CAIT-UTC-NC 55

Validation and Refinement of a Novel Deicing System for Stay Cables

FINAL REPORT
February 2020

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U.S. Department of Transportation
Federal Highway Administration

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1. Report No. CAIT-UTC-NC55	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle **Validation and Refinement of a Novel Deicing System for Stay Cables**		5. Report Date February 2020 6. Performing Organization Code CAIT/Rutgers University
7. Author(s) [1]Mott, S., [1]Moon, F., and [1]Basily, B.		8. Performing Organization Report No. CAIT-UTC-NC55
9. Performing Organization Name and Address [1] Center for Advanced Infrastructure and Transportation (CAIT), Rutgers University, 100 Brett Rd., Piscataway, NJ 08854		10. Work Unit No. 11. Contract or Grant No. DTRT13-G-UTC28
12. Sponsoring Agency Name and Address Center for Advanced Infrastructure and Transportation Rutgers, The State University of New Jersey 100 Brett Road Piscataway, NJ 08854		13. Type of Report and Period Covered Final Report 7/1/18 – 2/29/20 14. Sponsoring Agency Code
15. Supplementary Notes U.S. Department of Transportation/OST-R 1200 New Jersey Avenue, SE Washington, DC 20590-0001		

16. Abstract

Ice accumulating on the stay cable sheaths of cable-stayed bridges and falling to the roadway below has become a growing concern due to the traffic disruptions that they cause as well as the property damage to vehicles below. These large chunks of falling ice, known as "ice bombs" can cause high property damage as well as safety concerns. As of right now there is no industry standard when it comes to solving this issue. The novel deicing system, "SHAKEY", shows promise in alleviating this ice bomb dilemma. The SHAKEY deicing unit employs an array of vibrating masses that operate inside the protective stay cable sheath. Traveling between the steel cable strands and the protective sheath covering them, SHAKEY aims to use mechanical vibrations to shed any ice that has accumulated around these stays. This project will attempt to emulate the ice formation found on at-risk cable-stayed bridges and validate the effectiveness of the SHAKEY system at removing this ice. Fabrication of the prototype SHAKEY deicing unit as well as the design and construction of an appropriate operating platform on which to validate SHAKEY was also developed in this project.

17. Key Words De-icing, winter maintenance, cable-stayed bridge, environmental testing	18. Distribution Statement		
19. Security Classification (of this report) Unclassified	20. Security Classification (of this page) Unclassified	21. No. of Pages 44	22. Price

Form DOT F 1700.7 (8-69)

Acknowledgements

The authors would like to express appreciation to Carson Carney from SHAKEY Deicing, LLC, Jeff Purdy and his team of Tom Golecki, Navid Zolghadri, and Jack Reilly at Pennoni for their efforts with the weather monitoring system and predictive modelling, and to the Rutgers Center for Advanced Infrastructure and Transportation for making this project possible.

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Descriptions of Problem

Ice accumulating on the stay cable sheaths of cable-stayed bridges and falling to the roadway below has become a growing concern due to the traffic disruptions that they cause as well as the property damage to vehicles below. These large chunks of falling ice, known as “ice bombs” can cause high property damage as well as safety concerns. As of right now there is no industry standard when it comes to solving this issue.

Description of Ice Bombs and The Types of Ice Formed on Bridge Cables

As mentioned above, ice formed on stay-cables has the potential to eventually fall to the roadway below in large sections. These ice bombs damage the vehicles below and create a significant safety hazard to motorists. The ensuing lane closures on the bridge whenever there is potential for ice bombs also causes substantial economic losses as well as inconveniences to those traveling on the bridge.

Figure 1 Ice forming on a cable stay [1]

Figure 1 above shows what the icing on a cable-stayed sheath looks like. There is typically a layer of ice or “lens” formed over the top half of the stay sheath, forming into a less uniform distribution of hanging icicles on the underside. The ice formed on these cable stays happens primarily when a mix of certain weather conditions within the bridge’s microclimate are met.

