bridge

0. INTRODUCTION

The present report gives a summary of the investigations of the ship collision problem which have been carried out by Statsbroen Store Bælt (SSB) in connection with the preliminary work on the planned Great Belt Bridge.

The technical investigations regarding a bridge across the Great Belt (Danish: Storebælt) that were carried out at the end of the 1930s and the investigations carried out by the Storebælt Commission in the 1950s included no explicit treatment of the problem of ship collision. This was completely in line with the way in which the importance of ship collision was regarded throughout the world in the design of bridge piers.

It was not until the 1960s, after the Maracaibo-bridge collision in South America in 1964, that bridge designers all over the world began to pay special attention to the effects of ship collision. And the preparatory work on the planned Great Belt Bridge since the middle of the 1960s has included assessments and considerations relating to the risk and consequences of ship collision against the bridge piers.

In 1976 the preliminary design on the Great Belt Bridge was started, and in this connection a working group, the Ship Collision Committee, was appointed at the initiative of SSB to carry out a detailed analysis of the entire problem of ship collision with a view to the specification of collision loads.

Members of the Ship Collision Committee were:

Richard Strabo, M.Sc., Executive Vice Director, Statsbroen Store Bælt	A.G.Frandsen, M.Sc., Consulting Engineer, Cowiconsult, Consulting Engineers and Planners AS
F.Markvardt, M.Sc., Chief Division Engineer, Statsbroen Store Bælt	B.Højlund Rasmussen, Dr.Techn., B.Højlund Rasmussen, Consulting Civil Engineers
J.Hald Mortensen, Ph.D., M.Sc., Project Engineer, Statsbroen Store Bælt	P.Tryde, M.Sc., Associate Professor, Institute of Hydrodynamics and Hydraulic Engineering, Technical University of Denmark

The Ship Collision Committee was assisted by a number of specialists, individual consultants as well as firms and institutes. These are listed in Appendix 3.

1. THE GREAT BELT BRIDGE INVESTIGATIONS.

1.1 Location of the planned Great Belt Bridge.

The Great Belt Bridge is intended to connect Zealand and Funen by crossing the 19 km wide Great Belt, fig. 1. The alignment chosen is as shown in fig. 2, which also shows the belt's depth profile and the principal geometrical requirements of the bridge project. The bridge passes Sprogø, an island lying approximately midway in the belt. The waters between Sprogø and Zealand are designated as the East Channel, and the waters between Funen and Sprogø, the West Channel.

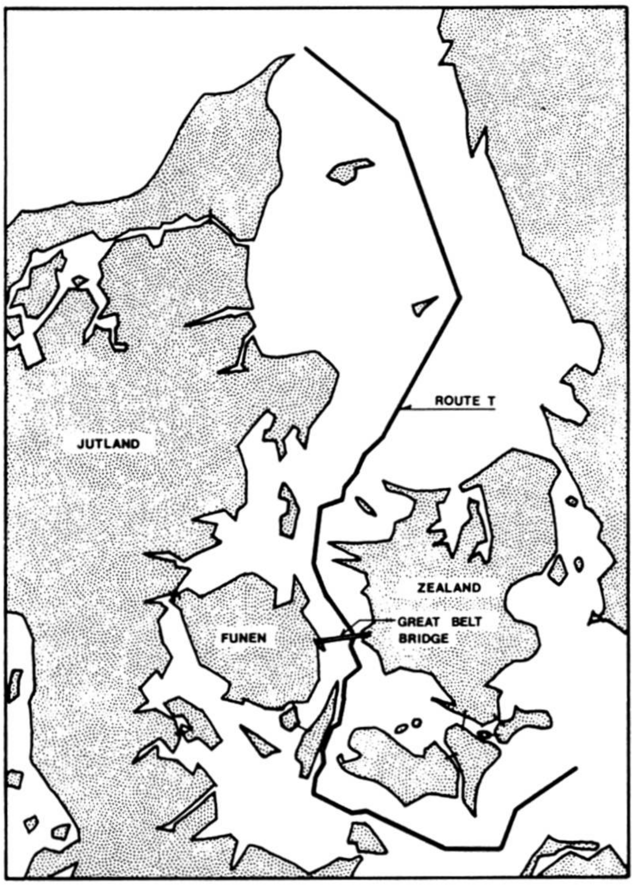

Fig. 1 Location of the planned bridge and the deep-water navigation route, T.

The preliminary investigations of the problem of ship collisions were based on a so-called deterministic method, in which each bridge pier was dimensioned for the impact force from the biggest ship that could sail in the water depth at the site of the pier. However, this simple design method, which is clearly on the safe side, would, for the reasons explained below, lead to unreasonably high costs.

Most ships follow the deep-water navigation route, T, through the East Channel, see fig. 1. The West Channel is little used and only by small ships. With the traffic thus concentrated in the East Channel, it did not seem reasonable to safeguard all the piers in both the West Channel and the East Channel against collision by the biggest ship passing the Great Belt, which - on account of the great depth of water over almost the entire line of the bridge - would have been the result of the deterministic method.

It was therefore decided to construct a risk model which would enable a differentiation of the risk distribution. The model is based on probability considerations and makes it possible for the client to determine the risk level of the bridge, expressed for example in the average time between collisions able to interrupt the bridge connection.

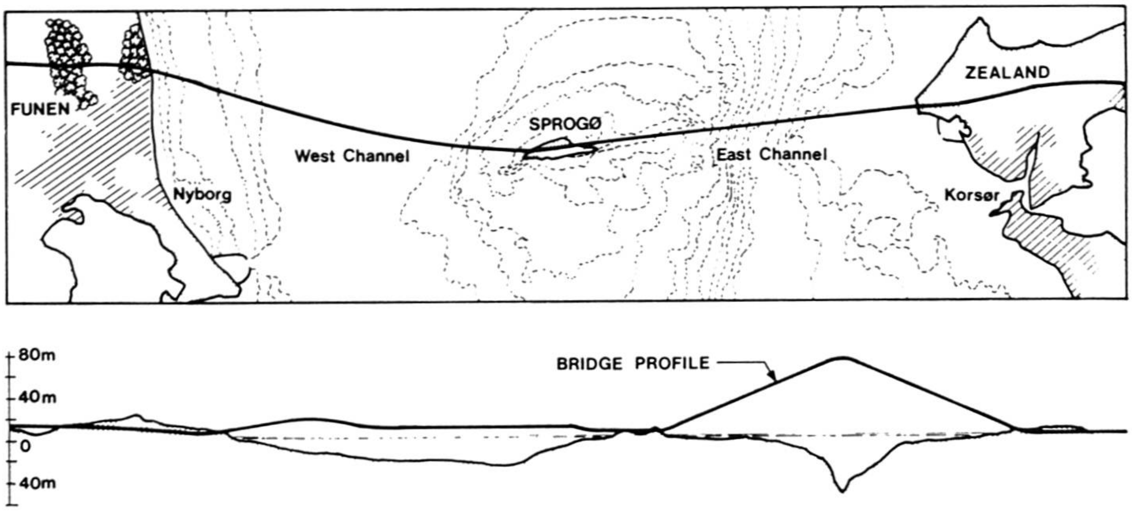

Fig. 2 Alignment and longitudinal profile of the planned Great Belt Bridge.

Owing to the concentration of shipping in the East Channel it was found natural to differentiate between the Eastern Bridge and the Western Bridge in the risk analysis, and separate risk models were therefore developed for these two sections of the Great Belt Bridge.

In this preliminary phase, a number of danish and international specialists were drawn upon, see Appendix 3. The final models were constructed by SSB's consultant CAP-Consult.

An intensive literature search for obtaining information upon risk evaluations as well as impact forces, was also performed during the preliminary phase. A selected number of the references found are presented in Appendix 4.

1.2 The risk models

1.2.1 The risk model for the Eastern Bridge

The risk model for the Eastern Bridge is based on the available statistics of shipping in the East Channel (route T), on the basis of which a distribution of ship sizes has been prepared, see fig. 4. In order to allow for the future development of shipping here, a forecast of the distribution up to the year 1990 has been made on the basis of present (and foreseeable) development trends. The number of ships that pass the belt each year is about 20,000.

A water depth of 17 m is guaranteed in route T, which, for safety reasons, corresponds to a draught of 15 m. It is therefore not possible for ships larger than some 150,000 dwt to pass the Great Belt fully loaded. In ballast, even the largest ships can pass; the biggest ship that has so far passed the Great Belt was 396,000 dwt.

