Proceedings of the 33rd European Safety and Reliability Conference (ESREL 2023)
Edited by Mário P. Brito, Terje Aven, Piero Baraldi, Marko Čepin and Enrico Zio
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doi: 10.3850/978-981-18-8071-1_P183-cd

Ship allision risk analysis for the 28-year-old Nordhordland bridge in Norway

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The Nordhordland bridge is a 1246 m long floating bridge in Norway, completed in 1994. Since its opening, the bridge has suffered two ship allisions leading to minor damage. With new and improved tools and knowledge about ship allision risk, ship impact analysis, and changes in maritime ship traffic, the original design requirements of the bridge are revisited to investigate if the structure meets the original and current design code requirements. A simplified frequency analysis for ship allisions against the bridge is performed based on past events as well as by using the software IWRAP to determine the design impact load for the bridge. Furthermore, a structural impact analysis is performed using the software LS-DYNA to investigate if the bridge can survive the previously determined impact load level. It is found that the pontoons are the weak spot when it comes to ship impacts and do not have sufficient capacity to meet today's requirements.

Keywords: Ship collision risk, ship allision risk, floating bridge, frequency analysis, impact analysis

1. Introduction

The Nordhordland bridge is a floating bridge located on the E39 Route on the west coast of Norway. Completed in 1994, it has an annual average daily traffic of roughly 17 000 cars according to the Norwegian Public Roads Administration (from now on NPRA) (NPRA 2023a) and can be viewed as critical infrastructure as the bridge connects the city of Bergen, Norway's second-largest city, with the municipalities north of the city as well as cities and counties further north along the coast.

During its 28 years of operation, the bridge has been subject to two ship allisions, fortunately with only limited, although permanent, damage to the structure. Due to this high observed frequency of ship impacts, there is reason to believe that the bridge, or at least parts of the bridge, might be exposed to a higher risk related to ship impact than what is considered acceptable today.

The objective of this paper is to investigate if the Nordhordland Floating Bridge meets the original as well as current design code requirements for brides in Norway related to ship allision risk. The study includes both simplified and more extensive frequency analysis for ship allisions as well as Finite Element Model (FEM)-analysis of ship impacts against a critical part of the bridge. This study is limited in its extent to general considerations for the bridge based on a limited number of models and analyses and could and should be expanded at a later point to give the full risk picture for the bridge related to ship allisions.

Ship allision risk related to bridges is, in general, a well-researched topic, (Xiao, Ma, and Wu 2022), and there are numerous studies into ship allision risk against bridges with fixed foundations (Pedersen et Al. 2020). However, relatively little research has gone into the specific topic of ship allision with floating bridges; at least this was the case before the development of the Coastal Highway Route E39 or "Ferry Free E39" by the NPRA started in 2010 (Askeland et al. 2021). Still, it is worth mentioning the Yumemai Bridge in Japan, where performing a ship impact analysis was an important design criterion due to the proximity of all vessels passing into and out of the port of Osaka (Maruyama and Kawamura 2000).

One important difference between ship allision risk to ordinary bridges and floating bridges is the consequences a ship impact can have on the structure. The sinking of the western half of The Hood Canal Bridge in 1979 and an 850m long section of The Lacey V. Murrow Memorial Bridge in 1990 shows that floating bridges might be prone to progressive collapse, meaning that when one pontoon sinks, it drags the next one down with it (Harik et al. 1990). For ordinary bridges with fixed foundations, it is possible to design the bridge in such a way that, if a foundation fails it will not lead to a progressive collapse, which was demonstrated when the General Rafael Urdaneta Bridge was hit by supertanker Esso Maracaibo and only a 340m section of the 8.7km long bridge collapsed (Sarcos-Portillo and García-Legl, 2002). This will, however, vary from bridge type to bridge type. While not the same design as the above-mentioned floating bridges sunk in the USA, the Nordhordland bridge has not been designed for the loss of one or more pontoons, so it is uncertain how it will behave in such a scenario.