The ice accretion which has been found to potentially lead to ice bombs forms primarily when freezing rain or snow occurs on the bridge, and supplemental weather conditions such as fog combined with ambient temperatures below freezing have also been know to form these icing patterns [1].

Once ice accretion has occurred on the stay cable sheaths, if additional weather conditions are met, the ice has the potential to begin falling to the roadway below in the form of ice bombs.

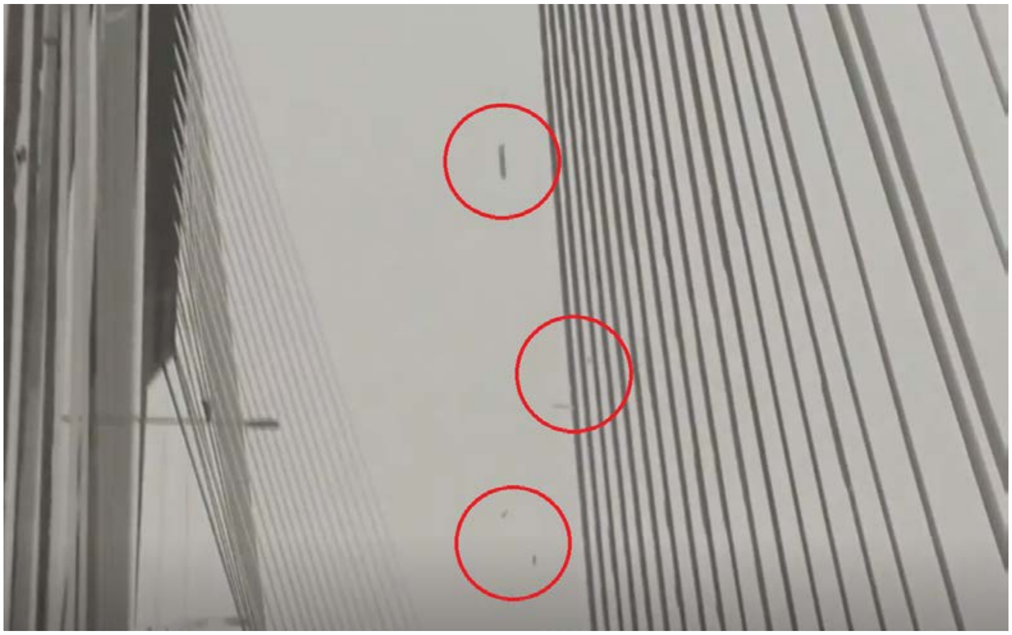

Figure 2 Ice bombs falling from cable stayed bridge

It has been observed that the combination of ambient temperature increasing above freezing, clear skies leading to an increase in solar radiation, and gusty winds, can lead to the formed ice to begin shedding. A rise in ambient temperature around the bridge alongside increased solar radiation from a sunny day will cause the ice directly touching the sheath's surface to begin to melt, forming a layer of water between the remaining outer layer of ice and the cable sheath below. As the ice begins to crack along the sheath, gusty winds can then begin to blow large pieces of the ice off of the cable stays and onto the roadway below [1].

