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Effects of a Ship Collision with a Bridge

Effets de la collision d'un navire avec un pont

Auswirkungen einer Schiffskollision mit einer Brücke

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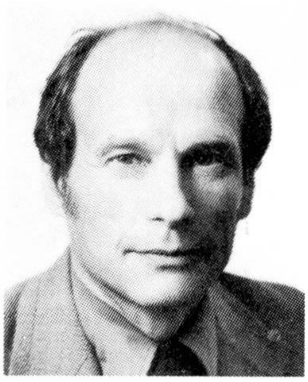

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SUMMARY
This study considers the after-effects of a hypothetical collision of a ship with the bridge connecting Lauttasaari with Salmisaari in Helsinki. Dynamic calculations for such a collision were carried out using a simple model having two lumped masses. The elasticity of the bridge and the reductions in rigidity caused by successive failures of the piers were also taken into account. The shear capacities of the bearings were found to be the most critical factors in the case of a collision. Lastly, an investigation was made as to how to reduce the possibility of further mishap which might result from such a collision.

RÉSUMÉ
L'étude s'intéresse aux conséquences d'une collision supposée d'un navire avec le pont reliant Lauttasaari et Salmisaari, à Helsinki. Des calculs dynamiques pour une semblable collision ont été effectués à l'aide d'un modèle simple faisant appel à deux masses distinctes. De même, il a été tenu compte de l'élasticité du pont et de la diminution de la rigidité du fait des défaillances successives des piles. La résistance au cisaillement des appuis est, selon cette étude, l'élement le plus important en cas de collision. Une étude a été menée sur la manière de réduire les conséquences d'un tel accident.

ZUSAMMENFASSUNG
Die Folgen einer hypothetischen Kollision eines Schiffes mit der Brücke zwischen Lauttasaari und Salmisaari in Helsinki werden untersucht. Unter Verwendung eines einfachen Modells aus zwei Massen wurden dynamische Berechnungen für eine solche Kollision vorgenommen. Die Elastizität der Brücke und die Minderung der Steifigkeit, die durch mehrfaches Versagen der Pfeiler verursacht wurde, ist ebenfalls berücksichtigt worden. Die Schubfestigkeit der Auflager stellte sich als kritischster Faktor im Fall einer Kollision heraus. Es wurde noch untersucht, wie die Folgen einer solchen Kollision verringert werden könnten.

1. PREFACE

1.1 General

In the year 1980, an accident took place in Sweden, at the Tjörnbro Bridge, where the entire bridge collapsed after a ship had crashed into the structures of the bridge. Apart from extensive economic damages, also several people were killed in the accident.

This incident attracted considerable attention among professionals of this field. Among others, the Town of Helsinki, the proprietor of the Lauttasaari bridge which also had been battered by ships a couple of times, decided to have a study made of the damages that would be caused by a possible collision. This study was prepared by Oy Insinööritoimisto K. Hanson & Co. (Consulting Engineers).

1.2 Bridge Site

The bridge is located in the town of helsinki between the Salmisaari and Lauttasaari districts, and it crosses a ca. 320 m wide strait in east-west direction. On the northern side of the bridge, in Salmisaari district, there is a power station to which coal is transported by sea through a gate in the bridge. The present bridge was built in 1967 as a result of an international design competition which was won by a Danish engineer, L. Steding-Jessen.

When approaching the bridge, the channel is very close to the Lauttasaari side bank. The water which is thus dammed between the bank and the ship, causes transverse flowings which make it difficult to steer the ship. In order to maintain manoeuvrability, the ship's speed cannot be decreased under 6 knots when sailing into bridge opening.

When the gate of the bridge is opened, traffic onto the bridge is prohibited by means of barriers located right next to the gate on both sides. Vehicles have, thus, free access to the stationary part of bridge when the barriers are lowered.

1.3 Bridge Construction

The base structure of the bridge consists of two rows of columns. The columns are supported partly by piled bases, partly by bases cast onto the rocks.

