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Performance of the Lake Erie Ice Boom, Eight Years After Major Design Modifications in 1997

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Since 1964, NYPA and Ontario Hydro (OH) install the 2,700-meter Lake Erie Upper Niagara River Ice Boom (LENRIB) every winter near the entrance to the upper Niagara River prior to ice formation on Lake Erie. The purpose of LENRIB is to promote the formation of a stable ice cover on Lake Erie near the entrance of the Niagara River. It significantly reduces the volume of ice entering the Niagara River and reduces the potential for ice jamming downstream. The ice boom was originally designed for fabrication from Douglas Fir timber (Figure 1) that was replaced in the fall of 1997 with cylindrical steel pontoons. The boom was designed to restrict, but not necessarily eliminate completely, the movement of broken lake ice into the Niagara River. The new design developed in 1997 increased the resistance of the boom by at least three fold while maintaining the maximum resistance at 40% of the span and anchor cables resistance capacity. One major event occurred on February 4th, 2003, where one anchor cable broke and precipitated the failure of 13 adjacent span cables. The analysis showed that the average wind during the event was at 49 km/hr, which constituted a 1-in-37-years event. To prevent such an event from occurring again, the NYPA started to monitor the Freezing Degree-Days (FDD) and break the ice that surrounds the boom using the icebreaker as soon as this value reaches 200 FDD. This recommendation was started during the winter season of 2004/05.

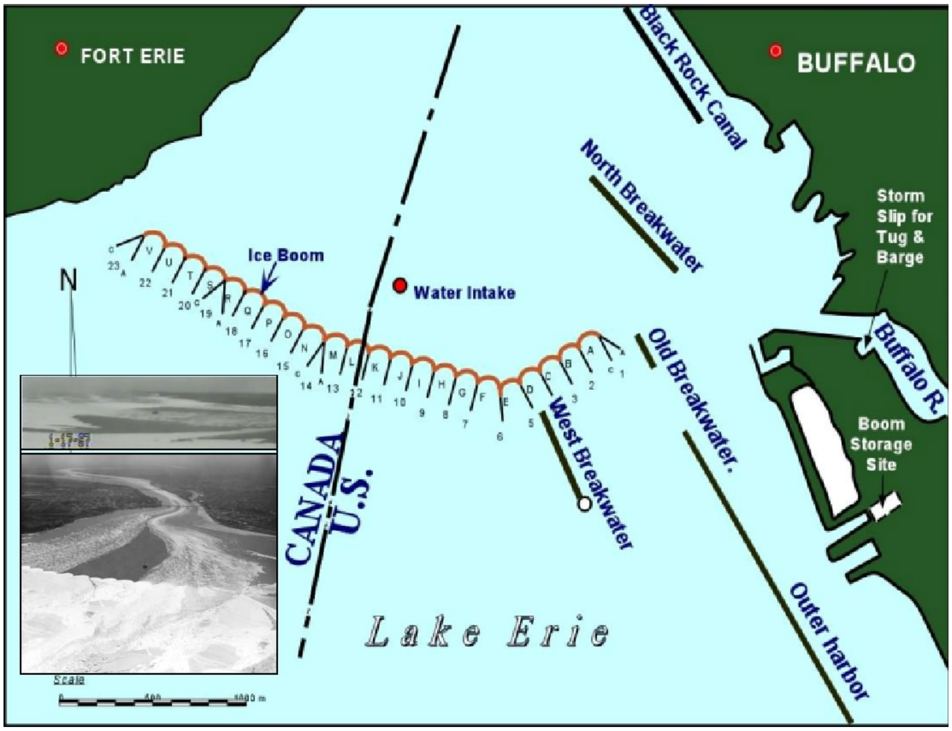


Figure 1: Location and Arrangement of Lake Erie-Niagara River Ice Boom
(Inserts show January 1997 prototype test, Steel and Timber Pontoons, Steel in center retain the ice)

1. Design Modifications in 1997

An investigation into new alternatives to the boom and its configuration started in 1993 (Abdelnour et al, 1994). It included an evaluation of the performance of LENRIB, and the determination of modifications to potentially enhance the performance of the boom. The new design consisted of replacing the 13 Douglas fir timbers pontoons per section with 10 (A to L) and 11 (M to V) Steel ones. The steel pontoons were 0.762 m diameter and 9.1 m long. The results obtained from two field data collection programs in 1994 and 1997 (Figures 1, 2 and 3), during which ice overtopping events occurred, showed that the resistance capacity of the boom increased significantly during the freeze-up period, from about 2 to 9 kN/m, while its resistance during the winter, when the ice was already formed, was not affected and averaged about 9 kN/m.

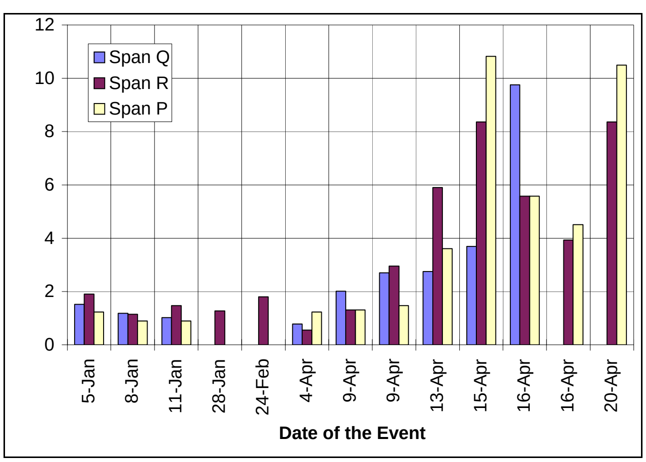


Figure 2: Line Load during 1994 Ice Run Even (Timber)

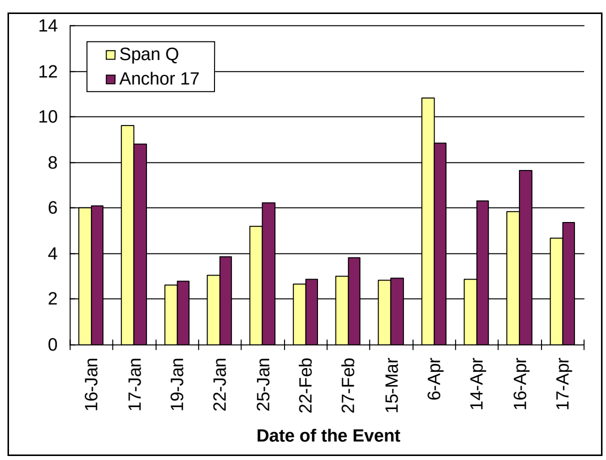


Figure 3: Line Load during 1997 Ice Run Even (Steel)

2. Recent Events, Post 1997

Since 1997, the operations of the hydro-plants located on the Upper Niagara River were not affected by ice. During the 1997 to 2005 period, the boom retained the ice despite recording higher wind events which had been the reason for many of the events recorded during the period between 1963 and 1996. One example of an event was recorded on a Web cam during most of the morning of January 24, 1999. The wind was over 30 km/hr as shown in Figure 4. The majority of the ice remained upstream of the boom. Some ice small floes ran under the boom first, then larger ice floes ran over the boom (Figure 5). This event did not result in any significant reduction in the power production or in increasing the water level of the Upper-Niagara River.

