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Ice Loads on the Confederation Bridge Piers

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ABSTRACT

The Confederation Bridge is a multi-span bridge which acts as a "fixed link" between New Brunswick and Prince Edward Island, Canada. The bridge opened in 1997 and cost approximately one billion dollars to construct. The Confederation Bridge is 12.9 kilometers long and sits approximately 40 meters above the water, with the exception of one section of the bridge that rises to approximately 60 meters to permit ship traffic to pass beneath it. The bridge is mostly comprised of high strength concrete and reinforcing steel, and rests on 44 piers that sit at a maximum depth of 35 meters of water.

The bridge crosses the Atlantic Ocean over a stretch of water known as the Northumberland Strait. This particular body of water is well known for the amount of ice that forms on the channel from January to late April of each year, with ice pans measuring up to four kilometers in diameter and one meter thick. Therefore, the piers needed to be designed so that the forces created by the moving ice would not cause the piers to fail, and cause a catastrophic collapse of the bridge structure. However, such a design has never been done before; therefore no design data was available.

The following paper will highlight a comparison of the method used to predict the annual ice loads on the bridge piers versus the actual loads generated from the ice as measured by equipment in the piers.

1 INTRODUCTION

The Confederation Bridge is one of the world's longest pre-stressed concrete box girder bridges, and is located between Borden-Carleton, Prince Edward Island and Cape Jourimain, New Brunswick (Figure 1). The thirteen kilometer long "fixed link" is one of Canada's top engineering achievements in the twentieth century (and arguably of all time). The project was not only renowned for its immense size, but also for its unique location and design requirements.

Figure 1: The Confederation Bridge. Figure retrieved from http://www.cbc.ca/sevenwonders/wonder_confederation_bridge.html

The Confederation Bridge crosses the Northumberland Strait, a portion of the Atlantic Ocean between Prince Edward Island and mainland Canada that can be described as a harsh environment at the best of times (Figure 2). This is because during four to five months of the year (January to April/May), this particular body of water is subject to thick and dangerous amounts of ice. As much as 1000 kilometers of ice can pass through the Strait per month during these winter months, and approximately 75% of this ice will impact the bridge pier from both the upstream and downstream side due to its extremely dynamic motion from strong wind and current forces. First-year ridge ice in this area has been measured up to as much as four kilometers wide, and can have a consolidated ice level thickness of up to three meters thick and a keel depth of up to sixteen meters (Figure 3). This information is important because the piers of the bridge stand in the direct path of the moving ice, which causes a significant amount of force on these piers.

Figure 2: Google Earth image of Confederation Bridge. Figure retrieved from Google Earth.

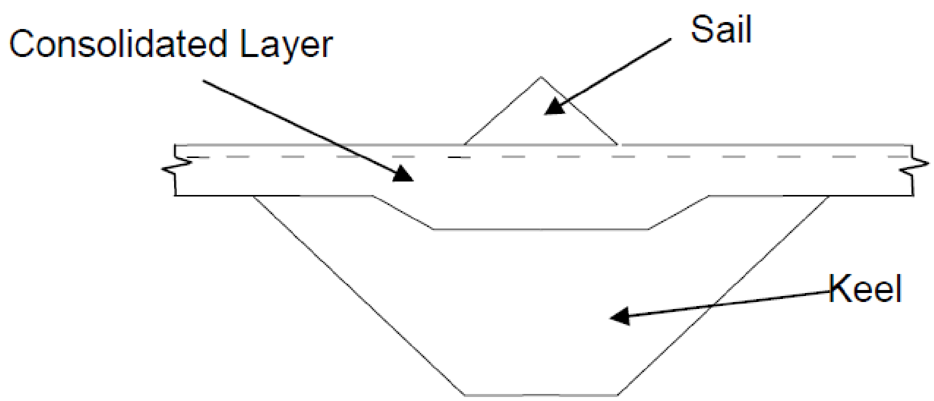

Figure 3: Typical Cross Section of First Year Ice Floe. Figure retrieved from [1].

Therefore, the piers had to be designed to withstand forces created by this ice, along with the usual environmental and traffic loads in which bridges are usually designed. However such difficult conditions, in relation to ice, had never before been used in design, therefore no design ice load data existed. It was obvious to the engineers that the Confederation Bridge pier design would be the first of its kind and it was going to be governed by this harsh environmental loading condition. Therefore, design data had to be developed using a probabilistic approach.