The risk model assumes that a certain fraction of the passing ships will be uncontrollable. The probability of this is designated the causation probability and is evaluated by Macduff, [3], and Y.Fujii, [4], at 2×10^{-4}. This causation probability allows for both human and mechanical failure.

Of the uncontrollable ships, only those that subsequently collide with a bridge pier constitute a real risk to the bridge. The probability of a ship out of control hitting a bridge pier is designated the geometrical probability.

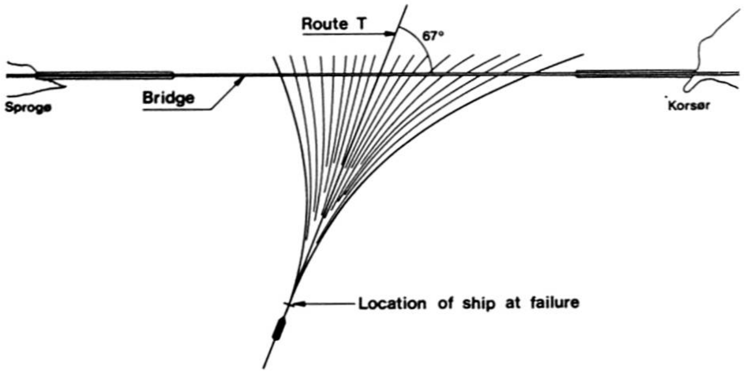

Fig. 3 Ships out of control: Estimate of possible courses towards the bridge

By estimating how the ships will move once out of control, see fig. 3, it is possible to calculate the geometrical probability for each pier of a collision by a ship out of control on the basis of the location and geometry of the pier and the sizes of the ships.

Then, in connection with the ship distribution curve, fig. 4, the product of the causation probability and the geometrical probability gives the biggest ship that can be expected to collide with each bridge pier within a given period. On the basis of an estimated average lifetime for the bridge, it is therefore possible to find the biggest ship for which each of the bridge piers must be designed.

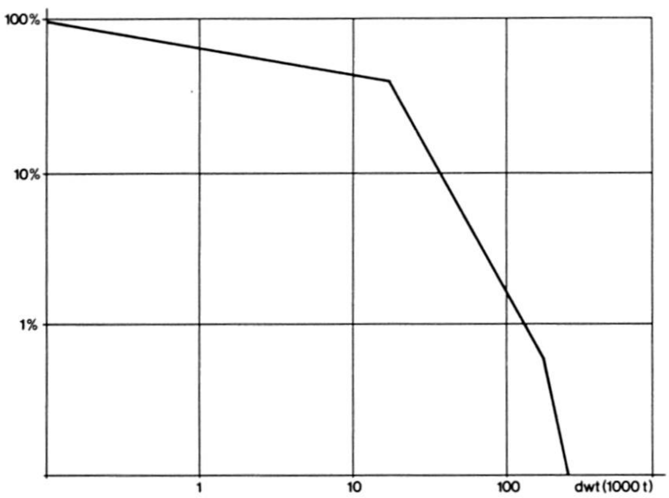

Fig. 4 Distribution of ship sizes in the Great Belt, forecasted to the year 1990.

It should be noted that the above presentation has been somewhat simplified for the purposes of clarity. In fact, the model also incorporates coefficients to take various other factors into account, for example, the fact that not all collisions are equally dangerous; in addition, efforts have been made to suit the causation probability to the special conditions applying in the Great Belt. The model also assumes that the total risk to the bridge is distributed over the individual piers, and this has to be done before the critical ships can be found for each pier.

1.2.2 The risk model for the Western Bridge

As mentioned, shipping in the West Channel is sparse and limited to small ships. The navigation span of the Western Bridge has thus a free navigation height of only 14 m. Ships that can pass this navigation span are designated legitimate ships. It was preliminarily decided that all bridge piers and bridge superstructures in the West channel should be able to withstand impact by the biggest legitimate ships.

In addition, an assessment has been carried out on how often a ship from route T can get engine failure and begin to drift in the direction of the Western Bridge, resulting in collision with this.

On the basis of wind and current statistics (velocities and directions), it is possible to evaluate the proportion of the drifting ships that will be able to hit the Western Bridge, and evaluate the time it will take a drifting ship to reach the bridge. By deducting from this quantity the ships whose drifting time is of such a magnitude that salvage vessels can be expected to reach them before they hit the bridge, we can find the biggest drifting ship in a given period in the same way as for the Eastern Bridge. These calculations show that the legitimate ships represent the greatest danger, even in the case of rather long average intervals between collisions which are able to interrupt the bridge connection.

1.2.3 Choice of risk level of the bridge

The above-mentioned two risk models enable the client to formulate load specifications for ship collision on the basis of the risk level chosen.

The choice of risk level is a difficult one. It seems clear that the level should be put in relation to the national risks normally accepted in the case of major structures, e.g. dams, hydro-electric power stations, nuclear power stations, multi-storey housing and big bridges and tunnels. However, the risk levels for these are far from well defined.

An alternative method of choosing the risk level is a "cost-benefit" analysis, in which the additional cost of safeguarding the bridge against ship collision is weighed against the possible loss from a collision. However, such a calculation depends on being able to evaluate the national economic loss resulting from an interruption of the bridge connection, and as it must be ascertained that such an estimate would, to a great extent, be based on arbitrary assumptions, this approach has not been found feasible in this case.

On the basis of all the above considerations, an average period of 10,000 years between collisions that can interrupt the Eastern Bridge and collisions that can interrupt the Western Bridge has been chosen. In this connection, it should be noted that the bridge is assumed to have a lifetime of 100 years.

1.3 Impact forces and structural measures against ship collision

1.3.1 Impact forces

Concurrently with the work on the risk models, an evaluation of the impact forces from ships of various sizes was carried out. The evaluation of the impact forces from small ships was based on Minorsky, [5], W.von Olnhausen, [6], and Woisin & Gerlach, [7]. The articles of W.von Olnhausen and Woisin & Gerlach are based on Minorsky's formula, which shows an empirical relationship between the impact energy and the deformed volume of steel, see fig. 5. The formula only has empirical cover for impact energies up to about 50,000 tm, corresponding, for instance, to the kinetic energy of a 10,000 dwt ship sailing at a speed of about 16 knots.

It was not considered justifiable, in the case of big ships, to accept the considerable extrapolation of Minorsky's formula that use of the results from the above-mentioned articles would imply.

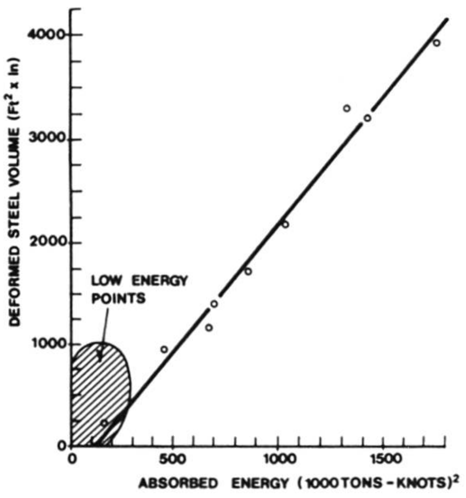

Fig. 5 Minorsky's equation: Empirical relationship between impact energy and deformed volume of steel.

It was therefore decided to contact Shiffbau-Ingenieur G.Woisin in West Germany, who, in the period 1967 to 1976, had been working at Howaldtswerke - Deutsche Werft in Hamburg on a series of ship model collision tests for the purpose of designing a protective structure for reactors in nuclear-powered ships. The tests consisted of letting a model of the bows of a ship run down a roller conveyor and hit a model of the reactor protection, see fig. 6.