Another factor that affects the risk of ship allisions against floating bridges is that most types of floating bridges have relatively low clearances and thus obstruct much of the crossing to ship traffic, increasing the probability of ship impacts.

A third factor is that floating bridges are often chosen over conventional bridges when there is significant water depth and/or challenging soil conditions at the crossing site, making it difficult or even impossible to introduce sacrificial structures as is done for the Incheon Bridge in South Korea (Cho 2020), or protecting the foundations with sand banks like for the Great Belt bridge in Denmark (Storebæltforbindelsen 1998).

To the authors' knowledge, there are 13 floating bridges around the world open for ordinary traffic today with a minimum of two lanes. Among these bridges, the Nordhordland bridge is among those most exposed to the risk of ship allisions due to the location in a fjord, and the busy ship routes passing through it. The limited research that exists on ship allision risk related to floating bridges has focused on new bridges in the design phase (Askeland et. al. 2021). We have not been able to identify research on ship allision risk for existing floating bridges, where the focus would not be on finding a suitable design load for ship impact, but rather to determine the level of risk an existing floating bridge is exposed to and if this meets the requirements in current codes as well as in the original design basis.

Based on the above mentioned, this article will attempt to contribute to fill the research gap on ship allision risk analysis for existing bridges. Due to the short length of the paper only a limited scenario will be described and analysed in detail.

This paper is organised as follows. In Section 2, the design of the bridge is laid out as well as the design philosophy related to ship impact. In section 3, two frequency analyses of ship impact against the bridge are described including the methodology. In Section 4, possible scenarios with consequences of ship impacts are discussed. In Section 5, a finite element analysis of a ship impact against a pontoon is described. Section 7 consists of a discussion and conclusion.

2. Design of the bridge and design philosophy

2.1. *The design*

Unless otherwise specified, the specifications given in this chapter are taken from a technical brochure on the Nordhordland bridge project published by the NPRA (NPRA 1994). The Nordhordland Bridge has a total length of 1614m. It consists of two parts, a 1246m long floating part to the north, and a single tower cable-stayed bridge with a main span of 172m across the ship channel to the south. The two parts meet at an underwater foundation at Klauvaskallen on the southern part of the fjord. The floating part of the bridge consists of an orthotropic steel box girder which rests on 10 concrete pontoons spaced 113.25m apart, in addition to the shore abutment and the underwater foundation. The floating section has an arched configuration with a radius of 1700m in the horizontal plane to take horizontal forces and eliminate the need for moorings.

Fig. 1. The Nordhordland bridge as seen from south-southwest. The floating part can be seen as the white beam resting on the pontoons. (Photo: Helge Sunde)

The two parts of the bridge are not structurally dependent on each other. For this reason, the analysis focuses on the floating part of the bridge including the deepwater foundation as the cable-stayed bridge is not vulnerable to ship allisions in the same way.

All pontoons of the bridge are made of 310mm thick prestressed concrete with lightweight aggregate, strength LC55, and have the same 42.0m by 20.5m semicircle-shaped footprint at each end. They are subdivided into 9 cells and the height varies from 7.0m to 8.6m with the tallest pontoons being close to the abutments.

The bridge deck is an orthotropic box girder, with a width of 15.9m and a height of 5.5m. It is built using steel with 355MPa yield strength, apart from the section from the abutments to past the first pontoons, where steel with a yield strength of 540MPa is used. The distance from the underside of the box girder down to the water is 5.5m.

The deepwater foundation is placed on a subsea ridge called Klauvaskallen at a depth of 30m and has a footprint of 20m by 21m. At water level, a circular "shield" has been cast in concrete around the foundation with the purpose of reducing the probability of a direct hit from a vessel, as well as giving extra protection from ship impacts.

2.2. *Design philosophy*

The bridge was designed using the Norwegian standards NS 3472 for design of steel structures (Standard Norge, 1984) and NS 3474 for design of concrete structures (Standard Norge, 1973), together with a design basis developed by the NPRA for the project (NPRA 1990). There were no specific requirements for ship impact loads in the NS design code series, and the NPRA did not publish handbooks for design of bridges until 1995 (NPRA 1995) and 1996 (NPRA 1996). The specific requirements imposed on the bridge in the design basis are likely derived from offshore engineering practice regarding "unusual" loads, meaning loads with a 1% probability of occurrence during 100 years, also called "10 000-year loads" (Moe, 1997).