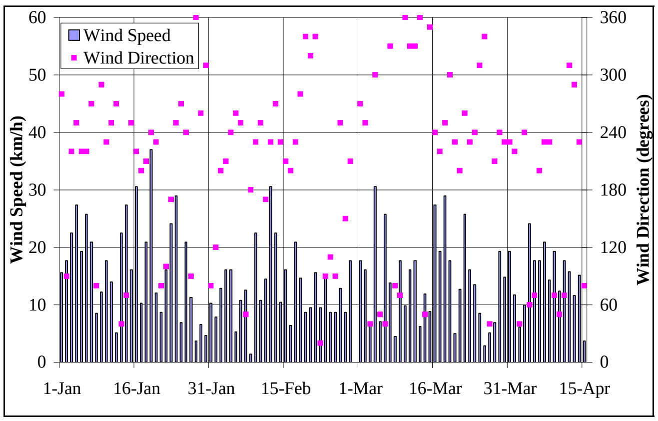


Figure 4: Resultant Daily Wind Speed, Winter 1998/99

Figure 5: January 24, 1999 Ice Run Event

One major event occurred on February 4th, 2003, where the anchor cable No. 18, located on the Canadian side of the boom, broke and precipitated the failure of 13 adjacent span cables. The event occurred when the ice was solidly formed and consolidated to the boom pontoons. The failure of the boom did not result in an ice run because the ice cover was wedged between the north and south shores of the lake. The failure of the boom is shown in Figure 6.

Figure 6: A Video Clip Showing the Failure of the Boom

Figure 7: The Failure Started on the Canadian Side

3. Analysis of the February 4th, 2003 Boom Failure Event

The boom failed at 10:54 AM on February 4th, 2003. An assessment of the environmental conditions that preceded the failure event of the LENRIB was carried out:

- The winter of 2003 was particularly cold. The average daily air temperature for the period between the 1st of January and the 5th of February is shown in Figure 8. The freezing degree-days curve had reached about 290 freezing degree-days by February 4, is also displayed on the same figure. The ice started to form on about January 11 as shown on Figure 8.
- The plots of the freezing degree-day records since 1972 shown in Figure 9 indicated that the FDD recorded during the winter of 2002/03 was a slightly above average winter.
- The daily wind speed and its prevailing direction for the period between the 1st of January and the 5th of February were quite active and is shown in Figure 10.
- The wind speed and its direction for February 4th, 2003, the day of the event, are shown in Figure 11. It showed that the wind peaked between 8:30AM and 12PM.
- The water level for the period from the 1st of January to the 5th of February is shown in Figure 12. The water level was constant for 15 days prior to the Feb 4th event and rose suddenly on Feb 4, between 6:00AM and 9:00AM, due mainly to the wind setup as shown in Figure 13.

The steps that led to the failure event are a set of successive events that led to very high pushing force on the boom while the ice was completely consolidated (frozen) to the boom. The following is the sequence of the event:

1. The cold temperature produced an ice cover during the second week in January.
2. The wind was blowing from the southwest direction at up to 40 km/hr during the period of ice formation until January 25th producing relatively thick pack ice, particularly upstream of the boom.
3. The period of high wind was followed by one week of relatively calm weather, with wind blowing at below 30 km/hr, combined with cold temperatures. This long period provided sufficient time to freeze and consolidate the ice, ridges and rubble ice, which accumulated around the boom's cables, chains and pontoons.
4. The last four days prior to the event, warm temperatures hovering around 0^{o}C prevailed, which led to the weakening of the shore ice.
5. During the day of the event, the following occurred:
   a. The wind was blowing from the south at an average of 49 km/hr and gusting at 90 km/hr.
   b. The water level rose about 0.75 m, from 173.75 m to 174.5 m.
   c. The high winds, and the rise in water level, may have caused the current velocity to increase significantly. This would have resulted in very high ice forces that exceeded the resistance capacity of the anchor cable No. 18 (this anchor cable was due to be changed the following summer, so it was in a less than perfect condition).
   d. Usually the shores take most of the wind and current drag forces applied on the ice. However, when the ice cover rose 0.75 m, it broke free from the shores, and they were no longer able to contribute as much to resist the ice load. Therefore, the shore resistance shifted almost entirely to the boom. This load can easily exceed the design load of the boom if the boom does not submerge, allowing the ice to overrun the boom.
   e. For example, if the ice cover upstream the boom is 5 km long; the uniform line load applied by the ice on the boom for 49 km/hr wind and 0.5 m/sec current is 29 kN/m

(Abdelnour et al, 1996). However, the maximum line load that an ice sheet can apply on the boom can exceed this value. The maximum load is only limited by its strength and its resistance to the start of ridge formation away from the boom. For a 0.5 m ice cover thickness, the maximum line load that it can apply before starting to form ridges is about 50 kN/m (Figure 14). Therefore, the load on the boom can reach a maximum of 50 kN/m.

f. The boom was designed to let the ice run past the boom pontoons when the line load exceeds 9 kN/m (Abdelnour et al, 1996). This assumes the line load is distributed uniformly and applied perpendicularly to the boom layout (from the southwest direction). If the ice was frozen to the boom (span cables, chains and pontoons), the boom can resist until the following occurs:
   i. It is expected that either the consolidated rubble ice surrounding the pontoons breaks and allows the pontoon to submerge through the rubble ice and subsequently releases the ice, or one of the two chains connecting the span cable to the pontoons breaks and allows the ice to pass over the boom span cable.
   ii. If more than 50% of the pontoons resist submerging, the tension load on the chains will be lower than the chain breaking load and the span cable will fail instead when the line load applied by the ice exceeds 22 kN/m (as shown in Figure 15).
   iii. The anchor cable is not expected to fail and it is designed to break when a line load, uniformly applied on the boom, exceeds 27 kN/m. Unfortunately, the cable broke, for a lesser load than its rated resistance capacity.