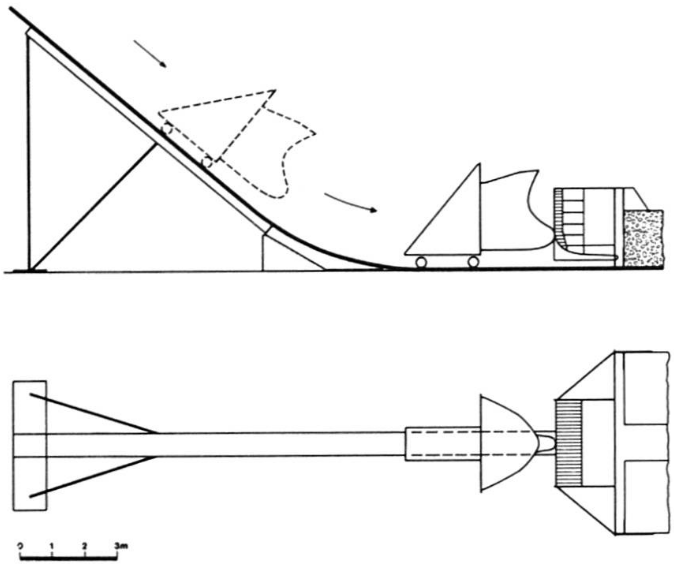

Fig. 6 Set-up for ship model collision tests at Howaldtswerke - Deutsche Werft, Hamburg.

One of the results of G.Woisin's investigations is that the impact force can be assumed to be approximately constant during the collision, although the impact force may increase to twice the average value for a brief period (.1-.2 sec.). In addition, Woisin states that the decisive factors for the magnitude of the impact force are as follows, in order of priority:

- design of the bows of the ship,
- speed of ship at moment of collision, and
- displacement.

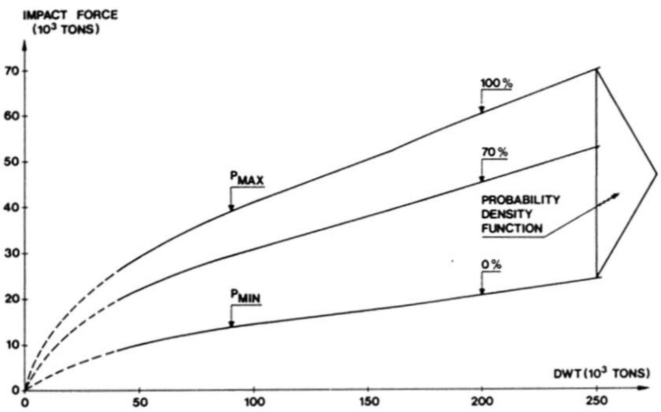

Fig. 7 G. Woisins estimate of the growth of the impact force with the size of ship.

Fig. 7 shows Woisin's estimate of the growth of the impact force with the size of ship, including an upper and a lower bound for the impact force and a proposal for a density function for use in a probability analysis. In the case of the Great Belt, it was decided to use the 70%-fractile for the following reasons: Consider the impact force given as the 50%-fractile, and the size of the dimensioning ship designated x dwt. It is then possible to determine the number of ships smaller than x dwt, and with an impact force bigger than the 50%-fractile as well as the number of ships bigger than x dwt and with an impact force smaller than the 50%-fractile. Since there are comparatively more smaller ships than big ones, cf. fig. 4, the number of ships in the first group is bigger than the number of ships in the second group, for which reason using the 50%-fractile would be on the unsafe side. With the 70%-fractile, there will be approx. the same number of ships in each group.

1.3.2 Fendering and protection measures

In addition to the aforementioned considerations, which imply designing the piers to withstand the impact forces of ships colliding with them, the question of providing protection enabling collisions to be avoided was looked into.

The possibility of establishing an emergency team with special ships to assist in dangerous situations was investigated as well as the possibility of establishing a fender-net to protect the Western Bridge. However, both these methods were quickly abandoned.

1.3.3 Protective islands

At a rather early stage the investigation was therefore concentrated on the possibility of safeguarding the bridge piers against ship collisions by means of protective islands, fig. 8, partly because these had been favourably mentioned in the replies to the questionnaire. However, neither the replies to the questionnaire nor a subsequent study tour to France, from which extensive material on protective islands had been received, gave sufficient information to enable the design of suitable islands.

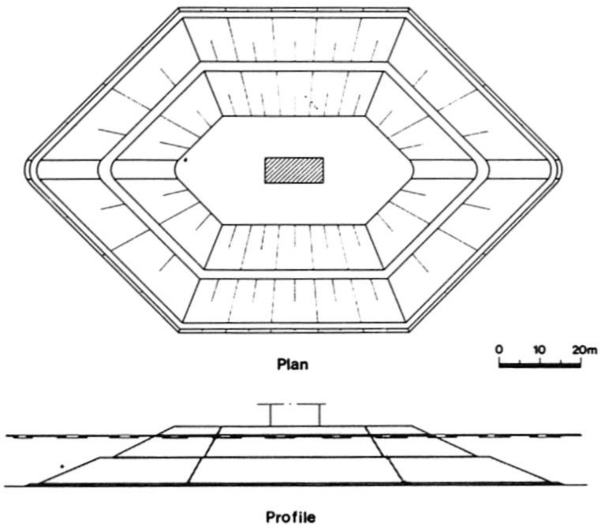

Fig. 8 Example of an artificial island.

SSB therefore initiated extensive model tests at the Danish Geotechnical Institute (DGI) and the Danish Hydraulic Institute (DHI).

At DGI tests were carried out in which a model of the front part of a ship of simple geometry was forced into a sand slope, while the earth pressure on the bows was measured. These tests enabled an equation to be formulated for the calculation of earth pressure on the bows.

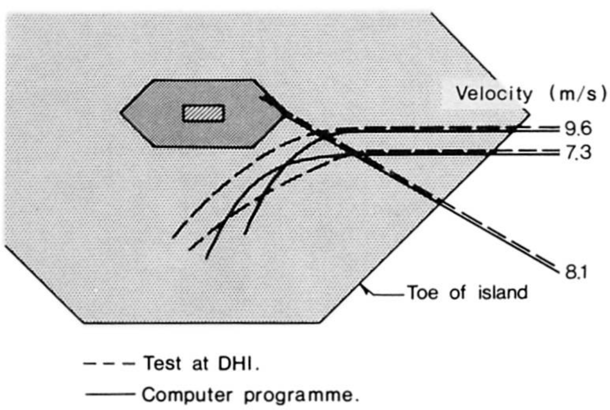

Fig. 9 Collision of ship with an artificial island. The figure shows tracks registered during hydraulic model tests and tracks calculated by means of the developed computer programme.

At the same time, at DHI, tests were carried out in which ship models (a 250,000 dwt tank ship and a 50,000 dwt container ship) were collided with a number of protective islands. During these tests the effect of a large number of parameters was investigated, including - especially - the geometry of the protective island and the effect of the draught and speed of the ship on the penetration length.

The results of the tests from DGI and DHI were co-ordinated by DHI in co-operation with SSB's consulting engineers, Storebæltgruppen, and a computer programme was developed for the simulation of a collision with a protective island. An example of a simulated collision is shown in fig. 9.

Protection of the bridge piers by means of artificial islands proved to be a financially favourable solution, but it was found that extensive use of such islands would result in an alteration of the exchange of flow through the Great Belt. As the consequences of this could not be directly assessed, it was decided initially only to use protective islands at anchor blocks and anchor piers.

2. THE TENDER PROJECTS

On the basis of the investigations described above, simplified load specifications have been prepared for ship collisions against the Great Belt Bridge. The specifications aim partly at ensuring the stability of the bridge and partly at ensuring that the individual structural members are sufficiently strong.

Stability is ensured by making the individual bridge piers able to resist the impact force from the biggest ship that can collide with the pier, in accordance with the risk model. For anchor piers, however, alternative protection in the form of protective islands can be provided.

For the tender projects for the Eastern Bridge the size of the biggest ship decreases from 250,000 dwt for the main piers to 4,000 dwt for the side-span piers that are farthest from the navigation channel. The impact force from the 250,000 dwt ship is estimated at 44,000 tons, which is a little less than the value corresponding to the 70%-fractile. This is due to the fact that a ship of this size cannot pass the Great Belt fully loaded. The impact force from the 4,000 dwt ship (fully loaded) is estimated at 6,000 tons.

For the Western Bridge, the biggest ship is 1,000 dwt. The impact force from this ship is estimated at 2,000 tons. As the superstructure of a ship of this size can hit the superstructure of the Western Bridge, impact forces are also specified for this type of collision.

The strength of the various structural members is ensured by specifying local loads during a ship collision, the impact force being in principle distributed over the cross section of the ship. For example, a local load consisting of line loads of 250 t/m combined with an uniformly distributed surface load of 15 t/m^2 is specified.