The spans of the bridge, starting from the Lauttasaari side, are:35.6, 56.6,

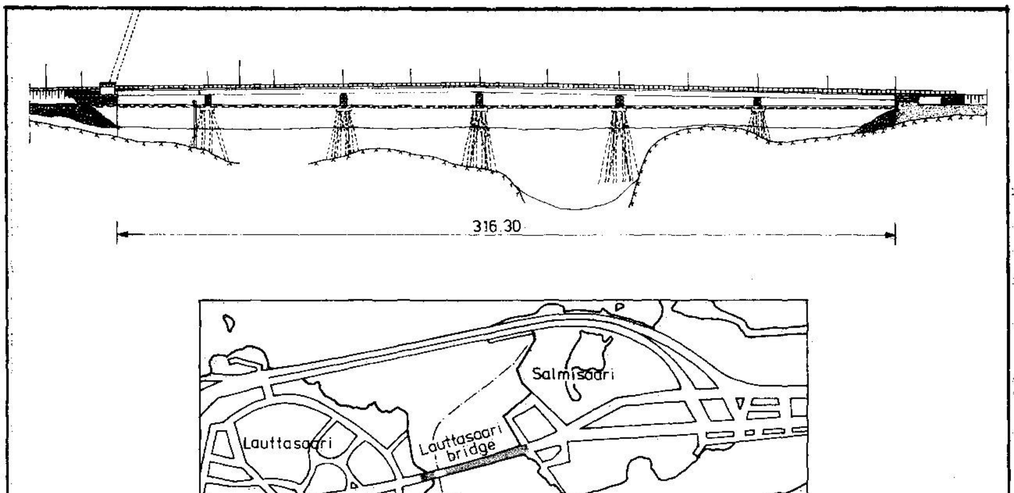


Figure 1. Side view of the bridge and map of the bridge site.

56.0, 56.6, 56.0 and 56.6 m (Figure 1). The gate whose machinery is located onto a ground support, is located in the opening at the Lauttasaari side. From the gate to the Salmisaari side bank, the bridge construction is of continuous composite beam. The 6-box cross section (Figure 2) is formed by a steel concrete cover, and 7 longitudinal main girders and a continuous base plate which are of steel.

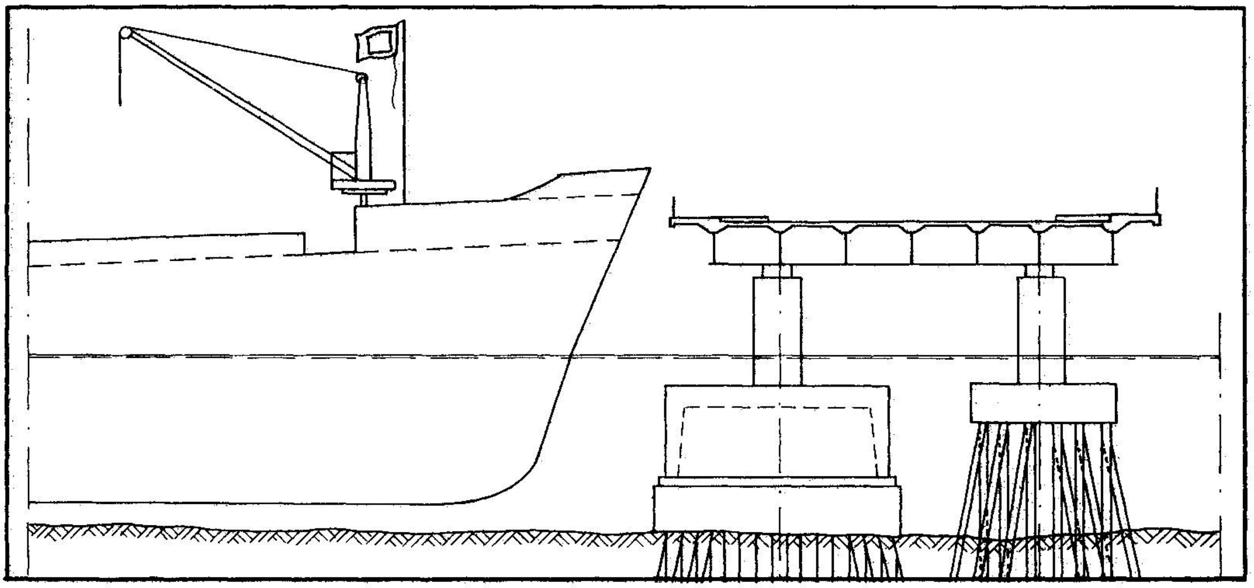


Figure 2. Bridge cross-section and the bow of a coal-carrying ship.