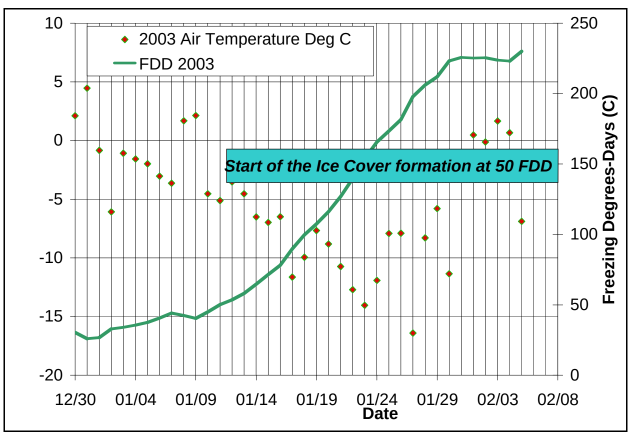


Figure 8: Air Temperature and FDD before the event

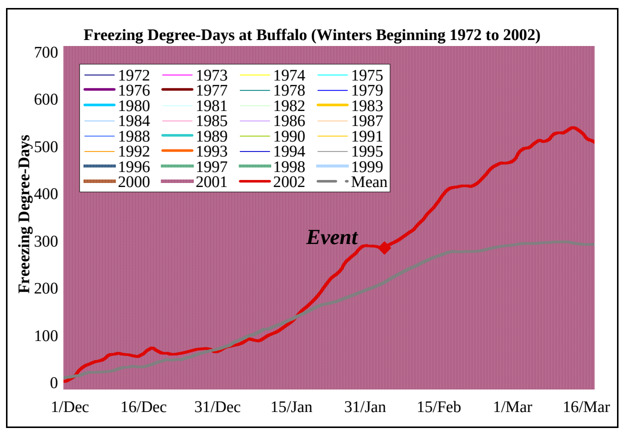
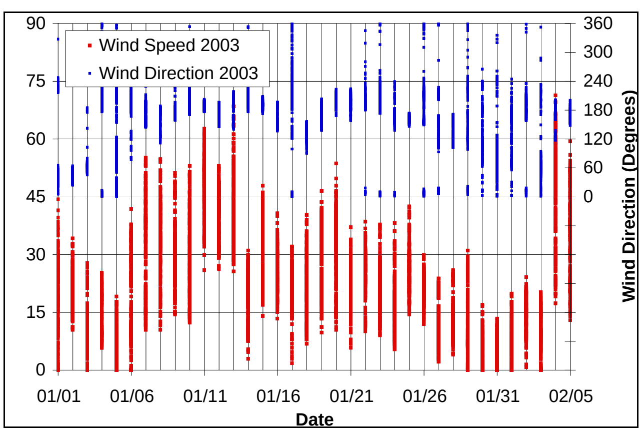


Figure 9: Comparison of the FDD with past years



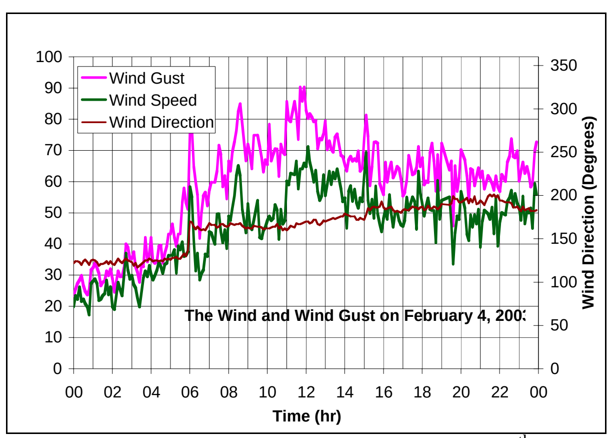


Figure 10: Wind Speed and Direction, winter 2002/03, Figure 11: Wind Speed and Direction on February 4th, 2003

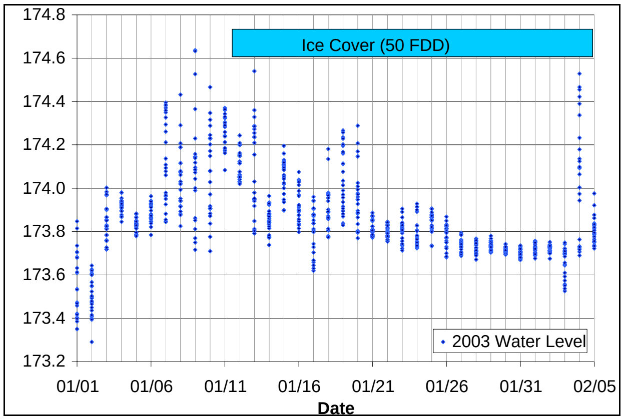


Figure 12: Water Level, winter 2002/03

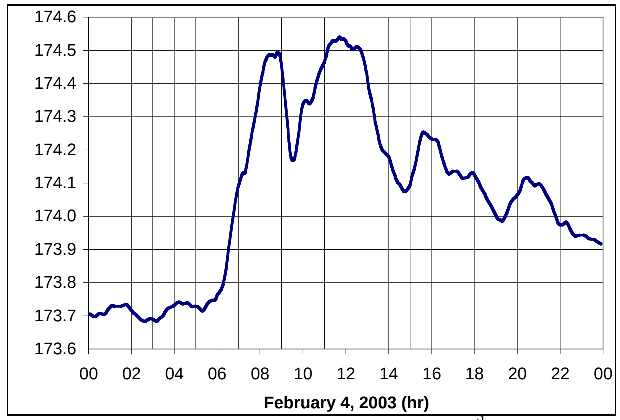


Figure 13: Water Level during February 4th, 2003 event

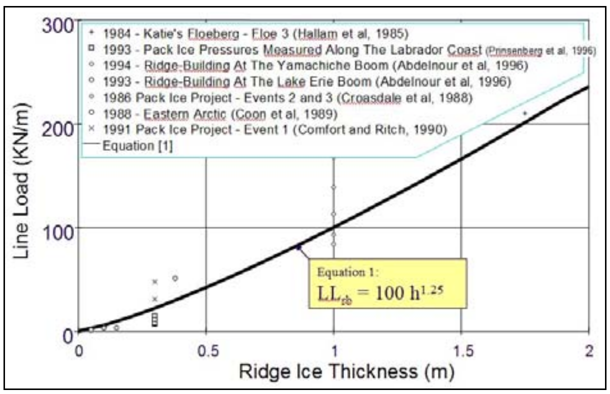


Figure 14: Pack Ice Pressure: Limiting Line Load

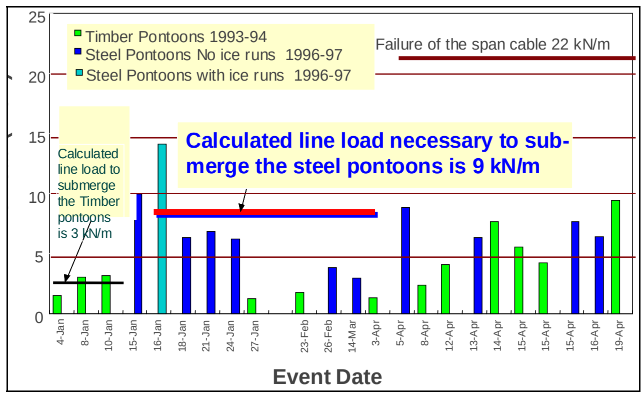


Figure 15: Resistance of the Boom's Span and Anchor Cables

4. Comparison of February 4th, 2003 Event with Past Events

A review of the environmental factors and the timing that led to the event of February 4th, 2003 are compared with several lake ice run events that have occurred since the construction of the boom between 1968 and until 1989 (Abdelnour et al, 1996).

A classification system was developed which rated each of the ice run events observed to be one of the following categories: Early freeze up, Late freeze up, Early break-up and Late break-up. The different events categories are described in Table 1. Using the ice run classification system, the lake ice run event seen on February 4th, 2003 would be classified as a late freeze-up lake ice run event. In Table 2, a summary of these lake ice run events is presented. Three types of lake ice run severity were observed. An event is defined in terms of its potential to cause ice stoppages or ice jams in the Grass Island Pool reach of the upper Niagara River (25 miles downstream) that may adversely affect power production and/or lead to flooding in the Tonawanda Channel. The first type is when an ice run occurs but no stoppage near the NYPA water intakes occurs (noted in the table as "NO"). The second type is when the ice stops near the NYPA water intakes and where action to dislodge the ice was taken (noted in the table as "YES"). The third type is when the ice stoppage caused significant water level rise and significant reduction in power production (noted in the table as "Severe"). All "Severe" events occurred under the early freeze up category. The February 4th, 2003 occurred under the late freeze up category.