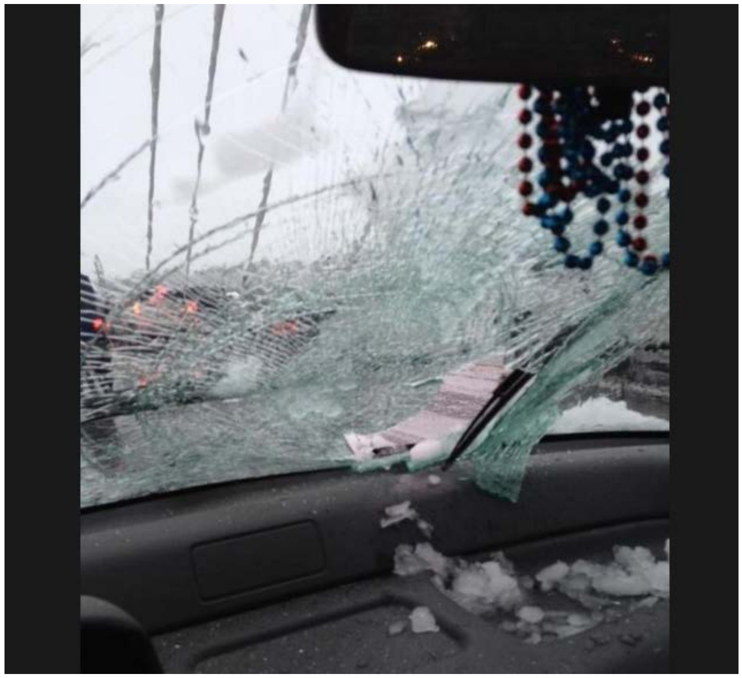

Figure 3 Ice bomb damage to car

The falling ice bombs can cause significant property damage to the vehicles below as well create a dangerous environment for motorists. Figure 3 above shows just how damaging these ice bombs can be with the potential to dent car bodies and shatter windshields.

Bridges & Areas at Risk

Although ice bombs are not a common occurrence on cable-stayed bridges, any bridge that has the potential to experience an ice storm within its location is at risk.