2 PROBABALISTIC APPROACH TO OBTAIN DESIGN ICE LOADS

The probabilistic analysis for the Confederation Bridge was developed in conjunction by three parties:

- Stanley-JMI Joint Venture, CODA/C-Core
- Buckland and Taylor, Canatec
- Public Works and Government Services Canada.

The probabilistic approach undertaken by this group was very extensive and complex, and required a lot of assumptions and two different modelling approaches. Description of the specific details and formulas of this analysis is not the purpose of this paper and therefore will not be discussed. However further information on this matter can be found in reference [1].

The group responsible for the probabilistic approach developed a simulation procedure for determining the ice load in any given year and is listed in Figure 4 below.

Fig. 2. Simulation procedure.

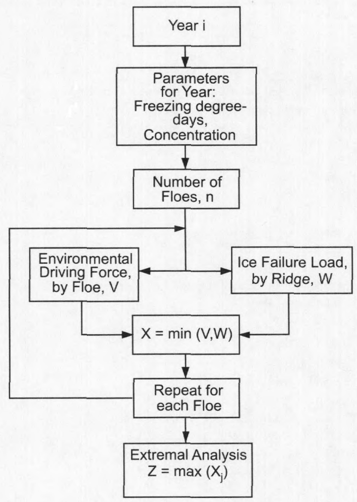

Figure 4: Simulation Procedure. Figure retrieved from [2].

The simulation was run for 1000 years, with the values of freezing degree-days and concentration from Summerside, Prince Edward Island for each month under consideration. The values of freezing degree-days used for the simulation were obtained from Summerside Airport from 1954 to 1989. Each floe had a limiting design load that would be used as the governing load on the pier and was equal to the lesser of two options: the environmental driving force (the load generated by ice momentum, wind, current, etc) and the ice failure load (the load required to buckle, crush, or split the ridges of the ice floe). The variables required for each load is listed in Figure 5 below.

Table 1. Modelling of random quantities.

Parameters	Quantities	Values
Ice failure model		
Floe concentration	Random	Normal, depending on month
Ice floe thickness	Random	Gamma, depending on month, modified for annual conditions
Ridge core thickness	Random	Normal, derived from thermodynamic modelling
Flexural strength	Random	Normal, depending on brine volume
Young's modulus	Constant	3400 MPa
Ice density	Constant	0.91 kg/m^3
Ice–structure friction	Random	Uniform, 0.10–0.30
Rubble height	Random	Uniform, 0 to maximum, based on stability
Rubble angle of repose	Constant	45°
Rubble porosity	Constant	0.3
Rubble internal friction angle	Constant	45°
Rubble cohesion	Constant	5 kPa
Ice–ice friction	Constant	0.1
Ridge keel depth	Random	Exponential, 1–15 m, transition to 20 m
Ridge keel width	Random	Based on keel depth
Ridge keel cohesion	Random	0–6 kPa
Environmental driving force model		
Floe diameter	Random	Gamma, after Bayes' theorem
Wind velocity	Random	Lognormal, by quadrant
Current velocity	Random	Lognormal, truncated at 2.0 m/s
Pack ice force	Random	Exponential, minimum 0.1 MN/m
Fetch	Random	Gamma, based on ice concentration
Air drag coefficient	Random	Uniform, 0.001–0.003
Water drag coefficient	Random	Uniform, 0.005–0.03
Density of air	Constant	0.13 kN/m^3
Density of water	Constant	10.06 kN/m^3

Figure 5: Variables considered in Ice Failure loading and Environmental Driving Force loading. Figure retrieved from [2].

The probabilistic approach has a high degree of complexity and variability due to the number of variables present in the analysis.

The exact relationship between these variables was not well understood at the time of the design phase. Because of this it would have been unrealistic to consider that the extreme value of all the variables combined together would create the most extreme design load, as is the case in similar design situations in which only a few variables are required. It was assumed that while all variables may not have a significant influence on the load on the bridge pier, they all will be present. Therefore, there was much debate about which variables would play the most significant role in the lateral force on the piers generated by the ice.