1.4 Aim of the Study

On the basis of preliminary research, it was decided to study a collision that would take place onto the stationary part of the bridge, in the area of the first span when counting from the gate opening (Figure 3). The ship's speed was set to the 6 knots required from point of view of manoeuvrability, and the load of the ship was set to the normal coal cargo amount, 12000 tons.

The aim was to find out the extensiveness of the damages to the bridge in a collision, the probable ways of breaking, as well as whether the damages and the risks to the vehicles could be minimized by, for example, traffic arrangements, protective structures or by stenghtening the bridge.

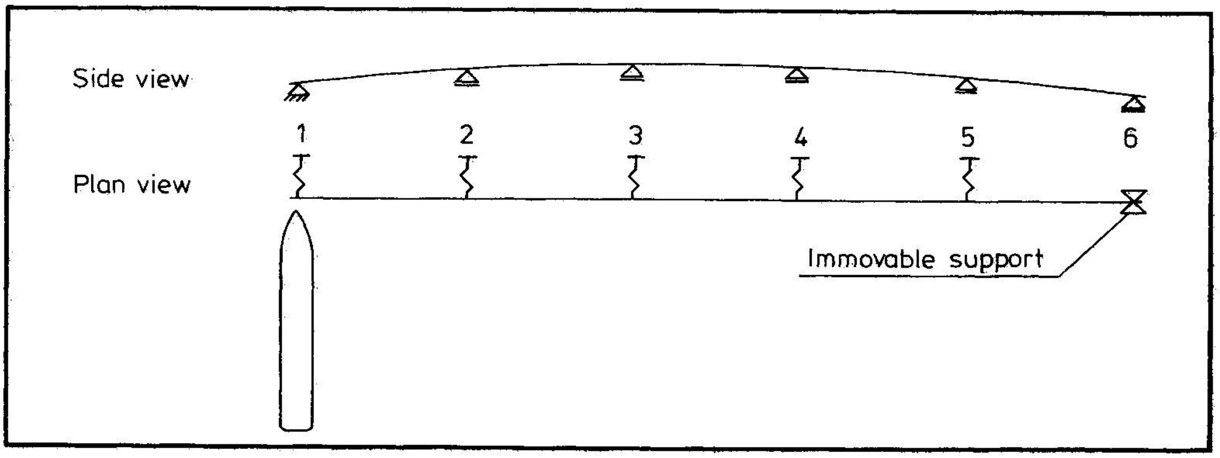


Figure 3. Construction model in a collision.

2. CALCULATION

2.1 General

In a collision, the ship and the bridge together form a system in which the ship pushes the bridge in front of it by its kinetic energy. The bridge's mass inertia and the supports, via the cover structure, counteract this motion. As the aim was to obtain a rough idea of the stresses imposed on the bridge in a collision, it was decided to use a system of two mass points. One of the masses would describe the ship, the other the bridge.

The connection between the two mass points was solved by using the Minorsky formula. This formula is well known in analysis of collisions between ships and is considered creditable owing to its straightforwardness. Its applicability has also been established in several collisions between ships (1, 2).

The connection of the bridge describing mass to its environment was described by a spring which contains the droop of the supports and the cover structure. The calculation of the spring constant was accomplished by a computer.

2.2 Components of the Model

2.2.1 Mass describing the ship (m_1)

The mass of the ship is ca. 5000 t and the weight of the load ca. 12000 t. As the vessel is moving in the direction of its longitudinal axis, the influence of the water moving with it corresponds to an increase of ca. 10% to the ship's mass. Thus, a numeric value of 18700 t was obtained for the mass m_1.

2.2.2 Mass describing the bridge (m_2)

The mass of the bridge was calculated to be 24.4 t/m. In the model, the bridge is described by a mass whose moment of inertia is the same as the moment of mass inertia of the cover structure. In this case, a value of 2330 t was calculated for the mass m_2 describing the bridge with respect to the eastern ground support which was supposed to be immovable.

2.2.3 Connection between the masses

The Minorsky formula describes the energy consumed in a collision into deformation of the structures. Converted into SI-units, it can be presented in the form:

$$E = 32.37 + 47.09\, R_T \qquad (1)$$

where E is the energy consumed (MNm) and R_T the amount of deformed steel (m^3).

The amount of steel of the bridge's cover structure is 0.091 m^3/m^2. As the bow of the ship is considerably sturdier than the 10...16 mm thick plate constructions of the bridge, it was supposed that deformation concentrate entire on the bridge. As, moreover, the ship's bow was simplified into a shape of a triangle (Figure 4), the following expression was obtained for the energy consumed in a deformation of the cover:

$$E(x) = 2.74\, x^2 + 32.37 \qquad (2)$$

where x is the penetration of the ship's bow into the bridge cover (m).