During all the event categories, the boom was not necessarily damaged as happened on February 4th, 2003. Only five late freeze-up events have occurred since 1968. A review of the main factors that resulted in the February 4th, 2003 lake ice run event is made.

Table 1
Values of Cumulative Freezing Degree-Days Used to Classify Lake Ice Runs With the LENRIB in Place
(Abdelnour et al, 1996)

Category of Lake Ice Run	Value for Classification	Character of Ice Cover and Ice Strength
Early Freeze-up	$\beta < 30$, $d\beta/dt > 0$	Lake ice is generally less than about 5 cm thick and is very fragile and may cover only a small area of the lake. The ice strength is not sufficient to transfer the environmental load to the shores to form the natural ice arch. Any movement of ice into the upper Niagara River is resisted solely by the LENRIB.
Late Freeze-up	$\beta > 30$, $d\beta/dt > 0$	Lake ice is generally more than 5 cm thick, covers a large area of the lake, and has strengthened to the point that most of the environmental load on the ice cover is transferred to the shores (natural ice arch). Movement of ice into the upper Niagara River is resisted primarily by the natural ice arch. In extreme wind events ice can be forced over the ice boom.
Early Breakup	$\delta < 50$, $d\beta/dt < 0$	Lake ice can be any thickness, but generally greater than about 20 cm and covers a large area of the lake. Early breakup is characterized by a short period of warming that causes the ice cover to weaken and become more susceptible to motion. Movement of ice into the upper Niagara River may be resisted by either the natural ice arch or the ice boom depending on the ice thickness and strength.
Late Breakup	$\delta > 50$, $d\beta/dt < 0$	Lake ice can be any thickness, but generally greater than about 20 cm and covers a large area of the lake. Late breakup is characterized by a long period of warming that causes the ice cover to weaken substantially and become very susceptible to motion. Movement of ice into the upper Niagara River is resisted by both the natural ice arch and the LENRIB, but a greater proportion of the resistance is by the ice arch until very late in the breakup period.

Air Temperature

The air temperature records from NOAA's Buffalo station for the past 30 years (1972 to 2002) were obtained and the freezing degree-days calculated and presented in Figure 9. The number of freezing degree-days calculated for the season of 2002/03 was not particularly different from many other years. When the event occurred, the value of the freezing degree-days was about 290, or a little more than half the value reached at the end of the winter.

However, it is important to note that the rate of increase of the freezing degree-days was higher than normal, especially for the period between January 11 and 30. A similar trend was observed for the years 1976, 1977, 1980, 1983, 1989 and 1993 (shown in bold lines). The ice stoppages occurred only in 1967 and 1977 as noted in Table 2. No similar trend was noted after 1997 when the new boom design was implemented (shown in Figure 9, dashed lines).

Wind Speed and Direction

The average daily wind speed and direction records (obtained from NOAA's Buffalo station) for a 19-year period (1984 to 2002) were obtained. The average daily wind measured for the day was 37 km/hr. As can be seen in Figure 16, this value is well below the high-resolution wind data obtained for the same period where the average wind from 6AM to 12PM was 49 km/hr during the event and the maximum gust reached was 90 km/hr. The wind data from Abdelnour et al, 1996, presented in Table 2 was more useful for comparison with the February 4th, 2003 since they were obtained for each observed lake ice run. The results of the comparison of all 45 events with the event of 2003 (event 46) are shown in Figure 17.

The average measured wind speed during the event of February 4th, 2003 compares closer to the maximum wind speeds recorded during all previous lake ice run events recorded since 1968 (Table 2). The maximum wind speed (gust) during the event was 90 km/hr, which is 34% higher than the maximum wind speed measured during the past 45 events.

A probability distribution was fitted to the wind speed during ice run events and to wind gusts during ice run events (without the 2003 wind gust of 90 km/h). The 2003 event gust of 90 km/hr is a significant outlier and was removed from the fitted data. In both cases shown in Figure 16, the Normal distribution provided the best fit. The average wind speed of 49 km/hr during the event constitutes a 1-in-37-years event, and the 90 km/h gust is approximately a 1-in-100,000-years event (keeping in mind that extrapolating to 100,000 years from 20 years of data can incorporate significant error).

Ice Thickness

The ice thickness upstream of the boom was measured on February 17 (Harding, 2003), about two weeks after the event occurred. The average ice thickness measured was 49 cm. The data is shown in Figure 18. Figure 19 shows the FDD on February 4th, 2003 and for all the seasons.

The ice thickness was calculated for the date of the event, February 4th, 2003, using a modified Stefan's formula [1] for the Lake Erie (Abdelnour et al, 1996) as follows:

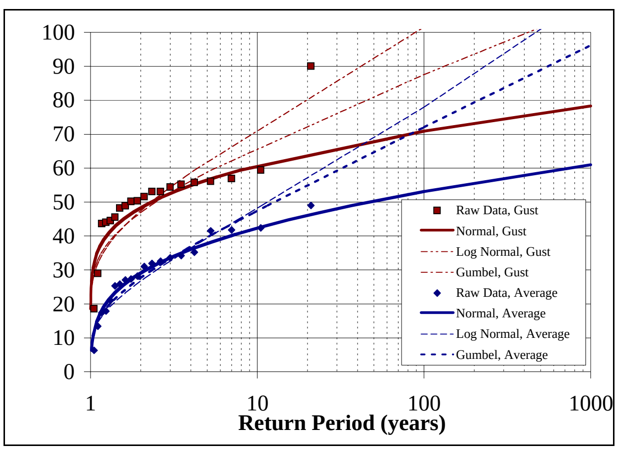


Figure 16: Return period of the Maximum Wind

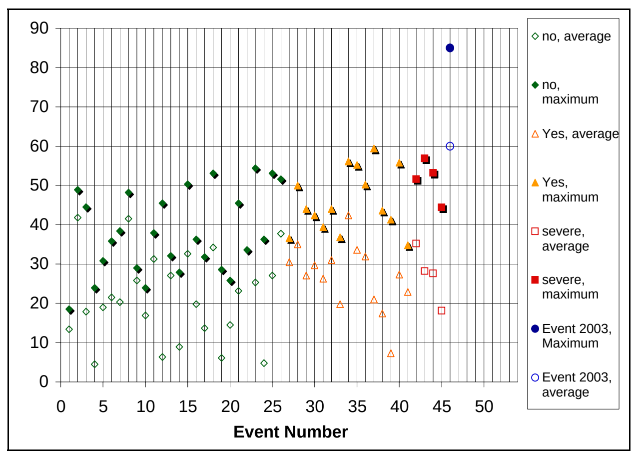


Figure 17: Maximum Wind during the Ice Run Event.