The problem of ship collision has had a decisive influence on the design of the tender projects. For example, the risk model has confirmed that solutions with a big free navigation width are preferable to solutions giving several less wide navigation spans.

The two tender projects for the navigation spans of the Eastern Bridge are shown in fig. 10. One is a cable-stayed bridge with a 780 m span, and the other a suspension bridge with a 1,416 m span.

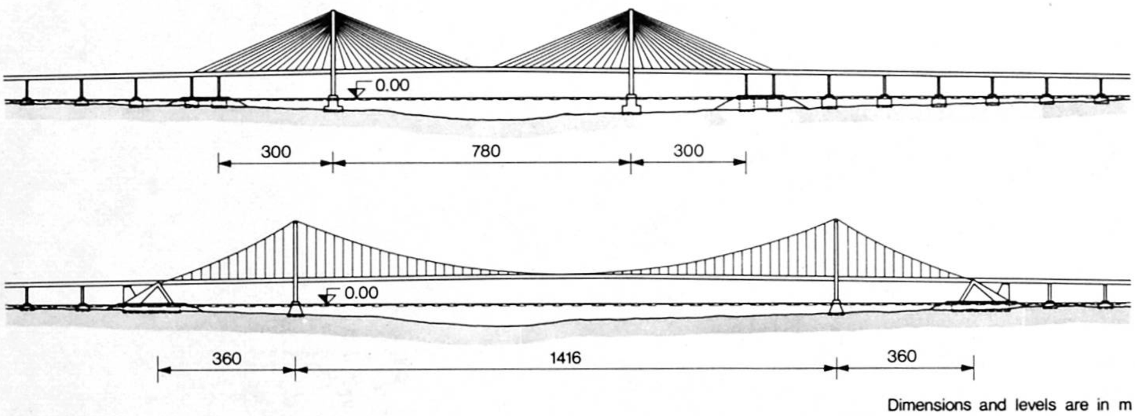

Fig. 10 Tender projects for navigation spans of the planned Great Belt Bridge: Cable-stayed bridge with 780 m span, and suspension bridge with 1,416 m span.

Part II: International Enquiry

0. INTRODUCTION

An international enquiry to procure information on the ship collision problem was carried out as part of the preliminary work on the planned Great Belt Bridge.

The work was undertaken by the Ship Collision Committee, appointed by Statsbroen Store Bælt (SSB), please refer to the introduction in part I of the present publication.

The idea of performing an international ship collision enquiry was found natural. The investigation made by Chr. Ostenfeld, [8], covered the period up to 1965, but the problem has been aggravated since then, amongst other reasons because of the well known increase in ship sizes.

The questionnaire was sent out in the period 1977 to 1978. It was originally sent to public authorities and organizations all over the world who could be expected to be in possession of information on the problem. Since then, the matter has been followed up when the replies received have required supplementation, and in many places, the questionnaire has been passed on by the original recipients to other authorities/firms.

The authorities and firms from whom replies have been received are listed in Appendix 1. Fig. 1 shows their geographical distribution.

The questionnaire, which took the form of approximately standardised letters of enquiry, primarily requested information on the following points:
- actual ship collision accidents,
- design specifications with regard to ship collision and
- protection measures.

Some addressees were also asked for information on radar monitoring of shipping etc.

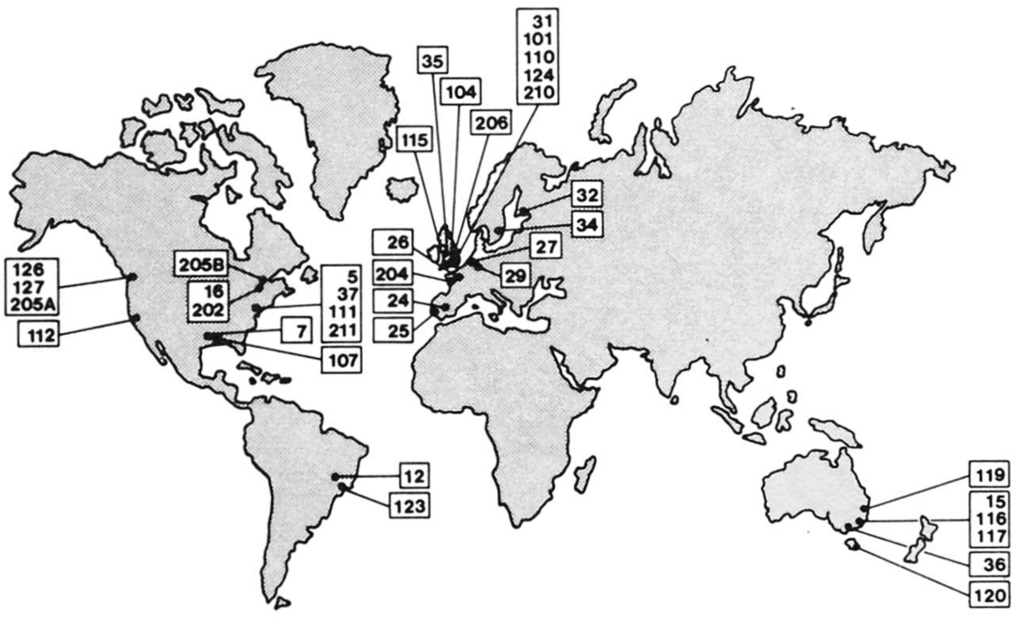

Fig. 1 Geographical distribution of the authorities and firms from whom answers to SSB's ship collision enquiry have been received. Numbers refer to Appendix 1.

1. SUMMARY OF SSB'S SHIP COLLISION ENQUIRY

1.1 General information on ship collision

It is clear from the replies received that most of the addressees consider the problem of ship collision to be of minor importance. This is probably because many of those questioned have been mainly concerned with small bridges passed by small ships (especially river traffic).

Many of the bridges described in the replies are characterised by having some form of protective structure, usually wooden fendering, either mounted directly on the bridge piers or, for example, fixed to a system of steel piles driven into the bottom. This fendering can only resist small impact forces, but is often adequate in the case of small ships. That these mini-fenders are primarily intended to protect ships does not alter the fact that they at the same time protect the bridges. This is demonstrated by the fact that many of the replies received report many examples of destroyed or damaged fendering, but very few examples of damage to bridges, and then, in most cases, only of minor damage. It is therefore hardly surprising that the problem of ship collision is often regarded as relatively unimportant.

1.1.1 Determination of impact force

In places where more serious consideration is given to the problem of ship collision, the impact forces are evaluated on the basis of energy considerations. In this connection, mention is often made of Minorsky's equation, [5] which gives an empirical relationship between the deformation of a ship's hull and the energy consumed for this deformation. However, simpler methods are also used; for example, one of the replies from Britain (115)*) mentions that the energy used in the deformation of a ship's hull is often put at half the impact energy.

In Sweden (34), an investigation was carried out by W. von Olnhausen in 1964-66 on the anticipated impact forces on a future bridge across the Øresund. Here, von Olnhausen used Minorsky's formula for an assessment of the growth of the impact force with the compression of a ship's hull, [6].

Other, rather extensive analyses for the determination of impact forces have been performed in France (26), also on the basis of Minorsky's theory.

In the reply from West Germany (29), too, an article is mentioned in which impact forces are evaluated analytically. The article in question, which is by Woisin & Gerlach, is also based on Minorsky's work, [7].

1.1.2 Risk analysis

Several of the addressees state that ship collision is so improbable that the risk can be neglected. However, except in one case, no actual assessment of the probability seems to have been carried out. The exception is a reply from the USA (37), concerning a planned off-shore nuclear power plant off the coast of New Jersey. Here, extensive probability analyses were carried out to determine the probability of a ship from a nearby waterway colliding with the power plant.

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*) Numbers refer to Appendix 1.

We have also been advised from Australia (120) that consideration was given to the risk of collision in connection with the planning of the Second Hobart Bridge. These considerations are described in [9]. It seems that the general approach in assessing the risk is very much like that used for the planned Great Belt Bridge, as described in part I of this publication.

1.1.3 Actual ship collisions since 1965

It is obvious from the replies that the rather general attitude to ship collision, that collisions are so unlikely to occur that the risk can be neglected, is not substantiated by experience. The replies mention quite a number of cases of ship collisions, often with serious consequences for the bridges and, in several instances, with loss of human lives.