By derivation, the following expression is obtained for the force of contact:

$$P(x) = dE(x)/dx = 5.485\, x \qquad (3)$$

on the basis of which the studied connection can be described by a linear spring.

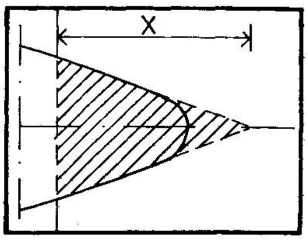


Figure 4.

2.2.4 Rigidity of the bridge

The bridge's rigidity characteristics were studied by using a grate model. In the model, each span was divided into four parts of equal length. The elasticity of the base structure was also taken into consideration. The most important parameters describing the bridge are:

- Moment of inertia of the cover construction with respect to the vertical axis $J_Y = 68.06\ m^4$
- Moment of torsional inertia $J_T = 2.47\ m^4$
- Moment of warping inertia $J_W = 26.34\ m^6$
- Rigidities of the supports in the ship's direction of motion varied between 123...182 MN/m

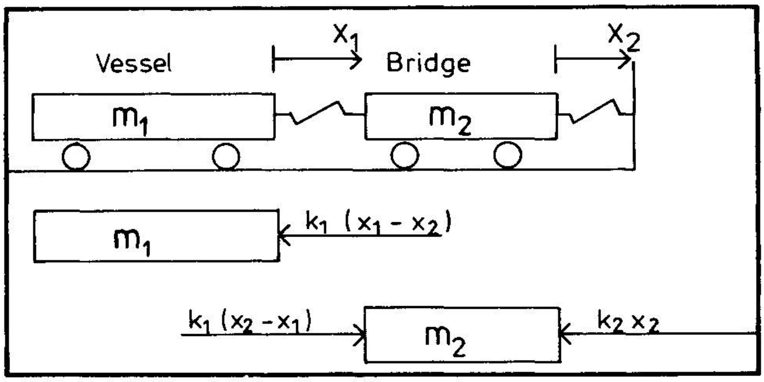
At the selected collision point, the rigidity of the bridge was: $k_2 = 143.8$ MN/m

As the calculation proceeded, it was established that the bearings of the bridge would seize as a result of a collision. For this reason, it was necessary to recalculate the rigidity of the bridge every time the displacement exceeded the displacement corresponding to the support's ultimate load.

There are two types of the bearings. The calculated seizing capacity of a stationary bearing is 1.13 MN and that of a roller bearing 0.61 MN. The capacity of a column with respect to a horizontal force at the bearing level is 3.1 MN.

2.3 Equations of Motion

Figure 5.
Masses and their connections



By means of the connections presented in Figure 5, the following equations of equilibrium are obtained:

$$\begin{cases} m_1\ddot{x}_1 + k_1(x_1-x_2) = 0 \\ m_2\ddot{x}_2 + k_1(x_2-x_1) + k_2x_2 = 0 \end{cases} \qquad (4)$$

These equations can be presented in the form:

$$\ddot{X} + KX = 0 \qquad (5)$$

When the friction forces F_μ , affecting at broken supports, are included into the model, the group of equations gets a form:

$$\ddot{X} + KX = F, \text{ where } F = \begin{bmatrix} 0 \\ F_\mu / m_2 \end{bmatrix} \qquad (6)$$

By transforming K into diagonal matrix, we get:

$$\ddot{\Psi} + \Lambda\Psi = C \qquad (7)$$

where:

$$\Psi = T^{-1}X \tag{8}$$

$$\Lambda = T^{-1}K\,T = \begin{bmatrix} \lambda_1 & 0 \\ 0 & \lambda_2 \end{bmatrix} \tag{9}$$

and

$$C = T^{-1}F \tag{10}$$

The solution of the group of equations (6) is:

$$\begin{aligned} \xi_i &= A_i \sin\omega_i t + B_i \cos\omega_i t + c_i/\omega_i^2 \\ \dot{\xi}_i &= \omega_i A_i \cos\omega_i t - \omega_i B_i \sin\omega_i t \\ \ddot{\xi}_i &= -\omega_i^2 A_i \sin\omega_i t - \omega_i^2 B_i \cos\omega_i t \end{aligned} \tag{11}$$