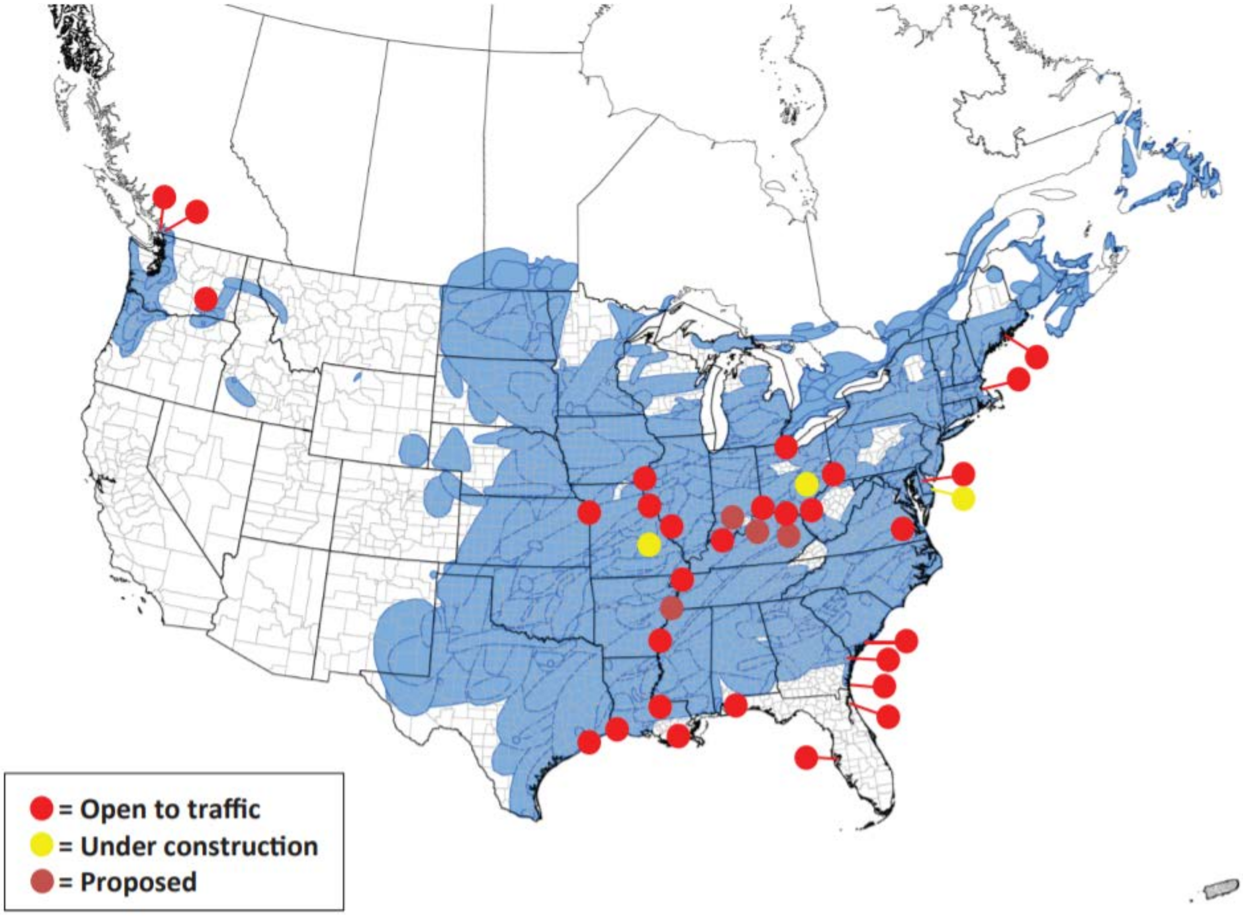

Figure 4 Known cable-stayed bridges in mainland United States and lower Canada, 1946-2014 [2,3]

Figure 4 above shows cable-stayed bridges throughout the United States and lower Canada that fall within areas, shown in blue, which have historically been subject to ice storms. Ice bombs have been known to fall from many cable-stayed bridges with multiple occurrences over different years. Some of the more significant ice bomb events are listed on the bridges below.

- 2005 – Leonard P. Zakim Bunker Hill Bridge, MA
- 2006 – Penobscot Narrows Bridge, ME
- 2009 – Severn Bridge, England
- 2011 – Uddevalla Bridge, Sweden
- 2012 – Port Mann Bridge, Canada
- 2012 – Alex Fraser Bridge, Canada
- 2014 – Ravenel Bridge, SC

The seriousness of this ice bomb issue has caused new construction of cable-stayed bridges, such as the Gordie Howe International Bridge joining Windsor to Detroit, to now begin including provisions for cable deicing.

Cable Deicing Systems Currently in Operation

One system that is currently in use on cable stayed bridges such as the Port Mann and Alex Fraser Bridges in British Columbia, is the snow clearing collar system.

Figure 5 The Port Mann and Alex Fraser cable-stayed bridges in British Columbia

These collars are essentially made up of lengths of heavy chain which are driven by gravity and the self-weight of the collar to scrape away any snow or ice built up on the stay sheath as it is released from the top of the stay and travels to the bottom. Up to 30 of these collars can then be loaded into a hangar located at the top of the stay which individually releases each collar when needed.

Figure 6 Deicing collar in operation

While these collars can effectively remove ice from the cable stays, they also cause damage to the helical rivulet on the outside of the cable-stay sheath as well as cause wear and tear on the HDPE sheath itself. Teams of rope access technicians also need to be deployed in potentially dangerous weather conditions in order to manually restock these collars so that they can be deployed when needed. A recent storm which occurred near the two bridges mentioned above had still experienced ice bombs even after with these deicing collars were installed, causing extensive damage to travelling vehicles.

Other Potential Proposed Cable Deicing Systems

A 2015 study performed by The University of Toledo for the Ohio Department of Transportation (DOT) to alleviate ice bombs experienced on the Veterans' Glass City Skyway (VGCS) cable-stayed bridge, explored a broad sampling of every anti-icing and deicing technology that was being used on any kind of structure for their potential effectiveness at removing ice from stay-cables. This study included a list of active and passive systems that were currently being used in fields such as aviation and for marine structures, and did not necessarily have to be directly related to bridges. All of the 75 potential technologies explored in the literature review were categorized into the following list of 13 categories (1)

1. Chemical and chemical distribution
2. Coatings
3. Modifying the stay design to prevent ice accumulation
4. Electro-expulsive electrical deicing systems
5. Pneumatic expulsive deicing systems
6. Hot air
7. Infrared radiant heat
8. Heating the ice–substrate interface
9. High-velocity water, air, or steam

10. Manual deicing methods
11. Piezoelectric
12. Vibration or covers
13. Ice detection

Out of all technologies investigated only three of the 13 categories were chosen as practical applications for stay-cable deicing and were further tested for their performance. The three selected categories were chemicals (sodium chloride, agricultural products, beet heat, calcium chloride), coatings (Hydrobead), and heat (internal heating, forced air, air with piccolo tube, steam heating element).