Many reasons are given for these accidents, but three of them appear to predominate: human error, i.e., cases in which the accident was caused by misjudgment, negligence, etc., on the part of one or more persons; mechanical failure, especially of the steering gear; and finally, weather conditions, i.e. cases in which anchored ships tore loose from their moorings in rough weather and drifted against the bridge.

Appendix 2 contains a list of actual ship collisions. For the sake of completeness, the list includes not only collisions described in the replies received, but also collisions mentioned in newspapers and technical literature. The appendix covers ship collisions after 1965. For ship collisions before this time please consult the article by Chr. Ostenfeld, [8].

1.1.4 Literature

The replies contain many references to literature on ship collision, which have been incorporated in Storebæltgruppen's bibliography. This can be found in extension in [2] and a selected extract can be found in Appendix 4 of this publication.

1.2 Structural measures against ship collision

In this section a brief description will be given of some of the protective structures mentioned in the replies.

As mentioned elsewhere, extensive use is made of fendering, but as this can only resist small impact forces and is, furthermore, a common engineering structure, it will not be described in detail here. Fig. 2 shows an example of what would normally be a considerable structure, but in the case of the Great Belt Bridge can be designated as a "small" fender only.

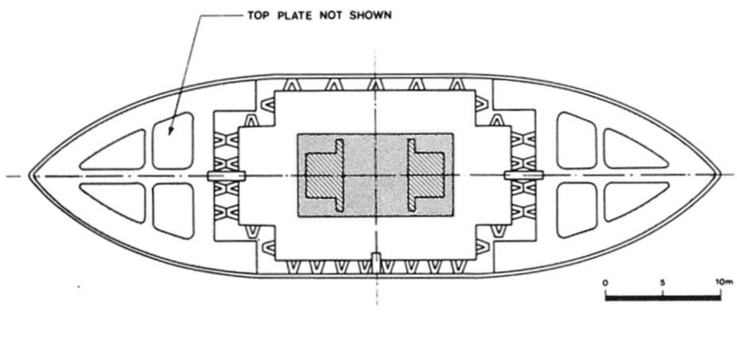

Fig. 2 Example of "small" fender. Received from State of California, Dept. of Transportation (112).

1.2.1 Reinforced piers

After fendering, this seems to be the most common structural measure used.

A reply from Canada (127) mentions, for example, that the piers of the bascule span of the Okanagan Lake Floating Bridge are designed to resist the force from a 1,135 ton barge, moving at a speed of 4½ knots, which grazes the pier at an angle of 5 degrees. The impact force is not mentioned.

The reply from Sweden (34) states that certain piers in a number of small bridges have been checked for ship collision forces of 1,000 tons, and that some of the piers of the Öland Bridge have been designed for impact forces of up to 5,000 tons.

In West Germany (29), in connection with the planning of a number of highway bridges over major rivers in 1971, impact forces of from 2,000 to 6,000 tons perpendicular to the bridge and of from 1,000 to 2,000 tons parallel with the bridge, depending on the water depth and locations of the piers, were specified. In 1974, the Bundesministerium für Verkehr carried out an analysis of the anticipated impact forces on a planned railway bridge over the Rhine. On the basis of articles by Minorsky, Olnhausen, Woisin and Gerlach, and Ostenfeld, the following impact forces were determined: 2,168 tons from a ship with a displacement of 6,150 tons, sailing at a speed of 9½ knots; 735 tons from a ship with a displacement of 10,150 tons, sailing at 5½ knots; and 2,819 tons from a ship with a displacement of 1,800 tons, sailing at 12 knots.

In a reply from Australia (120), it is stated that, after assessment of several other solutions, a decision has been taken to specify that the piers for the planned Second Hobart Bridge, which is to supplement the Tasman Bridge, shall be designed for impact from ships with a displacement of up to 10,000 tons.

A reply from the USA (7) indicates that the Luling Bridge over the Mississippi, which is at present under construction, was analysed for two impact forces, 2,000 tons and 27,000 tons. The ship sizes in question are 20,000 tons and 40,000 tons (gross ton?), and the speed is 7 knots. The reply does not indicate how the impact forces were determined. The bridge piers are of the caisson-type.

1.2.2 Dolphins

The replies from Brazil (12,123) advise that the Rio-Niteroi Bridge is the only bridge in Brazil that is protected against ship collision. The bridge has three navigation spans, and the four navigation piers are protected both upstream and downstream by gravel and stone filled, circular sheet piling caissons that are closed at the top with a concrete slab. By means of fender structures which connect the caissons in pairs and at the same time protect the long sides of the piers, the caissons are able to act together, which actually doubles their efficiency, see fig. 3.

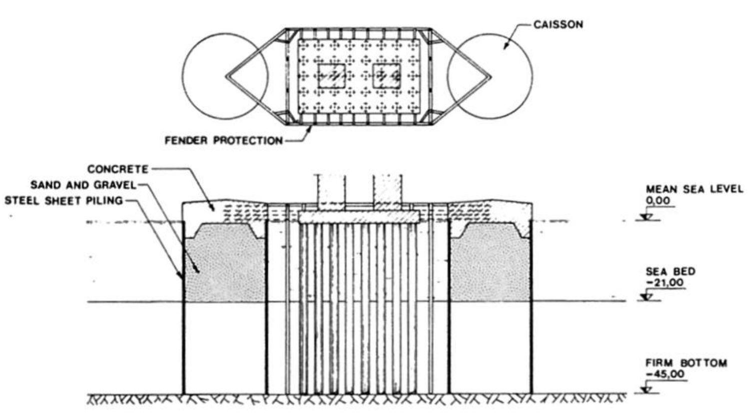

Fig. 3 Artur da Costa e Silva Bridge (Rio-Niteroi Bridge): pier protection. Figures based on Der Bauingenieur, jan. 1973.

In a reply from Canada (205A), big caissons filled with soft material are described as presumably one of the most efficient protection structures because they can act as a brake and possibly stop a ship.

1.2.3 Fender-net

This method of protection, although one of the more uncommon, is mentioned twice in the replies.

For example, in a reply from Australia (120), fender-net is mentioned as one of the methods of protection considered in connection with the protection of the Tasman Bridge.

In a reply from the USA (37), fender-net is mentioned in connection with protection against ship collision of the previously mentioned planned offshore nuclear power plant, Atlantic Generating Station in New Jersey. The net consists of a circular system of nylon cables supported by buoys and anchored in the sea bed. The power station is protected by a breakwater of Dolos elements, and the idea of the fender-net was to supplement the breakwater. However, the idea was abandoned for three main reasons:

- the net would be a danger to shipping, and especially to small ships in the area,
- the net would hardly be able to retain its efficiency throughout he entire lifetime of the power station (40 years) and
- in any case, the breakwater gave more than adequate safety.

The general lay-out for the fender-net is shown in fig. 4.

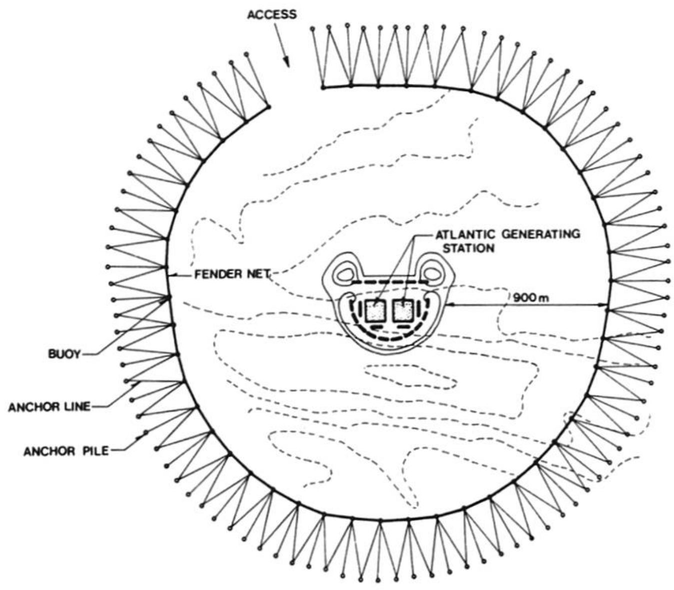

Fig. 4 Proposal for fender-net for Atlantic Generating Station, New Jersey, USA. Figure received from Public Service Electric & Gas Company (37).