In NPRAs latest handbook for design of bridges, as well as earlier editions, the following sentence is found: *"accidental loads…with an annual probability lower than 10^{-4} can be disregarded"* (NPRA 2023b). This has been interpreted as a requirement that a bridge needs to be designed for the largest ship impact with a probability of 10^{-4} or higher. This is consistent with the practice in other countries comparable to Norway, for instance Denmark (Storebæltforbindelsen, 1998).

In the design basis for the bridge (NPRA 1990), the probability of 10^{-4} is mentioned specifically for ship impact, and it states further that a centrical impact load against a stiff structure could be estimated by the following formula:

$$F = 0.5 \times \sqrt{Wd} \qquad (1)$$

where F is the equivalent static impact load against a stiff structure in MN and Wd is the size of the design ship in DWT (dead weight tons).

The design basis (NPRA 1990) goes on to specify that for the abutment, presumably the deepwater foundation on Klauvaskallen, Wd could be set to 4 000 tons. The design basis also gives conversion rates from DWT to GT (gross tonnage), as GT = 1.5×DWT, and Displacement = 1.33×DWT.

Using the specified value of Wd = 4000tons gives an equivalent static load of F = 32MN. For ease of comparison with the frequency analysis, the energy of the design ship is calculated and used for this purpose. Assuming a speed of 10 knots = 5.14m/s, and mass m = 1.33×DWT and an added mass from the water of 20% (NPRA 2013), the kinetic energy is calculated to be E = 84MJ.

The design loads for ship impact to the pontoons are not stated in the design basis, but a design value is found in the structural analysis (NPRA 1992). Here it is found that two design ships are used for the pontoons and the bridge girder: A drifting vessel with a displacement of 4200 tons, and a smaller vessel with a displacement of 1250 tons, and a speed of 10 knots. The drifting vessel is disregarded in the further structural calculations as the kinetic energy is much lower compared to the smaller vessel at speed. The kinetic energy of the smallest vessel is E = 20MJ.

In the design calculations for the bridge,it is stated that the design energy from this vessel is 25MJ. The discrepancy is probably related to the value used for the added mass from the water where a value of 50% might have been used. For a sphere traveling through water, an added mass of 50% can be used (DNVGL 2019), but not for a ship traveling at speed. For a vessel steaming straight ahead 20% added mass is often used, like for the ship impact analysis for a floating bridge across the Sognefjord (NPRA 2013). However, based on the calculations in the design, it is for now assumed that the pontoons are designed for an impact load of 25MJ.

In the calculations, only the deepwater foundation and the next 5 pontoons are checked for ship impact. Still, all the pontoons were built almost the same and are symmetrically distributed from the middle of the bridge as described earlier, so it is assumed that the remaining 5 pontoons also are designed for a ship impact of 25MJ.

3. Frequency analysis for ship allisions against the bridge

To estimate the probability of ship impacts against the bridge, two methods will be used. The first method is a simplified method which estimates the frequency of ship impacts based on past events and ship traffic. The second method will use the software IWRAP (Friis-Hansen, 2008) by International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) (Čorić et al., 2021). The benefit of the second method is that it can estimate allision frequencies at a location without any previous incidents having occurred there, and the results will not be shaped by a possible unrepresentative limited sample size.

3.1. *Simplified method*

The two past incidents are important inputs to the first method. The incidents are described below, together with the most important data related to the vessels.