Figure 7 Passive coating system being used for aviation

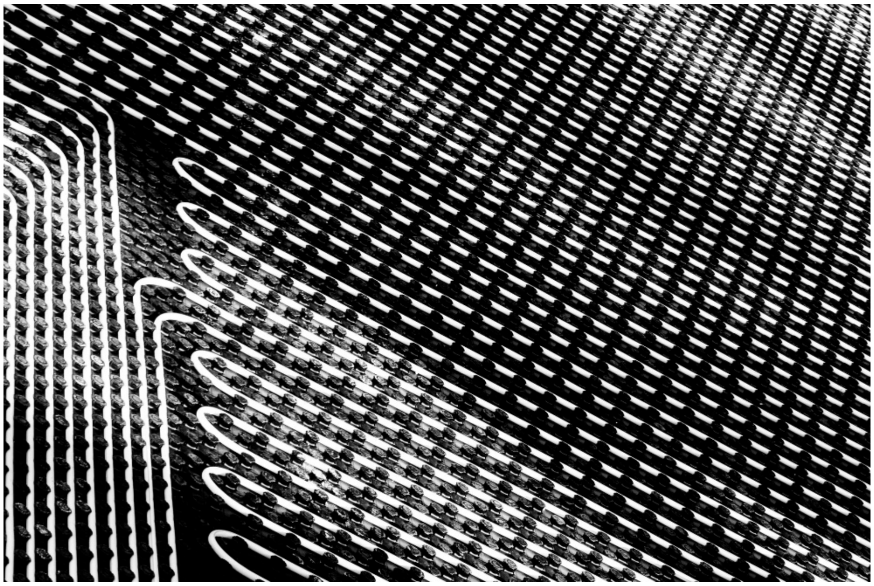

Figure 8 Active thermal deicing system

After each potential technology had been extensively tested, it was determined that none of them would be adequate to fill the needs of Ohio DOT for the prevention of ice bombs on the VGCS bridge. Each of the particular technologies tested either could not effectively remove the ice or prevent it from forming on the stay-cable sheaths (chemicals and coatings), or were financially impractical due to high energy consumption while in operation (heating).

Approach

The novel deicing system evaluated within this report was developed to alleviate the shortcomings of the current solutions available to the ice bomb dilemma. This deicing system, named "SHAKEY", employs vibrating masses to shake free any ice formed around the protective stay cable sheath and would be deployed within the lower free interstitial space between the steel cables and the sheath.

Concept Behind SHAKEY

One of the key concepts behind the development of SHAKEY is that it would be internally deployed, preventing any damage to the outside of the cable sheath. Operating within this interstitial space, SHAKEY would rely on its multi vibrator sled to shed any ice that may form around the HDPE sheath during ice storms through mechanical vibrations.