1.2.4 Protective islands

Protective islands presumably provide the best possible protection of bridge piers. This view is, for example, given in a letter from the USA (111), which mentions that the Verrazano-Narrows Bridge at the entrance to New York harbour is protected by means of artificial islands, see fig. 5.

In connection with the preliminary investigations for the Burrad Inlet Crossing in Canada (126), which was, however, never built, the possibility was looked into of having the planned, temporary working platforms extended into a permanent ship collision protection. This protection was to have consisted of a closed ring of caissons protected on the outside by rock/sand fill. The effect from 20 frequent size ships in the area was investigated. The ships covered were between 600 and 100,000 dwt. The critical ship was found to be one with 35,000 tons displacement, draught about 10 m and stem projection of about 17 m. Impact speeds of 5 and 10 knots were assumed. The reply gave no details regarding the method of analysis.

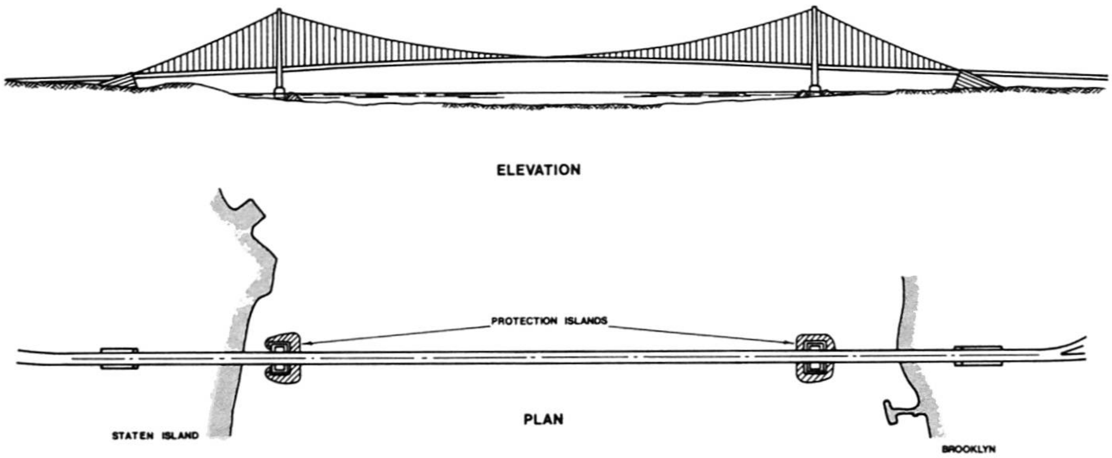

Fig. 5 Verrazano-Narrows Bridge. The piers are protected by means of artificial islands. The figure is based on material from Triborough Bridge and Tunnel District (111).

The planned nuclear power station off the coast of New Jersey in the USA is meant to be protected by means of an artificial island built up of Dolos elements. The Dolos elements are placed against a number of caissons which are placed in a semi-circle around the nuclear power station, with an inlet opening in towards land; this inlet is closed with caissons without Dolos protection. Supply ships have access to the area between the row of caissons and the power station via narrow channels through the Dolos protection. Inside this area the power station is protected by a fender structure. The artificial island is primarily intended to act as a breakwater, but its efficiency against collisions has been demonstrated by model tests, which included a test with a 326,000 dwt tanker in ballast, moving at 16 knots. A typical cross-section of the breakwater is shown in fig. 6.

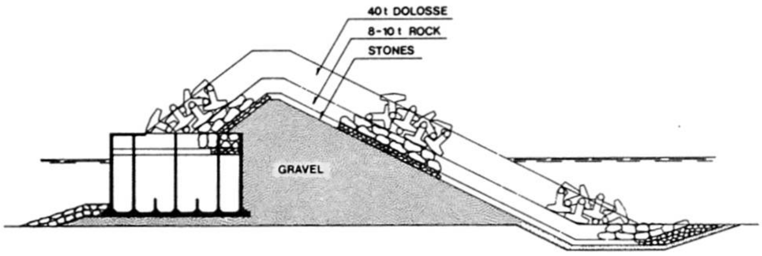

Fig. 6 Typical cross-section of the breakwater for Atlantic Generating Station. Figure based on Nuclear Technology, Vol. 22, may 1974.

A reply from Britain (115) mentions that model tests have been carried out there on protective islands for the planned Orwell Bridge at Ipswich. The tests covered ships up to 12,000 tons, moving at a speed of 8 knots.

In France (26, 204), model tests have been carried out on artificial islands in connection with the planned Pont Honfleur, where the biggest ship is 100,000 dwt. The reply from France also mentioned that the St. Nazaire Bridge is protected by means of artificial islands. The St. Nazaire Bridge crosses the River Loire and is passed by ships of up to 240,000 dwt.

1.3 Non-structural methods of reducing risk

Non-structural methods of increasing the safety of a bridge include beaconing, navigation restrictions and traffic monitoring. Some examples of these methods are given in the replies.

1.3.1 Beaconing

Beaconing is mentioned in several replies. There are apparently official requirements in many places that the navigation through bridges be eased by means of various types of beaconing, for example, buoys, sound and light signals, radar reflectors and similar.

However, these types of aids are well known and will therefore not be discussed in detail here.

1.3.2 Navigation restrictions

Replies from Brazil (12, 123) advise that there are navigation restrictions for the Rio-Niteroi Bridge. As mentioned elsewhere, this bridge has three main navigation spans, the piers of which are protected by means of sheet piling caissons. Only big ships are allowed to use these three navigation spans, while small ships are required to use the side spans.

The replies from Australia (116, 117) mention two examples of navigation restrictions:

- At a number of bridges, a type of light regulation has been introduced, indicating when the bridge may be passed in one direction and when it may be passed in the other. This system is claimed to reduce the risk of collision and, in one case, the Spit Bridge, "has created some order out of chaos".
- After a number of cases of fender damage and minor damage to the bridge across the Richmond River at Wardell, an analysis of the causes of the accidents was carried out in 1970. It was found that all the accidents had occurred under identical circumstances, i.e.:
  - tidal current in the navigation direction,
  - ships in ballast,
  - strong winds from one specific direction.

  Consequently, passage of the bridge is forbidden when these three conditions apply.

In a letter from Chesapeake Bay Bridge and Tunnel District it is advised that restrictions on navigation in the vicinity of the bridge have been introduced. The bridge has been subjected to several serious collisions, and the U.S. Coast Guard has therefore prepared a set of rules to regulate traffic in the area. These rules are described as being extremely effective and have reduced the risk of collisions.

1.3.3 Traffic monitoring

Traffic monitoring of harbours and rivers is extremely common, and there are therefore naturally also many traffic-monitored bridges. However, none of the replies mention examples of monitoring primarily for the sake of the safety of a bridge. The principal reason for introducing traffic monitoring seems to be the desire for greater safety for ships and for greater efficiency.

In West Germany (29), several major rivers are monitored with long radarchains. The experience with this form of monitoring has been good: the number of collisions has fallen and navigation conditions, especially in fog, have improved.

In San Francisco there is a very advanced radar monitoring system. The California Department of Transportation (112) manages 4 bridges in this area, but advises that the efficiency of the system has not yet been demonstrated in connection with a collision situation.

The literature contains references to plans for a radar system developed specially for the Sidney Lanier Bridge in Georgia, USA. However, there is at present no information on the state of this project.

2. SYNTHESIS OF THE SHIP COLLISION ENQUIRY

One of the main impressions from the replies to the questionnaire is that special structural measures to protect bridges against ship collision are not common. At the same time, the replies (and the technical journals) show that ship collisions actually occur - and are even comparatively frequent.

However, most of the collisions involve small ships that only graze bridge piers, and as small fendering is almost a matter of course, the consequences of such collisions are usually rather limited.

More serious collisions are rarer, but do occur.

For example, the Pontchartrain Bridge in the USA has been exposed to 4 collisions. The last in 1974, when 4 of its spans fell down and 3 people were killed. This accident was caused by a tug towing 4 empty barges, which hit a bridge pier a long way from the navigation span. The tug-skipper had fallen asleep at the wheel.

The Chesapeake Bay Bridge-Tunnel has also been subjected to several serious ship collisions, the latest of which occurred in 1972. In almost all cases, the accidents were caused by ships being repeatedly thrown against the bridge in stormy weather.

In a collision against the Benjamine Harrison Memorial Bridge, USA, in 1977, two spans collapsed. This accident was caused by an electrical fault in the ships steering gear.