Table 1. Data regarding the two vessels alliding with the Nordhordland bridge. Information regarding the ships is given by the ships' owners (Sveholmen Management 2022; Peak Logistics 2016)

	Incident 1	Incident 2
Name of ship	MS Nyfjell	MV Framfjord
Date of incident	02.06.09	06.06.19
Type of ship	General cargo	General cargo
IMO nr.	7602584	8913473
MMSI	258221000	341392000
LOA	67.0m	80.0m
BOA	11.7m	10.9m
DWT	1700 tons	2300 tons
GT	1155tons	1508 tons
Speed	10 knots	9.5 knots
Possible impact energy	36MJ	42MJ

3.1.1. *Description of incident 1*

The vessel was traveling south-southwest towards the ship passage but did not make the minor adjustments necessary to clear the deep-water foundation, hitting the foundation on the east side.

Fig. 2. MS Nyfjell after the impact with the bridge (Photo: Inger Åse Skage)

The point of impact was not centred on the foundation, making it a glancing blow pushing the vessel back into the ship passage. It is believed that the impact has not resulted in permanent damage other than the spalling of concrete at the point of impact. A photo of the ship's bow after impact can be seen in Fig. 2.

3.1.2. *Description of incident 2*

The vessel was traveling south-southwest on Salhusfjorden towards the bridge but failed to make a turn at the last turning point, leading the vessel to hit the bridge between the deepwater foundation and the first pontoon. The bow of the vessel was not tall enough to hit the steel box girder. However, the excavator on the ship deck hit the bridge, causing the excavator to be pushed backwards until it hit the superstructure of the vessel. The bridge sustained damages to the steel box girder, but no repairs were needed before the bridge could re-open after inspection. It is however estimated that the damages have negatively impacted the remaining lifespan of the bridge. A photo of MS Framfjord right after impact with the bridge can be seen in fig 3.

Fig. 3. MS Framfjord after it hit the bridge (photo: Redningsskjøyten Kristian Gerhard Jebsen)

3.1.3. *Description of the method*

In both incidents, the impact energy may very well have exceeded the design value of the pontoon by a good margin if the vessels were traveling at 10 knots and 9.5 knots respectively. It is however also possible that the speed was less than the max speed, giving an impact energy closer to 25 MJ.

In the simplified frequency analysis, it is assumed that a vessel must hit the centre part of the pontoon to avoid a glancing blow and transfer enough of the kinetic energy to critically damage the pontoon. The width of the critical area is set to 10m per pontoon. This gives a critical length of the bridge of 100m (out of 1267m).

Further, it is assumed that all vessels with a length overall (LOA) > 100m will give a critical impact on a pontoon, keeping in mind that the two previous incidents involved vessels with LOA of 67m and 80m.

Table 2. Values relevant for the simplified frequency analysis:

Length of bridge	1267m (including deepwater foundation)
Critical length of the bridge	100m (10m pr pontoon)
Number of impacts by ships<100m LOA	2
Years in service	28 years
Average annual frequency of ship impact (1994-2023)	7.1×10^{-2}
Annual frequency of ships<100m LOA	5922
Annual frequency of ships>100m LOA	688

It is assumed that ships out of control can hit randomly along the bridge. We start by finding an estimate P_A* of the probability of a ship allision P_A from a ship with LOA < 100m against the critical area of a pontoon, simply by dividing the number of hits with years in operation and multiplying this with the ratio between the critical length and the total length:

$$P_A^* = \frac{number\ of\ impacts}{years\ in\ service} \times \frac{critical\ len}{total\ lengt} \tag{2}$$

Using the number of impacts from ships < 100m LOA and other values in Table 2 gives an estimate $P_{A,\ LOA<100m}$* = 5.6×10^{-3}. We continue to estimate the probability of ship impact from ships with LOA > 100m by multiplying the probability found above with the ratio between vessels over 100m length, and under 100 m length:

$$P^*_{A,LOA>100m} = P^*_{A,LOA<100m} \times \frac{\sum ships\ LOA>100m}{\sum ships\ LOA>100m} \tag{3}$$

Again using the values in Table 2, this gives a $P_{A,LOA>100m}* = 6.5\times10^{-4}$. This probability is more than six times greater than the requirements in the code. Although this is just a simplified estimate, it still gives an indication that the bridge may be subjected to more ship impacts in the coming years.