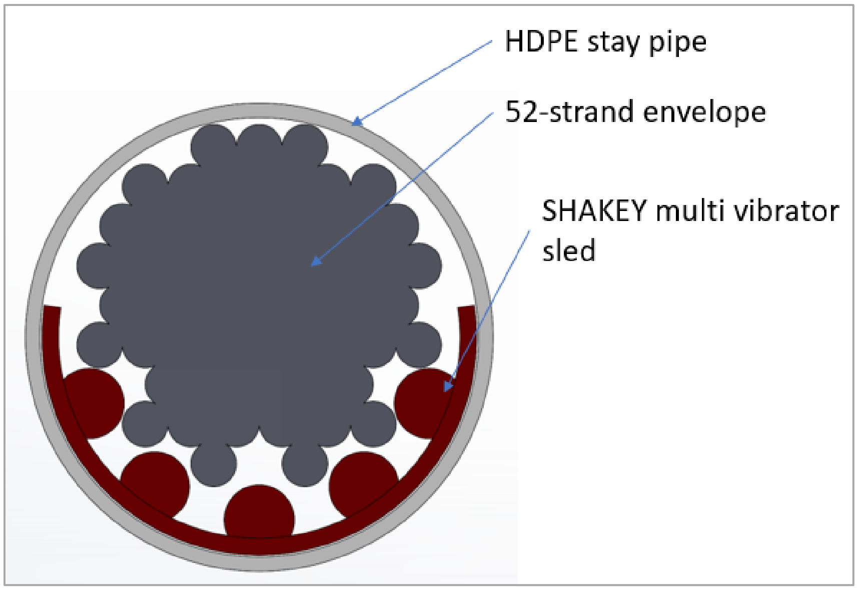

Figure 9 Conceptual SHAKEY device within the interstitial space between stay cables their and sheath

The prototype SHAKEY "sled" portion of the system would carry anywhere from one to five of these individual vibrators and would slide up and down the length of each stay cable through the use of a winch system as shown in Figure 10 below.

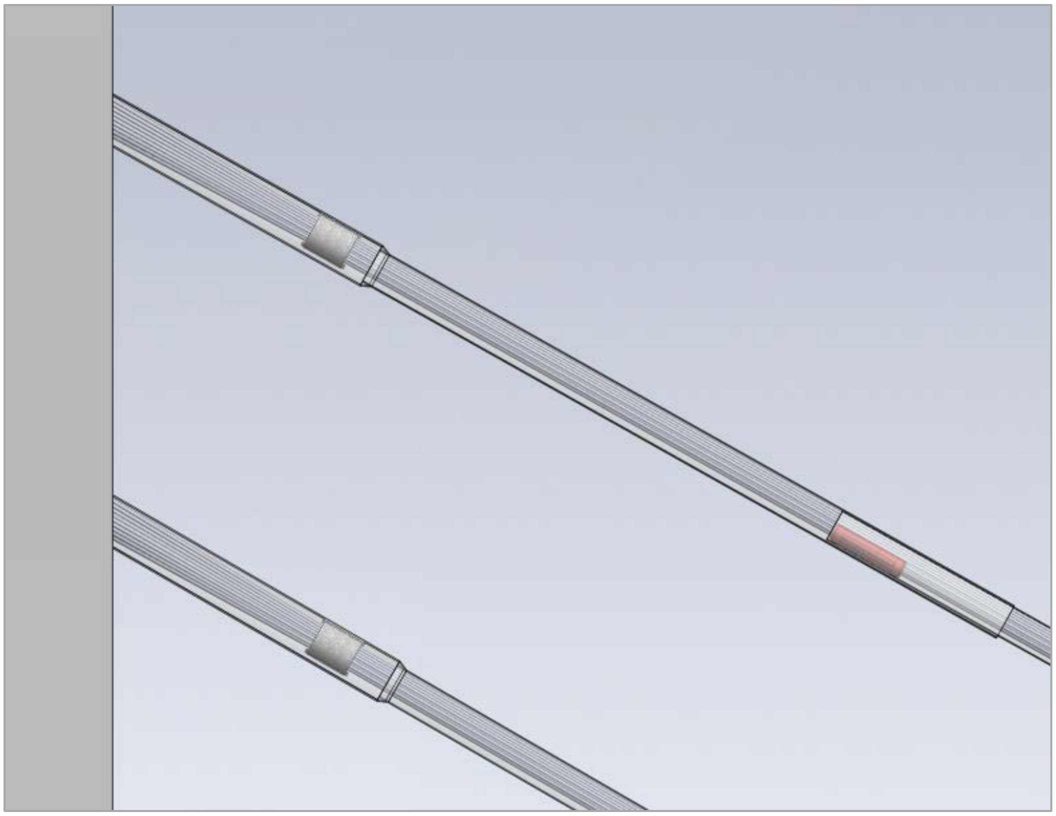

Figure 10 Concept of SHAKEY sled (in red) internally moving up and down the stay cable

The proposed deployment system would either allow for the sled to be gravity driven downward through the sheath via a rope or cable and raised back up with a winch system, or driven both ways by the winch depending on how well the sled's gravity driven performance allows its travel downward.