These three examples of serious ship collisions serve to show that such accidents have a wide variety of causes. However, it does seem that the three causes described here - human error, mechanical failure and bad weather - have the highest frequency.

The last major bridge disaster involving loss of human life occurred in Tasmania in 1975. Here, the Tasman Bridge was hit by a ship a long way from the navigation span, resulting in the collapse of 3 spans. The reason was human error. Several people were killed.

One of the things noticed about the Tasman Bridge disaster and several other bridge accidents, including those at the Chesapeake Bay Bridge-Tunnel and the Pontchartrain Bridge, is that the collisions occurred a long way from the navigation spans, at locations where the bridges were unprotected.

Another thing - which also applies in the above three cases - is that the structures are often lightweight structures, for example, bridges founded on high piling. This may explain why the ship collisions had considerably more serious consequences than might have been expected with the rather moderate sizes of the ships involved in the accidents.

The above two factors can, perhaps, be taken as an indication that it is not sufficient just to safeguard the navigation span piers of a bridge and, further, that the structural design of a bridge is of great importance to its ability to withstand ship collisions.

Officially, the problem of ship collision is only recognized to a limited extent. In places where it is taken into consideration, this is apparently done from project to project, with the client himself determining the extent to which his bridge is to be safeguarded, in the absence of official directions. Put in another way, the client fixes his own risk level.

France is the only country of those from whom replies have been received to state that it has a clear, official line, requiring the safeguarding of all bridges against ship impact. For small ships, this is done by reinforcing the piers, while in the case of big ships, steps are taken to ensure that the ships go aground on artificial islands around the piers. The official French view is that ship collision is so frequent an occurrence that it is absolutely essential to safeguard against it.

The ship collision enquiry, apart from yielding concrete information that has been taken into account in the design work on the planned Great Belt Bridge, has also given the clear impression that there is very great interest in some places in the problem of ship collision and that this interest is increasing.

Part III: References and Appendices

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[2] "Investigation into the Ship Collision Problem", Statsbroen Store Bælt, February 1979.

[3] T. Macduff: "The Probability of Vessel Collisions", Ocean Industry, Septemper, 1974.

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[5] V. U. Minorsky: "An Analysis of Ship Collisions with Reference to Protection of Nuclear Power Plants", Journal of Ship Research, Oct. 1959.

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[8] Chr. Ostenfeld: "Ship Collisions Against Bridge Piers", AIPC-Mémoires, 1965.

[9] Maunsell & Partners: "Tasmann Bridge-Risk of Ship Collision and Methods of Protection", September 1978.

APPENDIX 1

List of authorities and firms who have participated in Statsbroen Store Bælt's ship-collision enquiry.

The list is arranged in alphabetical order by nationality.

In cases in which the authority or organization to whom the questionnaire was sent have delegated the task of replying to others, e.g. the consulting engineers for the bridge in question, it is the replying body that is listed.

The numbers beside each name are used as references in the text.

Australia
- 15 Ministry of Public Works
- 36 G.Maunsell and Partners
- 116 Maritime Services Board of New South Wales
- 117 Department of Main Roads New South Wales
- 119 Harbours and Marine Dept. and Marine Board
- 120 Department of Main Roads Tasmania

Belgium
- 27 Ministère des Travaux Publics

Brazil
- 12 Ministerio dos Transportes
- 123 ECEX

Canada
- 10 St.Lawrence Seaway
- 16 Ministry of Public Works
- 126 C.B.A. Engineering Ltd.
- 127 Swan Wooster Engineering Co. Ltd.
- 202 Transport Canada
- 205A Port of Vancouver
- 205B Port of Montreal

Britain
- 31 National Ports Council
- 35 Liverpool Underwriters Association
- 101 Salvage Association
- 104 The Hydraulic Research Station
- 110 Dept. of Transport
- 115 Sir W.Halcrow and Partners
- 124 LLR Shipping Information Centre
- 206 National Maritime Institute
- 210 Lloyd's of London Press Ltd

Finland
- 32 Väg- och Vattenbyggnads-styrelsen

France
- 26 Ministère de l'Equipement
- 204 Port Autonome de Nantes - St.Nazaire

Portugal
- 25 Ministerio des Obras Publicas

Spain
- 24 Ministerio de Obras Públicas

Sweden
- 34 Statens Vägverk

USA
- 5 Port of New York
- 7 State of Louisiana
- 8 State of Virginia
- 37 Public Service Electric and Gas Company
- 103 Int.Bridge Tunnel and Turnpike Ass.
- 107 Port of New Orleans
- 111 Triborough Bridge and Tunnel District
- 112 California Dept. of Transportation
- 201 Chesapeake Bay Bridge-Tunnel Commission
- 211 Steinman, Boynton, Gronquist & Birdsall

West Germany
- 29 Bundesministerium für Verkehr

APPENDIX 2

List of registered ship collisions since 1965

The following is a list of registered ship collisions since 1965. With the period covered here, the ship collisions listed constitute a supplement to those described in Chr. Ostenfeld's article from 1965, [8].

The data listed are based on the replies to SSB's ship collision questionnaire, supplemented by information found in technical journals. The list includes ship collisions not only with bridges, but also with quays and oil piers, because this type of accident, too, helps to give an impression of how a ship collision occurs and of the risk level in general.

The list is arranged in alphabetical order by nationality and in chronological order within each nation. The reference numbers following SSB correspond to those used in Appendix 1. The list covers the period from 1965 to the end of 1978:

Country/Collision Year/Structure - Description. References.

Australia/1975/Tasman Bridge over the River Derwent, Hobart, Australia. Opened 1964. The bridge is a 4-lane concrete bridge on double columns resting on a plinth supported by high piling. The water depth is up to 37 m. The navigation span has a width of 94 m and a height of 45 m. The river is heavily trafficated. Upstream of the bridge there is a zinc mine served by bulk-carriers of up to 40,000 dwt. The two piers of the navigation span are protected by gravitation fenders designed to absorb a glancing blow (15^{o}) from a 15,000 t (dwt ?) ship sailing at 8 knots. The bridge deck (continuous) has weak joints over the supports. This built-in failure mechanism functioned perfectly during the accident in 1975. On 1975-01-05, the bulk-carrier SS Lake Illawara (7,200 dwt. loaded with zinc concentrate) collided head on with two piers, hitting the bridge at a relatively small angle. One of the causes of the accident was a fault in the steering gear, but the captain was held responsible on grounds of poor seamanship both before and after discovering of the steering fault. Three bridge spans (á 42 m) fell in the water, two piers were totally destroyed. Between 12 and 20 people lost their lives and the ship sank. (Ref.: SSB 15 and 36, Civ.Eng.Transact. April 67., Int. Constr. May 1977, Eng. News Record (ENR) 1975-01-09 and 1975-01-16, New Civil Eng. 1975-01-09 and Constr. News 1975-01-09).

Brazil/1977 The oil pier in Sao Sebastiao was seriously damaged in a collision. (Ref.: Ingeniøren 1977-12-13).

Canada/1968/The railway bridges in Vancouver Harbour, Canada. The old railway bridge, built in 1925, the new railway bridge under construction in 1968. On 1968-05-08, the freighter Yohu Maru (cargo 23,000 tons coal) hit first a pier in the old bridge and then a pier in the new bridge. No information on the reason for the accident. It is understood that the old bridge suffered considerable damage. (Ref.: SSB 205A)

Canada/1975/CNR swing bridge over the Fraser River in New Westminster, Canada. The 700 m long Swiftsure Prince tore loose from its moorings in heavy winds and collided with the bridge on 1975-12-26. The barge apparently hit the bridge superstructure. One span (130 m) fell down. The bridge piers were undamaged. (Ref.: SSB 126).

Canada/1975/CNR swing bridge over Grand Narrows, Canada. On 1976-08-27 the Shirley Ann W (146 BRT) hit one of the bridge supports (placed below water level). As the swinging span was only partially open, the ship had to pass close by the submerged support, whereby the accident happened. The ship went aground on the support. There was apparently little damage to either ship or support. (Ref.: SSB 202).

Denmark/1973/The pierhead at the entrance to Copenhagen habour. On 1973-04-29 the Swedish freigther MS Vikaren (7,100 dwt) hit the pier head, which suffered considerable damage. The accident was caused by a fault in the steering gear. (Ref.: Report of C.H. Simonsen to NVF-Committee 60, 1973-05-22).