Since it is possible for the piers to encounter many ice floes of various properties during the year, this process had to be repeated until all combinations of properties had been exhausted for each year. At the end of the analysis for a single year the highest load calculated was the design load.

Ultimately, the analysis revealed that the bridge piers were to be designed for a 24 mega-Newton (hereafter referred to as MN) extreme load for a 10,000 year design life, a 16MN extreme ice load for a 100 year design life, and an annual maximum of 8MN. This paper will compare the annual load of 8MN on the piers only.

3 MEASURED ANNUAL ICE LOADS ON THE CONFEDERATION BRIDGE

Before opening in May 1997, the Confederation Bridge was equipped with state-of-the-art monitoring equipment, used to measure the actual impact of the ice against the piers. The main data collection mechanism for ice impacts are tilt-meters, located on piers 31 and 32, which are approximately five kilometers from the New Brunswick shore. These tilt-meters are located in the piers at 3.2 meters and 24.56 meters above mean sea level and measure the frequency of the pier as the ice impacts it (Figure 6).

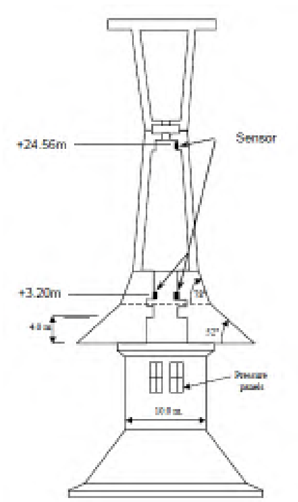

Figure 6: Typical Cross section of pier with tilt-meter locations. Figure retrieved from [2].

As the ice impacts the bridge piers, it pushes on the tilt-meters and rides up the ice shield. This causes the tilt meter to tip and subsequently causes a change in conductivity in the mechanism, which is then converted into a frequency. Using a series of calibrations, this frequency is then converted into a force.

The maximum annual ice loads measured in piers 31 and 32 from 1998-2008 are listed below in Table 1. Load measurements for 2009 onwards could not be obtained at the time of this paper.

Table 1: Annual Measured Ice Loads on Piers 31 and 32.

YEAR	LOAD (MN)
1998	3.8
1999	4.5
2000	3.5
2001	3.1
2002	2.4
2003	6.7**
2004	3.4
2005	3.0
2006	1.8
2007	3.5
2008	6.1**

*** Denotes abnormal values, possibly due to unusually low temperatures. This caused more extreme icing conditions. Table and note retrieved from reference [3].*

4 DISCUSSION

The majority of the values from the tilt-meters are significantly lower than the estimated annual design load from the probabilistic analysis. However, during the years with "abnormal values", the annual loads are much closer to the design load for the piers. This indicates that the probabilistic approach was an appropriate method for predicting the ice loads as ice and air density were two of the variables in the analysis, and the abnormal values were assumed to be caused by the lower than usual temperatures which causes changes in these densities. Because of this, it is not unreasonable to believe that the annual design load could be surpassed one day if there is another abnormal condition more extreme than in 2003 or 2008. Since the bridge is capable of withstanding a 24MN load (10,000 year load), the bridge is in no danger of collapsing if it does exceed the 8MN annual load.

Based upon the data from the tilt meters on piers 31 and 32 in Table 1, the accuracy of the annual measured ice loads for this time period to predicted annual loads for the highest load is:

$$\frac{Highest Annual Load}{Annual Predicted Ice Load} = \frac{6.7MN}{8MN} = 0.8375 \approx 84\%$$

5 CONCLUSION

Simply put, the Confederation Bridge is an engineering marvel. When the Confederation Bridge was being designed, ice load data for such an extreme ice environment was not available. Therefore, an analysis using probabilistic functions and expressions was used to determine peak design ice loads for annual and extreme conditions. This approach was very complex and required a great deal of engineering judgment to account for the many variables that it required. From the available data, the maximum annual load from the ice that has been measured on the piers is approximately 84% of that of its annual design load.

The approach to obtaining design loads using a probabilistic methodology was an appropriate and accurate method. This process, along with the ice load measurements being obtained from the data collection devices on the Confederation Bridge piers, will go a long way to helping future structural offshore designs in icy waters.

6 REFERENCES

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