Keeping the system internal to the stay pipe sheath allows each unit to be protected from the surrounding weather conditions. This internal placement will also not change the outside dimensions of the stay pipe, keeping all of the original aerodynamic characteristics of the sheath. Another advantage of the internal deployment is that it will not damage or wear the raised helical rivulet found along the outside of cable stay sheaths which is critical in reducing rain and wind oscillations.

Operationally, the SHAKEY units could be activated at a time convenient for the bridge owner to close down the bridge in question to traffic and shed any ice from the cable stays without risk of damage to vehicles below.

Development of SHAKEY Prototype

Fabrication of the prototype SHAKEY unit was made using carefully selected commercial concrete vibrators attached to an machined aluminum sled. These vibrators would be set into appropriately sized slots in the sled and fixed to the sled through custom machined nose blocks and tail attachment pieces as shown in the design plans below in Figure 11.

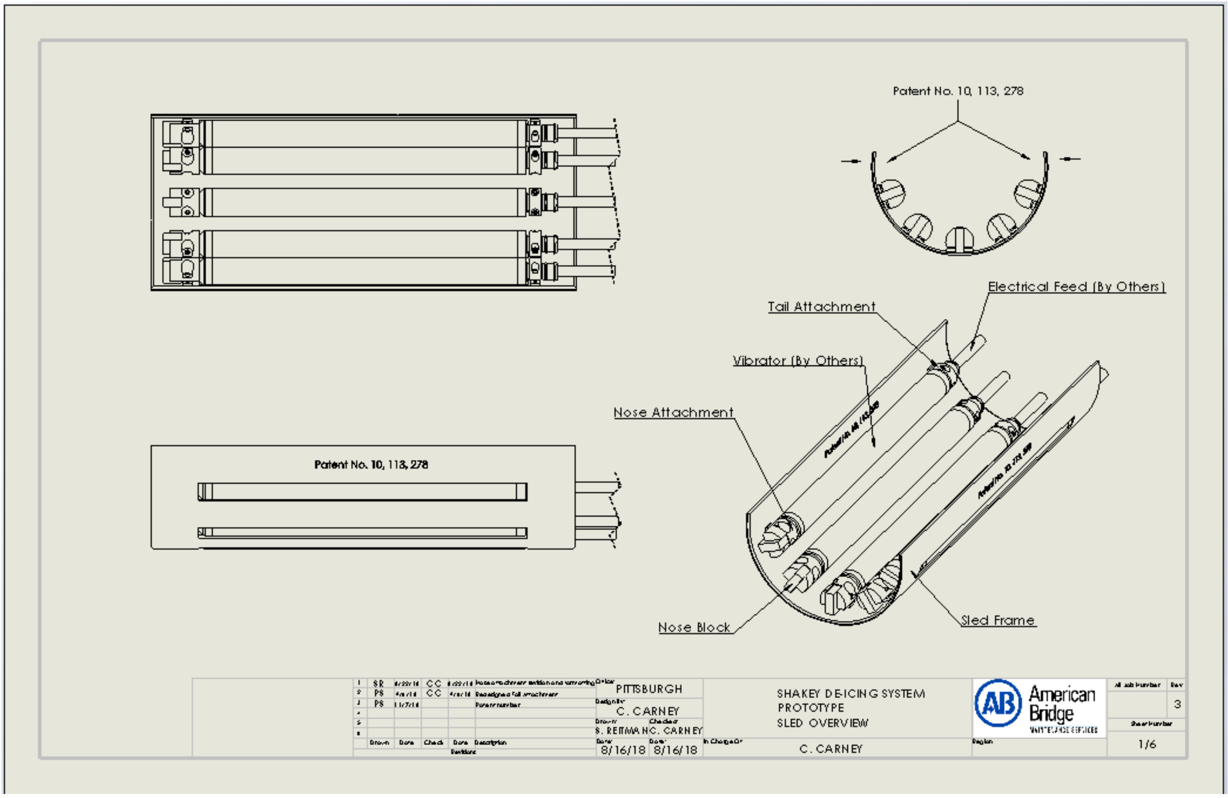

Figure 11 SHAKEY prototype design plans

The sled was originally designed with five of these cylindrical concrete vibrators powering the system acting as the primary mechanism for ice shed. The number of vibrators was later reduced to three in order to bring down the overall power required to operate the completed unit, with the option to expand back up to five if the additional vibrating power seemed necessary.