3.2. *Frequency analysis using IWRAP*

For the second method, the software IWRAP MK2 is used to calculate the probabilities of ship impacts along different parts of the bridge (Friis-Hansen 2008). This is a very commonly used software for calculating probabilities of ship collisions and ship groundings (Čorić et al., 2021) and is recommended by the International Maritime Organization (IMO) for performing quantitative risk assessments (IMO 2010). The theory the software is based on the Pedersen method (Pedersen 1995), wich in turn is based on works by Fujii (Fujii et al. 1974). The theoretical background has not changed since the Nordhordland bridge was designed, but greater computational power has since made it easier to do more extensive analyses of the problems today compared to what was possible earlier.

The analysis used 2 years of AIS data, from 2021 and 2022, retrieved from the Norwegian Coastal Authorities. This analysis has the benefit of using data from the ship traffic after the bridge was built. A heatmap plot of the AIS data can be seen in Figure 4. Legs for ship traffic is manually created along the ship routes, and the software creates a distribution of the ship traffic in both direction along the given leg, as can be seen in Figure 5.

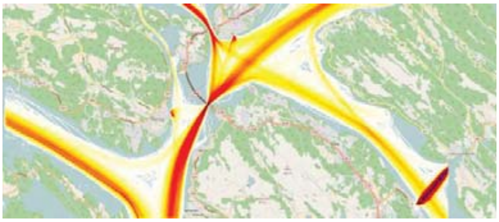

Figure 4: Heatmap of AIS track of the ship traffic in the area for 2021 and 2022 in IWRAP.

The bridge is modelled as it stands today, with 10 pontoons and one deepwater foundation, and a steel girder 5.5 m above sea level. Default causation factors are used as recommended by IALA. A plot of the modelled bridge and the modelled traffic legs together with the relative probability of ship impacts for different parts of the bridge can be seen in Figure 5. Here it can be seen that the bridge girder and the pontoons closest to the ship passage are most exposed to ship impacts.

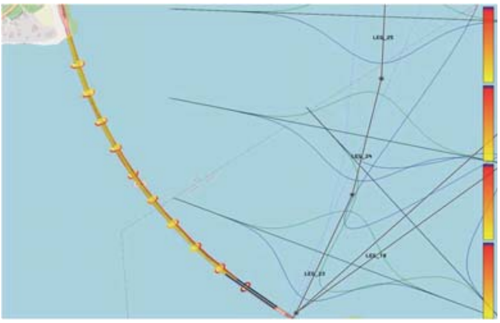

Figure 5: Illustration of the model of the bridge and some of the ship traffic legs, together with relative intensity plot of impact frequencies in IWRAP

The model estimates the annual probability of ship allision for the entire bridge to be 3.4×10^{-1}. This is five times the annual frequency of ship allisions to the bridge so far. The probability of ship allisions to the pontoons for ships with LOA > 100m is estimated to be 1.6×10^{-3}, but this is for the entire pontoon, not taking into consideration that many allisions will end in glancing blows. Using the same approach as in the simplified method for a critical length of the pontoons of 10m, roughly half the pontoon, the estimated probability of ship allisions to the pontoons from ships with LOA > 100m is 8.1×10^{-4}. This is a mere 25% more than the estimate made using the simplified method.

Both analyses estimate that the probability of a ship allision against a pontoon with an impact energy above 25MJ is much higher than the requirements in the design basis (NPRA 1990) and the requirements in the handbook today (NPRA 2023).

4. Scenarios for the damages inflicted by ship impact

There are several different scenarios that are possible based on the damages a ship might inflict. A large enough ship could topple over the deepwater foundation, or even severely damage the steel box girder or shear of the connections between the girder and the foundations. However, previous research shows that this would require a significantly higher collision energy (Sha 2019). The most vulnerable parts of the bridge as it stands today are the pontoons, even if they only make up less than 20% of the length of the bridge. The bridge is not designed for an incident where more than two cells in a pontoon are filled with water. For this reason, an impact analysis is needed to study the consequences of a 25 MJ ship impact against a pontoon.