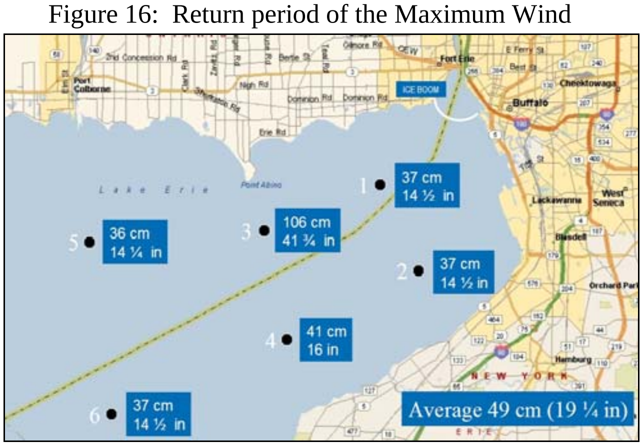


Figure 18: Ice thickness taken on February 17, 2003

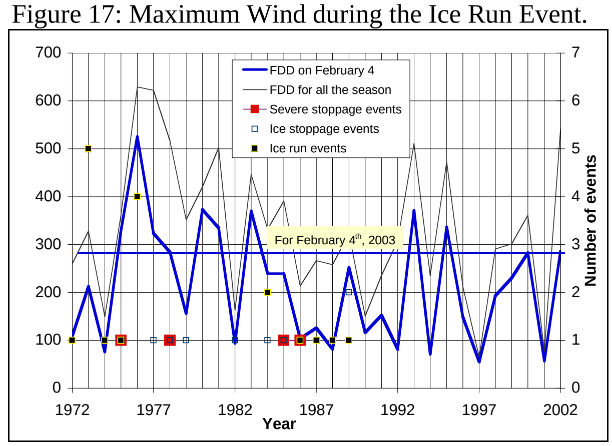


Figure 19: Freezing Degree Days, 1972 to 2002

Ice thickness (cm) = 1.308 $\beta^{0.6}$ [1]

Where β is the number of freezing degree-days starting when the water reached 0°C. After assuming that the start of the ice growth was at 50 freezing degree-days (water temperature reached 0°C), the number of freezing degree-days (β) after the formation of the ice cover and up to the date of the event was 240°C-days. Using a value of β of 240°C-days, the calculated ice thickness on February 4th, 2003 was 35 cm. The natural ice thickness growth at the end of the winter was estimated to have reached 54 cm for a value of β of about 490°C-days.

Table 2: A Summary of the 45 Recorded Lake Ice Run Events between 1968 and 1993 and the February 4th, 2003 event. (Abdelnour et al, 1996)

Event No.	Start Date	Ice Stoppage	Freezing Degree-Day α (1)	Freezing Degree-Day β (2)	Type of Event	Duration of Lake Ice Run	Air Temperature During Run	Estimated Ice Thickness	Water Level IGLD 1955	Wind at Start of Ice Run	Wind During Ice Run	Max Wind During Ice Run	Wind Direction During Run
			(FDD °C)	(FDD °C)		(hr)	(°C)	(cm)	(m)	(km/hr)	(km/hr)	(km/hr)	(km/hr)
1	05/Jan/68	NO	24	12	Early Freeze-up	9	-13.4	6	173.9	18.5	13.4	18.5	275
2	21/Mar/69	NO	323	239	Early Break-up	9	2.1	35	174.02	39	41.8	48.9	243
3	26/Mar/70	NO	471	331	Early Break-up	25	3.4	43	173.9	18.2	17.9	44.5	200
4	09/Apr/70	NO	438	298	Early Break-up	21	5.6	40	174.05	23.9	4.5	23.9	295
5	10/Jan/71	NO	124	29	Early Freeze-up	13	-0.8	10	174.1	24.2	19	30.8	258
6	26/Jan/71	NO	211	116	Late Freeze-up	9	-9	23	174.1	35.8	21.5	35.8	270
7	30/Jan/71	NO	253	158	Late Freeze-up	17	-7.1	27	174.1	14.4	20.3	38.4	268
8	28/Feb/71	NO	318	223	Early Break-up	9	1.1	34	173.97	45.6	41.5	48.2	253
9	04/Feb/72	NO	119	62	Late Freeze-up	9	-5.6	16	174.02	26	25.8	29	265
10	12/Jan/73	NO	82	16	Early Freeze-up	13	-5.1	7	174.55	23.4	16.9	23.9	260
11	16/Jan/73	NO	84	18	Early Break-up	33	4.1	7	174.55	30.8	31.3	37.9	237
12	19/Jan/73	NO	61	-6	Early Break-up	37	-0.6	8	174.55	29	6.3	45.5	289
13	22/Jan/73	NO	58	-8	Early Break-up	13	8.1	8	174.55	24.7	27.1	32.1	178
14	03/Feb/73	NO	68	2	Early Break-up	13	0.2	8	174.42	27.9	8.9	27.9	282
15	14/Jan/74	NO	149	45	Early Freeze-up	17	2	13	174.36	50.3	32.6	50.3	247
16	12/Feb/75	NO	77	61	Late Freeze-up	9	-5.8	15	174.37	21	19.8	36.3	260
17	28/Feb/76	NO	269	159	Early Break-up	13	3.3	27	174.25	25.2	13.7	31.8	260
18	12/Mar/76	NO	256	146	Early Break-up	21	2.2	26	174.53	32.1	34.2	53.1	220
19	06/Apr/76	NO	141	31	Late Break-up	9	6.4	10	174.55	28.6	6.1	28.6	285
20	17/Apr/76	NO	57	-53	Late Break-up	37	20.3	10	174.55	12.7	14.5	25.8	205
21	10/Mar/84	NO	391	295	Late Freeze-up	21	-6.2	40	174.27	25.2	23.2	45.5	250
22	16/Mar/84	NO	414	318	Early Break-up	17	-2.4	42	174.27	33.6	-8.2	33.6	218
23	10/Mar/86	NO	345	236	Early Break-up	29	7.3	35	174.65	29.4	25.3	54.4	254
24	08/Feb/87	NO	80	11	Early Freeze-up	49	-5.7	6	174.52	6.5	4.8	36.3	271
25	30/Mar/88	NO	151	104	Early Break-up	13	7.1	21	174.13	46.1	27.1	53.1	209
26	15/Mar/89	NO	201	133	Early Break-up	13	4.9	25	173.77	41.3	37.7	51.6	236
27	08/Jan/70	YES	173	33	Early Freeze-up	41	-15.6	11	173.94	33.4	30.5	36.6	236
28	15/Feb/76	YES	316	206	Early Break-up	9	6.6	25	174.25	27.3	35	50	195
29	05/Mar/76	YES	249	139	Early Break-up	49	0.4	25	174.53	44	27.1	44	246
30	27/Mar/76	YES	201	91	Late Break-up	13	7.1	20	174.53	24.2	29.7	42.4	234
31	12/Apr/76	YES	256	146	Early Break-up	29	3.8	26	174.55	39.4	26.3	39.4	237
32	05/Apr/77	YES	430	352	Late Break-up	29	3.7	44	174.13	22.7	31	44	222
33	11/Apr/78	YES	513	438	Early Break-up	65	5.1	50	174.33	26.1	19.8	36.8	253
34	06/Apr/79	YES	361	313	Late Break-up	13	-4.6	41	174.23	41.9	42.4	56.1	240
35	10/Jan/82	YES	92	45	Early Freeze-up	29	-18.2	13	174.2	20.2	33.6	55.2	249
36	22/Mar/84	YES	409	313	Early Break-up	25	1.6	41	174.21	11.9	31.9	50.2	219
37	12/Mar/85	YES	262	171	Early Break-up	45	2	29	174.53	59.4	21	59.4	238
38	02/Mar/87	YES	173	104	Early Break-up	45	-0.9	21	174.46	25.8	17.4	43.6	263
39	13/Jan/88	YES	76	29	Early Freeze-up	21	-9.4	10	174.2	22.7	7.3	41.3	298
40	07/Feb/89	YES	68	0	Early Freeze-up	77	-9.4	0	173.88	16.5	27.3	55.8	238
41	11/Feb/89	YES	99	31	Early Freeze-up	9	-3.1	10	173.88	21.3	22.9	34.8	250
42	25/Feb/75	SEVERE	62	47	Early Break-up	33	0.4	13	174.37	31.1	35.2	51.6	233
43	09/Jan/78	SEVERE	97	22	Early Freeze-up	61	-9.7	8	174.19	43.6	28.2	56.9	280
44	18/Jan/85	SEVERE	67	0	Early Freeze-up	133	-9.3	0	174.38	11.1	27.6	53.2	242
45	05/Jan/86	SEVERE	109	0	Early Freeze-up	36	-5.9	0	174.44	21.3	18.1	44.4	266
46	**04/Feb/03**	**NO**	**290**	**240 (3)**	**Late Freeze-up**	**3**	**1**	**35**	**174.55**	**16**	**60**	**85**	**160**