The factors Ai and Bi are obtained from the group of equations:

$$\begin{bmatrix} \sin\omega_i t_o & \cos\omega_i t_o \\ \omega_i \cos\omega_i t_o & -\omega_i \sin\omega_i t_o \end{bmatrix} \begin{bmatrix} A_i \\ B_i \end{bmatrix} = T^{-1} \begin{bmatrix} x_i(t_o) \\ \dot{x}_i(t_o) \end{bmatrix} - \begin{bmatrix} c_i(t_o)/\omega_i^2(t_o) \\ 0 \end{bmatrix} \tag{12}$$

When the $x_i(t_o)$ and $\dot{x}_i(t_o)$ are known.

2.4 Solution

The solution was calculated by proceeding in time in steps of 0.2 s, until the displacement of the mass x_2 describing the bridge, exceeded the precalculated displacement corresponding to the ultimate load of one of the supports. After the support had broken, a new rigidity value k_2 was used in the model as well as the friction force affecting the broken support. Calculation was proceeded with these values until the displacement corresponding to the breaking of the next support was achieved, etc.

In total, 4 phases (j) were calculated, during which the lateral rigidity of the bridge changed as is shown in Table 1.

The solution is presented in Figure 6. The contact force between the bridge and the ship developed as is shown in Figure 7. The ship's kinetic energy was divided onto the various components of the model as is shown in Table 2. The stresses imposed on the bridge were studied by means of the bridge's displacements. In the studies, the lateral displacement, the inertia forces and the changed position of the cover structure with respect to the seized supports, were taken into consideration. On the basis of the studies, it was found possible that the cover structure be not broken in a collision, but would move in front of the ship and finally collapse as a "rigid piece" after it has passed a certain critical position.