Denmark/1978/The lighthouse on Romsø Tue. The West-German freighter Ando (578 dwt) ran into and knocked down the lighthouse. Cause unknown. The ship had to seek harbour for repairs. (Ref.: Politiken 1978-01-28).

Britain/1968/A 90,000 ton tanker did £ 1 1/4 mill. worth of damage in a frontal collision with an oil pier in Liverpool. (Ref.: Times 1968-11-08).

Britain/1972/The crane quay in Felixstowe was hit and sunk. A complete new quay had to be built at a cost of £ 300,000 (93 x 31 m). (Ref.: Dock & Harbour Authority Nov. 1972).

Sweden/1977/The Tingstad Bridge across the canal at Göteborg Port, Sweden. A railway bridge with a swinging span - steel lattice structure. On 1977-09-10, the bridge was hit by the gas tanker Sørine Tholstrup (1600 dwt in ballast). Reason unknown. (The pilot advised after the accident that there was a fault in the steering gear). One end of the bridge fell down (acc. to the source, the connection to land was pulled loose). Only slight damage to the ship. (Ref.: Politiken 1977-09-11 and 1977-09-12).

USA/1965/Richmond-San Rafael Bridge, California, USA. In the autumn of 1965, a US naval ship out of control collided with one of the piers. The fender system was damaged as well as a beam (3.6 x 1.2 m) in the pier. (Ref.: SSB 112).

USA/1967/1970/1972/Chesapeake Bay Bridge-Tunnel, Virginia, USA. Opened 1964. 28 km long bridge (with 2 tunnels and 4 artificial islands). Water depth varies between 7 and 21 m. Ship-collision loading was not taken into account in the design. The bridge was involved in collisions in Sept. 1972, Jan. 1970 and 1967. In all three cases, a ship was repeatedly thrown against the bridge in a storm. In 1967 and 1972, the ship involved was a barge which had torn loose from its moorings, and in 1970 it was the USS Yancy, which apparently had engine trouble. In 1967 one span fell down and five others were seriously damaged. In 1970, five spans fell down and five others were seriously damaged. In 1972 two spans fell partly down and five others were damaged. In addition to these accidents, the bridge was hit once in 1966 and again in 1967; in both these cases, the bridge could be kept open during the repair-work. (Ref.: SSB 201, ENR 1972-11-23, 1970-01-29 and 1970-03-12).

USA/1972/A barge, SCC 620 collided with the quay in Louisville, Kentucky. Impact force: approx. 2,000 tons. (Ref.: NTIS AD-902 863).

USA/1972/The Sidney Lanier Bridge across the Brunswick River, Georgia, USA. Started 1949, opened about 1960. 1340 m long, 4-lane bascule bridge. Main span and towers in lattice girders, other spans: concrete slabs on steel girders, supported by double columns. Free height outside navigation span: about 13-14 m. On 1972-11-07, the freighter SS African Neptune (12,900 dwt) hit the bridge superstructure with her bows beside the bascule span. Two reasons: the helmsman failed to follow the pilot's instructions properly, and neither the pilot nor the captain discovered the mistake in time. Three spans fell down (a 135-m long section). The bridge piers were apparently undamaged. 10 people killed. Only slight damage to ship. (Ref.: NTIS AD-781 298, ENR 1972-11-16).

USA/1974/The Pontchartrain Bridge, New Orleans, USA. Actually two parallel bridges, the old one opened in 1956 and the new one in 1969. Both bridges in prestressed concrete, founded on high piling. A tug pulling four empty barges hit an unprotected pier some way from the navigation span in August 1974. The tugskipper had fallen asleep. A 72 m long section spanning over four spans fell down. Three people killed. The bridge has been involved in 9 collisions since 1956. (Ref.: SSB 7, ENR 1974-08-08).

USA/1975/Mount Hope Bridge, Rhode Island, USA. Suspension bridge main span about 300 m, towers in steel lattice. The bridge was hit during the night in heavy fog in 1975. The pilot had apparently not heard the bridge's warning bell. The sides of the bows of the ship projected far enough beyond the outlines of the pier to cut through 25% of one of the towers. The bridge pier itself was only glanced, and the damage of this is described as of minor extent. (Ref.: SSB 211).

USA/1976/The Pass Manchac Bridge over the canal between Lake Pontchartrain and Lake Maurepas (US Route 51), Louisiana, USA. 900 m long, 2-lane bridge, concrete slab on steel girders, intermediate supports with 2, 3 or 4 concrete columns in each. Bridge deck about 15 m above water level. In 1976 the bridge was hit by an unmanned barge, which collided with an unprotected pier. The barge was off course because of strong current. The tugboat skipper was held responsible. Three spans (24, 32 and 21 m) fell down. At least one person killed. The barge was hit by the collapsing bridge spans but did not sink. (Ref.: SSB 7, ENR 1976-09-23).

USA/1977/Benjamine Harrison Memorial Bridge - US Route 156 over the James River, Hopewell, Virginia, USA. Opened in 1967. 1340 m long, 2-lane bridge with bascule span. Main span (105 m) and adjacent span on either side in steel lattice (these spans built together with the towers). The bridge deck is supported on double columns. On 1977-02-24 the tanker Marine Floridan (25,000 dwt in ballast) hit and destroyed a bridge pier, after which the ship's superstructure hit the steel lattice span (the ship's hull passed under the bridge). Reason: electrical fault in the steering gear. One end of the steel lattice span fell into the ship, while an adjacent span (34 m) fell into the water. The bascule span got wedged in its top position. During attempts to save this span (10 days later), the tower collapsed taking the lattice span with it as it fell. One end of the bascule span remained hanging by a few wires from the other tower. The ship was only slightly damaged by the falling bridge span, but when the tower fell down it caused considerable damage to the ship's superstructure.
(Ref.: SSB 8, ENR 1977-03-03).

USA/1977/The San Francisco-Oakland Bay Bridge, California. In September 1977, the bridge was hit by a crane mounted on a barge. The bridge was seriously damaged. (Ref.: ENR 1977-09-22).

USA/1977/The Union Avenue Bridge across the Passiac River, New Jersey, USA. Built in about 1897. A 2-lane bridge with a swinging span. Main piers founded on wooden piles. In April 1977 the bridge was hit by an empty oil barge when the tow-rope to the tug snapped. The barge hit a pier at the navigation span. The pier was destroyed and one of the adjacent bridge spans (16 m) fell down. (This was later raised and a new pier was built under it). (Ref.: ENR 1977-08-25).

West Germany/1977/Oil pier at Wilhelmshaven. The oil tanker Al Fountas (209,000 dwt) hit the oil pier. Fault in engine (steering gear ?). 109 m of the pier were destroyed. Only slight damage to the ship. (Ref.: Dock & Harbour Auth. Aug. 1975).

APPENDIX 3

The following persons, firms and institutes have participated in the investigations relating to the ship collision problem (in alphabetical order):

CAP-Consult,
Computer Aided Planning

Danish Geotechnical Institute

Danish Hydraulic Institute

Danish Ship Research Laboratory

Ferry-Leader on M/S Romsø,
DSB - Danish State Railways

Dr. Y. Fujii,
Electronic Navigation Research Institute,
Tokyo, Japan

T. R. Funder, Chief of Section,
Ministry of Commerce
(Leader of the Ministry's Reference Group on Ship Collision)

Dr. E. M. Godwinn,
Marine Traffic Research Unit,
England

Commander F. Heimdal,
Royal Danish Navy

Professor A. Jensen,
Institute of Mathematical Statistics and Operational Analysis,
Technical University of Denmark

K. E. Hansen ApS
Consulting Naval Architects - Marine Engineers

V. U. Minorsky,
Principal Naval Architect,
U S A

Storebæltgruppen, Consulting Engineers.
Joint venture between:

Cowiconsult,
Consulting Engineers and Planners AS,

B.Højlund Rasmussen,
Consulting Civil Engineers, and

Rambøll & Hannemann A/S,
Consulting Engineers

G. Woisin, Schiffbau Ingenieur,
Geesthacht, West Germany

APPENDIX 4

Bibliography on ship collision literature.

The following list of references on ship collision literature is an extract from Storebæltgruppen's bibliography, which can be found in [2].

However, the order of the references has been changed and is in this publication given in chronological order, subsequently alphabetically by authors. Furthermore, a few amendments and additions have been made.

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