1) α is the cumulative freezing degree days (°C-days) from the time the lake temperature reaches 4°C to the day ice run begins.
2) β is the cumulative freezing degree days (°C-days) from the time the lake temperature reaches 0°C to the day ice run begins.
3) Estimated value.

Based on the freezing degree-days, the ice thickness for the winter of 2002/2003 was above average, making this the third coldest winter since 1972. Figure 9 shows the freezing degree-days for all 45 events that have occurred since 1972.

The ice thickness was one of the factors that led to the severe event of February 4th, 2003. Although previous analyses by Abdelnour et al, 1996 showed that the most severe ice stoppage events occurred when the ice thickness was below 15 cm, in this case, the event was due to the failure of the boom to resist the applied load rather than the ice over topping the boom. No ice overtopped the boom before February 4th, 2003. The boom failed because the boom structure could no longer resist the ice forces applied. Therefore, the occurrence of the February 4th event is likely due to a combination of factors; namely the consolidation of the ice around the boom and the ice thickness at this early time during the season and the considerable southwesterly wind that prevailed during the day of the event.

Ice Consolidation around the Boom

The ice thickness calculated above does not take into consideration the ridge building that occurs immediately upstream of the boom, especially during the ice formation period. Previous measurements of the submergence of the junction plate located under the buoy have shown that the depth of submergence by the moving ice during an overtopping event (in January) was at least 1.5 m below the water surface (Abdelnour et al, 1997). This provides an indication of the depth of accumulated rubble ice. This relatively thick ice later consolidates and forms a strong bond with the boom pontoons. The packed ice starts to consolidate from the surface and gradually freezes toward the bottom. The thickness of the consolidated layer expected in Lake Erie can be twice the ice thickness calculated from the freezing degree-days or up to 1 meter of consolidated rubble ice.

It was therefore likely that on February 4th, 2003, the ice surrounding the pontoons was thicker and the accumulated rubble ice was partly consolidated. This can be observed in Figures 20 and 21, taken on February 7.

Figure 20: Consolidated Ice around One of the Pontoons

Figure 21: Consolidated Ice around the Buoys

The ice consolidation around the boom pontoons will likely hinder the boom from submerging under the ice, which normally allows the ice pressure to be released when the applied load exceeds the capacity of the pontoon thereby releasing the pressure on the boom.

5. Performance Comparison of the New Steel Boom and the Timber one

Following the failure event of February 4th, 2003, a question was raised about the effect of replacing the timber pontoons with steel ones on the occurrence of the event. A comparison of the performance of both types of booms is presented for both the period with ice and in open water.

In Presence of Ice

The timber ice boom was replaced with steel pontoons to provide a higher resistance to ice during the early freeze-up period. As shown in Figures 2 and 3, the ice boom resistance measured during the 1994 and 1997 field trials increased significantly from 1 kN/m for an ice boom with timber pontoons to 9 kN/m for steel pontoons. Based on the same test results, the loads measured during the latter part of the winter (late freeze-up, early and late break-up) were relatively similar for both the timber and the steel pontoons. Therefore, the performance of the two types of pontoons (timber vs. steel) was assessed during two different periods:

1. During the early freeze-up period when the ice starts to form on the lake, (most severe ice overtopping events that occurred in the past 30 years occurred during this period)
2. During the winter and when a fully developed ice cover forms upstream to the ice boom (the event of February 4th, 2003 occurred during this period)

<u>During Early Freeze-up</u>: The increase of the boom's resistance capacity during the early freeze-up period significantly reduced the potential of the ice run event occurrences experienced about 45 times between 1968 and 1993 (Table 2). These ice run events caused blockages at the NYPA power plant water intakes 19 times, of which four were severe. No ice run events have occurred since the installation of the new steel pontoons in the fall of 1997. With the steel pontoons, ice accumulated upstream of the boom rather than over-topping the boom pontoons. The ice cover quickly progressed upstream to form a stable ice cover that remained intact until the end of the winter.

In Table 3, eight early ice-overtopping events were compared with high wind events that occurred on January 11, 2003. No ice overtopping was reported. In general, the critical wind velocity required to initiate an ice overtopping event during the early freeze up period increased from about 20 km/hr for the timber pontoons to more than 34 km/hr for the steel ones.

Table 3: Comparison of the Conditions that Caused Past Severe Events during the Early Freeze-Up with the Conditions on January 11-16, 2003

Event No.	Start Date	Ice Stoppage	Type of Event	Duration of Lake Ice Run (hr)	Air Temperature During Run (°C)	Estimated Ice Thickness (cm)	Wind at Start of Ice Run (km/hr)	Wind During Ice Run (km/hr)	Max Wind During Ice Run (km/hr)	Wind Direction During Run (km/hr)
39	13/Jan/88	YES	Early Freeze-up	21	-9.4	10	22.7	7.3	41.3	298
27	08/Jan/70	YES	Early Freeze-up	41	-15.6	11	33.4	30.5	36.6	236
35	10/Jan/82	YES	Early Freeze-up	29	-18.2	13	20.2	33.6	55.2	249
40	07/Feb/89	YES	Early Freeze-up	77	-9.4	0	16.5	27.3	55.8	238
41	11/Feb/89	YES	Early Freeze-up	9	-3.1	10	21.3	22.9	34.8	250
43	09/Jan/78	SEVERE	Early Freeze-up	61	-9.7	8	43.6	28.2	56.9	280
44	18/Jan/85	SEVERE	Early Freeze-up	133	-9.3	0	11.1	27.6	53.2	242
45	05/Jan/86	SEVERE	Early Freeze-up	36	-5.9	0	21.3	18.1	44.4	266
47	11/Jan/03	No	Early Freeze-up	120	-5	0	34	20	NA	240
48	11/Jan/03	No	Early Freeze-up	24	-3.5	0	34	34	NA	240
49	11/Jan/03	No	Early Freeze-up	72	-5	0	34	30	NA	250