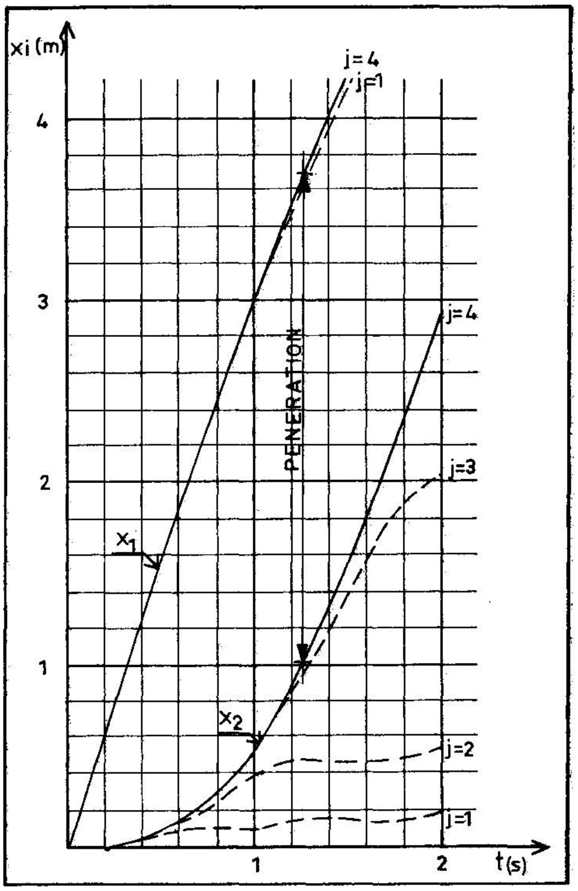


Figure 6. Solutions of the equations of motion

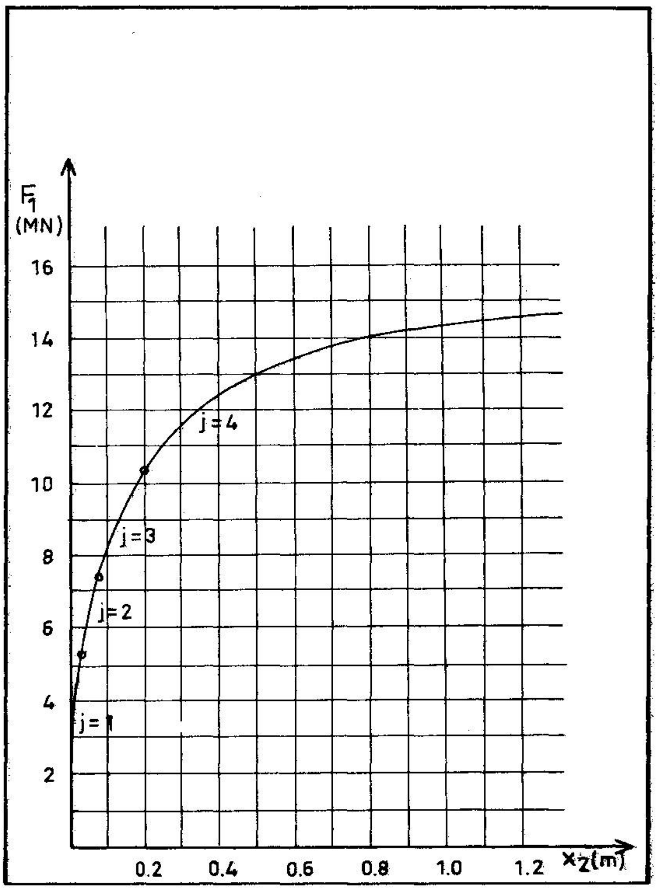


Figure 7. Curve of contact force - displacement

Table 1. Changes in the rigidity of the bridge as the supports are broken.

Phase	k_2	%	Notes
1	143.88	100	
2	34.53	24	as support 1 is broken
3	9.55	7	as support 2 is broken
4	3.97	3	as support 3 is broken

Table 2. Division of energy as a function of time

t	E_1	E_2	E_3	E_4	E_5	E_{tot}
0	89.04	0	0	0	0	89.04
0.335	86.18	0.05	2.72	0.07	0	89.02
0.465	83.70	0.17	5.00	0.14	0.05	89.06
0.700	77.50	0.73	9.96	0.32	0.55	89.06
1.000	67.51	2.50	15.90	0.81	2.33	89.05

E_1 = ship's kinetic energy
E_2 = bridge's kinetic energy
E_3 = work performed at contact point
E_4 = bridge's elastic deformation work
E_5 = work performed by friction forces

3. POSSIBLE MEASURES ON THE BASIS OF THE STUDY

3.1 Prohibiting collisions

In the studied case, the ship is being assisted by two tugs as it is sailed through the bridge opening. A more effective, but also more expensive way than the tugs to prevent collisions would be to use on the eastern side of the channel dolphins forming a sufficiently long guide-way. Depending on the bottom conditions, one possible solution could be application of protective ground structures on the eastern side of the channel. From the point of view of the ship, this solution is, however, obviously not as good as the use of dolphins. In the case we're discussing where the only risk of a collision is caused by the coal-carrying ships, transfer of the coal port onto the southern side of the bridge might be an applicable solution. If a suitable site could be found near enough, the coal could be transported to the power plant by means of a belt conveyor.

3.2 Traffic arrangements on the bridge

If we start by assuming that the probability of a collision cannot be sufficiently minimized, the risk to people can be decreased by prohibiting access to the bridge when a ship is approaching. In practice, this could be a accomplished by transferring the Salmisaari side barrier on a ground support. This arrangement is, however, difficult as due to the curved equalizing line of the bridge, the sight contact would be lost between the barrier and the bridge guard's cabin. Thus, using a barrier would make it necessary to employ eg. television equipment by means of which the bridge guard can check the situation at the barrier when making traffic arrangements.

3.3 Strengthening of the bridge

On the basis of the performed study, one can draw a conclusion that the bridge cannot be strengthened sufficietly to withstand a collision when the ship's speed is 6 knots and the ship's mass what was presumed in the study. By growing the seizing capacity of the bearings higher, to 3 MN, i.e. 4.4-fold of the original in average, the energy absorption of the support structures can be made ca. 19.5-fold.

3.4 Thoughts concerning bridge design

When considering design of new bridges, it can be noted that the lateral design loads are very small as compared with the forces created in ship collisions. As it is often necessary to design the groundwork of the bridges for ice loads, employment of stronger bearings could considerably increase the bridges capacity of carrying lateral loads. On the other hand, this would result in the damages spreading out to concern also the groundwork of the bridge in a collision. Factors affecting safety include, among others, straightness of the ship channel when approaching the bridge, spaciousness of the bridge openings, access of traffic to the bridge when a ship is approaching, effect of wind and water height on the ship, location of support and cover structures beyond the range of the ship, etc.

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