5. Ship impact analysis for the pontoons

This type of extensive FEM-analysis was not possible at the time when the Nordhordland Bridge was designed, so a detailed FEM-analysis is warranted. The software package LS-DYNA (LST 2021) is used to perform the ship-pontoon collision simulation in this study. The numerical model of the pontoon is developed based on the design drawing. To save computational efforts, only half of the pontoon is modelled in detail. The pontoon model is considered sufficient as the rear part of the pontoon is not expected to be impacted by the ship in a head-on collision scenario. The pontoon walls are constructed of LC55 lightweight concrete with two layers of internal reinforcements. Detailed modelling was applied to both concrete and reinforcements.

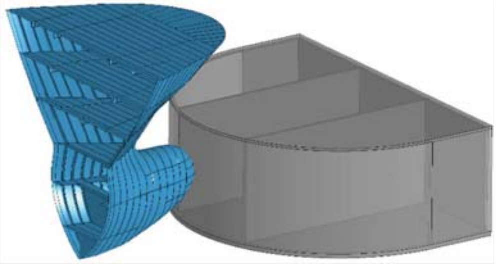

Figure 6: Illustration of the finite element model used in LS-DYNA

A typical service vessel bow is modelled as the striking ship. It has a similar design as the two ships that allided with the Nordhordland bridge. In the simulation, the 2000-ton ship hit the pontoon at a speed of 5m/s which gives an impact energy of 25MJ. No added mass is considered in the simulation. The numerical model setup is shown in Figure 6.

Figure 7 shows that the pontoon wall is not able to sustain the impact from the ship bow. Local punching shear damage occurs in the region where the ship bulb contacts the pontoon wall. Large strains can also be observed in the perimeter of the impacted pontoon compartment. In the simulation, only 3.5MJ of the collision energy is dissipated through the structural damage of the pontoon wall. The ship still has a significant remaining kinetic energy and will thus continue to crush into the pontoon wall. As the breadth of the ship is in the similar range of the pontoon compartment width, further penetration into the pontoon will inevitably cause structural damage in the two adjacent pontoon compartments. Based on the simulation results, it is found that the current pontoon design is not able to resist the head-on impact of a service vessel with an impact energy of 25MJ. The damage in the pontoon can lead to the flooding of up to three compartments and consequently will lead to significant damage, even to the collapse of the bridge.

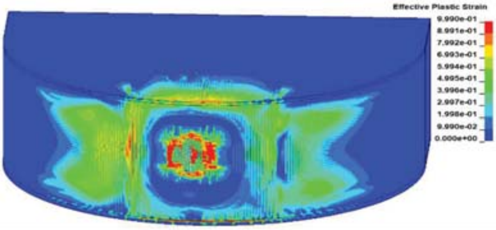

Figure 7: Illustration of strains in the pontoon at 3.5MJ

6. Discussion and conclusion

As seen from both frequency analysis, it is clear that the bridge in its current condition is in breach of the original design criteria based on the assumption of the pontoons being able to withstand a 25MJ impact energy.

The simplified method based on past events proved to be a good first approximatino when compared to the results from the analysis done in IWRAP, indicating it might be a useful method for quick estimates, but further studies are needed to conclude on this.

With the additional information from the impact analysis against the pontoon where it is clear that the pontoons would not survive an impact of 25MJ, it is clear that the gap between the requirements and the actual performance of the bridge is even bigger than first assumed. It must also be assumed that the bridge will be subject to more ship allisions over the remaining service life if nothing is done to reduce the probability of ship allisions.

To prevent catastrophic consequences to the bridge and to meet current requirements, pontoon retrofitting and/or other risk reduction measures are deemed necessary. Further studies are required to ensure the safetylevel of the bridge.

In Norway, it is not mandatory to update risk analysis for existing bridges, unlike for tunnels, where a change in the risk picture could require an upgrade of the existing tunnel or initiation of mitigating measures. When reflecting on the different approaches to risk for bridges and tunnels, this study indicates that existing bridges do not get the attention required.

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