During the winter: Several winter events have occurred in the past. Two major ones are the events that occurred in 1975 and in 2003. The first one took place on February 25th, 1975 when the ice moved and over topped the boom and caused a "severe" ice blockage event downstream along the Upper Niagara River. The second event took place on February 4th, 2003 when the ice cover had already formed and was consolidated to the boom. The ice consolidation prevented the boom pontoons submergence and did not allow the ice to overtop the boom (a design feature). This permitted the boom to resist much higher loads than its capacity, which led to the failure of the anchor cable No. 18 (Section 3).
Another minor event occurred on January 24th, 1999 when large ice floes overtopped the boom (Figure 5) but the volume remained below the amount that would cause any blockage or the water level to rise.
In Table 4, the events of February 4th, 2003 and of January 24, 1999 are added to past events that occurred during the winter (late freeze-up, early breakup and late breakup) recorded between 1968 and 1993.

Table 4: Comparison of the Conditions that Caused Past Severe Events
Subsequent to Early Freeze-Up with the Conditions on January 11-16, 2003

Event No.	Start Date	Ice Stoppage	Type of Event	Duration of Lake Ice Run (hr)	Air Temperature During Run (°C)	Estimated Ice Thickness (cm)	Wind at Start of Ice Run (km/hr)	Wind During Ice Run (km/hr)	Max Wind During Ice Run (km/hr)	Wind Direction During Run (km/hr)
28	15/Feb/76	YES	Early Break-up	9	6.6	25	27.3	35	50	195
29	05/Mar/76	YES	Early Break-up	49	0.4	25	44	27.1	44	246
30	27/Mar/76	YES	Late Break-up	13	7.1	20	24.2	29.7	42.4	234
31	12/Apr/76	YES	Early Break-up	29	3.8	26	39.4	26.3	39.4	237
32	05/Apr/77	YES	Late Break-up	29	3.7	44	22.7	31	44	222
33	11/Apr/78	YES	Early Break-up	65	5.1	50	26.1	19.8	36.8	253
34	06/Apr/79	YES	Late Break-up	13	-4.6	41	41.9	42.4	56.1	240
36	22/Mar/84	YES	Early Break-up	25	1.6	41	11.9	31.9	50.2	219
37	12/Mar/85	YES	Early Break-up	45	2	29	59.4	21	59.4	238
38	02/Mar/87	YES	Early Break-up	45	-0.9	21	25.8	17.4	43.6	263
42	25/Feb/75	SEVERE	Early Break-up	33	0.4	13	31.1	35.2	51.6	233
46	04/Feb/03	NO	Late Freeze-up	3	1	35	16	60	85	160
50	24/Jan/99	NO	Late Freeze-up	8	5	29	36	36	NA	240

Table 4 shows that the wind speed during the event of February 4th, 2003 was by far greater than the average and the maximum wind speed measured in any of the past ice overtopping events.
Based on this, there is strong evidence that if the boom had timber pontoons instead of the steel ones, on January 24, 1999 and on January 11 and 12, 2003, a "severe" event would have occurred. The environmental conditions measured during the event of January 11, 2003 including the wind, its duration, the cold air temperature, the rise in water level, are comparable with the two "severe" events recorded on January 9, 1978 and January 18, 1985 (Table 3).
The events experienced in 1978 and 1985 resulted in significant rise in water level, which led to the reduction of water for power generation and resulted in important power production losses. The wind experienced on January 24, 1999 was also quite significant and was above the events experienced in 1978 and 1985. In summary, the differences in the behavior of the timber and steel pontoons are:

- The steel pontoons retain ice during early freeze-up much better than the timber pontoons.
- The ice grown around steel pontoons melts faster when exposed to the sun. This allows the boom to be free from ice and to submerge freely when the ice load starts to increase above the resistance capacity of the boom. This reduces the risk of overloading the boom during high ice load events that are typically seen during spring break-up.

- It is possible that the steel boom will resist more than a 9 kN/m line load, particularly during a Late Freeze-up loading event, such as the February 4th, 2003. This is probably true of both steel and timber pontoons, although no data is available for the timber pontoons.

To prevent a repeat of the February 4, 2003 event, particularly during cold winters and in the presence of a large, stable ice cover upstream of the boom, an icebreaker should be used to free the boom from the ice. This should include the pontoons, the span cables, the junction plates, the buoys and the anchor cables. This will allow the pontoon to submerge and let the ice run over the boom when the load exceeds 9 kN/m.

In Open Water

The deployment of the boom without the presence of ice exposes the boom cables to significant cyclic loads from waves. The length of time for which the boom is exposed to strong waves (the number of cycles with large amplitudes) varies from year to year. In some years, the ice takes several weeks to form while on rare occasions the ice does not form at all.

The waves produce a motion cycle that generates significant heave and pitch movement of the boom components, particularly the pontoons and the buoys. It was reported that the icebreaker crew observed during a visit to the site on a stormy day that the timbers were seen to pitch almost 90 degrees (stand vertically) during every large wave cycle. With steel pontoons this would very likely still be the case.

During a storm, the ends of the span and anchor cables, particularly near the buoys, are subjected to large cyclic pull forces resulting from combined pitch and heave motions that accelerate fatigue failure of the cable ends (Figure 22). The average horizontal load on the span cable in open water is close to 76 kN (0.5 kN/m, measured in 1994, timber pontoons) while the vertical force depends on the pitch of the pontoon, its mass, the wave height and the wavelength. It also depends on the buoyancy of the buoys.

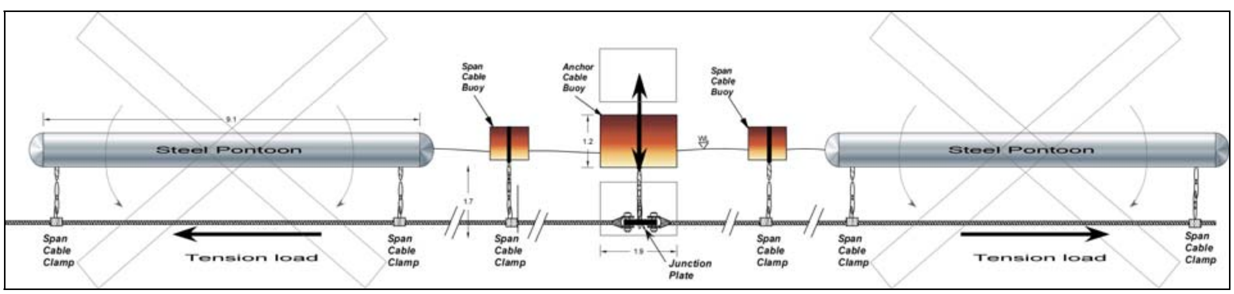


Figure 22: The Motion of the Buoys and the Two End Pontoons in a Storm

With the replacement of the timber pontoons with steel ones, the horizontal load on the boom should be smaller since the steel pontoons are cylindrical (lower drag) and have a draft of only half of the pontoon diameter (0.76 m diameter), compared to a draft of 70 to 90% of the depth of the timber pontoons (drafts between 0.4 and 0.5 m for a 0.56 m thick timber).

Despite the reduced resistance to the water currents in waves, the vertical loads on the span cables must have increased due to the much greater buoyancy of the steel pontoons (three to ten times larger, depending on the timber density).

In summary, to reduce the impact of the waves on the failure of the boom cables it is important to reduce the pitch and heave of the pontoons that are close to the ends of the span cable. Reducing the length of these pontoons will reduce the vertical load and the fatigue of the cable. For example, by cutting these pontoons in half, they would continue to provide the same resistance to the ice (by keeping the total buoyancy of a span the same) while reducing the heave and pitch as shown in Figure 23.

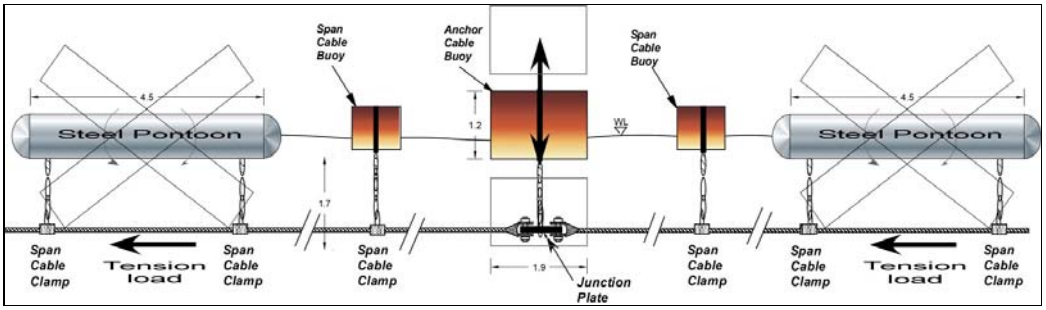


Figure 23: The Suppressed Motion of the Cut Pontoons during a Storm

A prototype tests was carried out during the winter of 2004/05 where a number of pontoons were cut in half as shown in Figure 24. No wear was observed when the boom was inspected in May 2005.

(a) Long Pontoons (Left) and long pontoons (right)

(b) Long Pontoons

(c) Short pontoons

Figure 24: The Motions of the Long and Short Pontoons in Waves (December 28, 2004)

Another area of improvement would be to redesign the buoys to reduce their buoyancy and their resistance to water drag (Figure 25). The new design would offer much less resistance to waves, while meeting the design criteria for ice, thus reducing the vertical loads on the cable during a storm and eventually reduce the risk of fatigue failure.

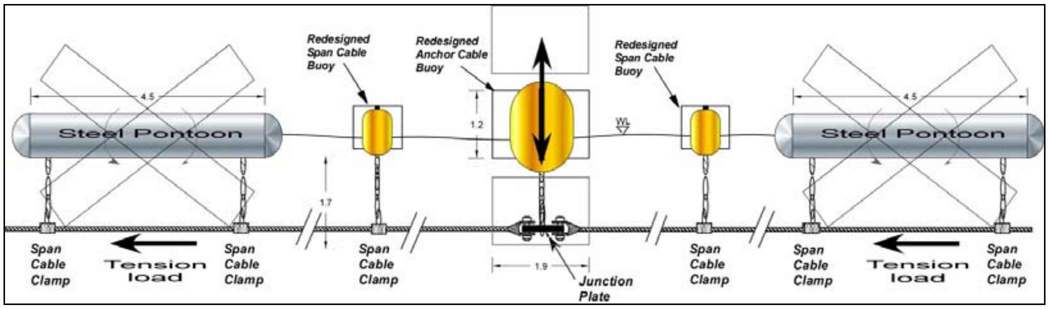


Figure 25: The Suppressed Motion of the Cut Pontoons during a Storm

Conclusions

The analysis of the events that occurred post 1997 modifications of the Lake Erie Ice Boom resulted in the following conclusions:

- The boom performed extremely well and seems to have significantly reduced the potential of occurrence of early freeze-up event. All the early freeze-up ice overtopping events that occurred after the 1997 modification were minor and caused no water level increase or power generation loss.
- The boom failure on February 4th, 2003 was a rare event. The previous timber Lake Erie-Niagara River boom "failed" and allowed SEVERE ice runs to occur under much less severe environmental conditions.
- The new Lake Erie-Niagara River boom "failed structurally. However, an ice blockage did not occur. The ice had thickened enough to resist its breakup and its drift through the Upper-Niagara River.
- The failure that caused the February 4th, 2003 event was caused by a combination of unfavorable events, as follows:
    - Cold temperatures that likely resulted in considerable ice growth and caused the boom pontoons to become frozen in the rubble around them, followed by warm temperatures that released the ice cover from the shorelines.
    - The wind speed was 49 km/hr with the maximum gust speed at 90 km/hr. The maximum wind speed recorded during the 45 lake ice run events (between 1968 and 1989) was 42 km/hr. The maximum gust recorded was 59 km/hr. That is an increase of 14% and 34% above the past record.
    - The 49 km/hr wind during the event constitutes a 1-in-37-years event while the 90 km/hr gust is approximately a 1-in-100,000-years event.
    - The boom anchor cable should not have failed before the span cables. The anchor cable is designed to resist up to a 27 kN/m line load while the span cable is designed to resist up to 22 kN/m. Anchor cable fatigue due to wave action could be the source of this inconsistency.

To minimize the occurrence of major events, such as the February 4th, 2003 event, the following measures to reduce the risk were implemented:

- Monitor the air temperature and the Freezing Degree-Days and as soon as this value reaches 200 FDD, break the ice that surrounds the boom using the icebreaker to ensure that the boom will submerge, even late during the winter, before the ice pressure reaches the anchor or span cable failure loads. This was implemented successfully during the winter season of 2004/05. Icebreaking should be repeated on by-weekly basis, if the air temperature remains cold (below -15°C), a very rare event in Lake Erie.
- Investigate solutions to the problem of fatigue failure of the boom anchor and span cables. This should include the following:
    - Assess the potential of shortening the two end pontoons from 9m to 4.5m for all spans where the waves are large (center of the lake, spans E to Q). A wave climate survey of the boom site would greatly assist in this assessment.
    - Assess the potential of redesigning the buoys to reduce their buoyancy and their drag coefficient to reduce the vertical forces due to waves on the span and anchor cables.

- Evaluate the possibility of deploying the boom as close as possible to the ice formation start date.
- Continue the rigorous inspection of the anchor and span cable to minimize premature failure.

There is always the “do nothing” option, which may be attractive in this case. The event of February 4th, 2003 was a rare event combining a sustained period of cold weather with a sudden warming and high winds. However, the cost for the above-recommended changes is relatively inexpensive and should be paid off by the savings in avoiding a similar failure event in the future.

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