Figure 12 Machined aluminum SHAKEY sled with vibrator attachment pieces

The sled as well as all vibrator attachment pieces were machined with lightweight aluminum and was slotted to hold up to five vibrating units and their respective attachment pieces as shown in Figure 12 above. Each of the vibrator attachment pieces would be held to the sled through four stainless steel screws. The height on each nose block could be adjusted via a larger internal screw mechanism that would hold the spherical front end of the vibrator tightly in place.

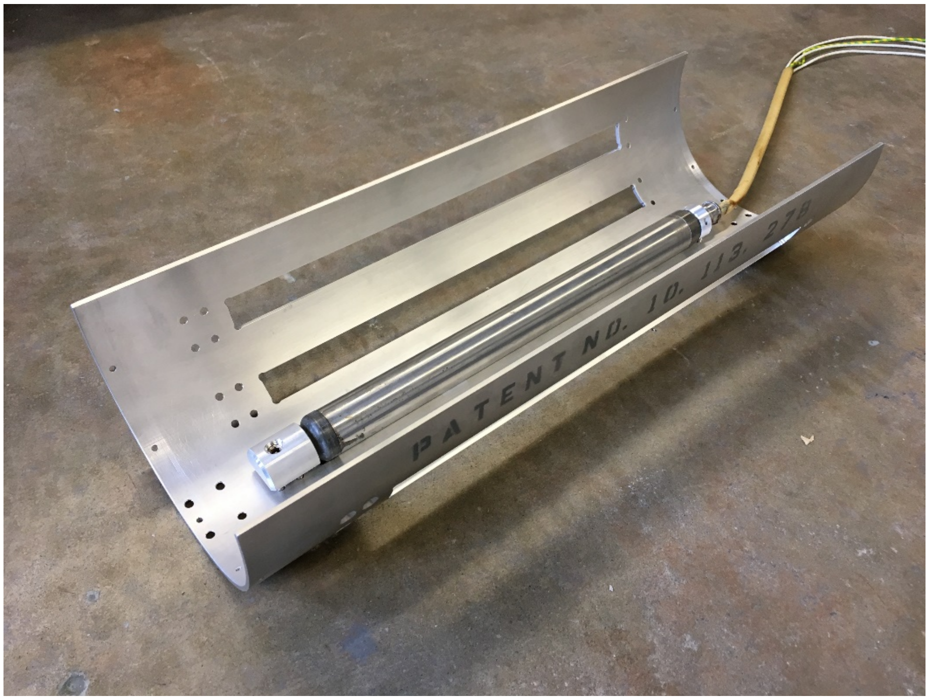

Figure 13 SHAKEY sled with single vibrator attached

Once attached, the slotted aluminum sled would allow each vibrator to settle into the sled and sit flush with the sleds outside diameter. This in turn would allow the kinetic energy from the vibrations produced from each vibrator to be directly transferred to the HDPE sheath and any ice which may have formed around it.

Deicing Prototype Operating Platform

In order to test the effectiveness of SHAKEY's deicing potential, an operating platform was designed which would emulate a small section of stay cable on a full-sized bridge, as well as the ice accumulation which may form around it.

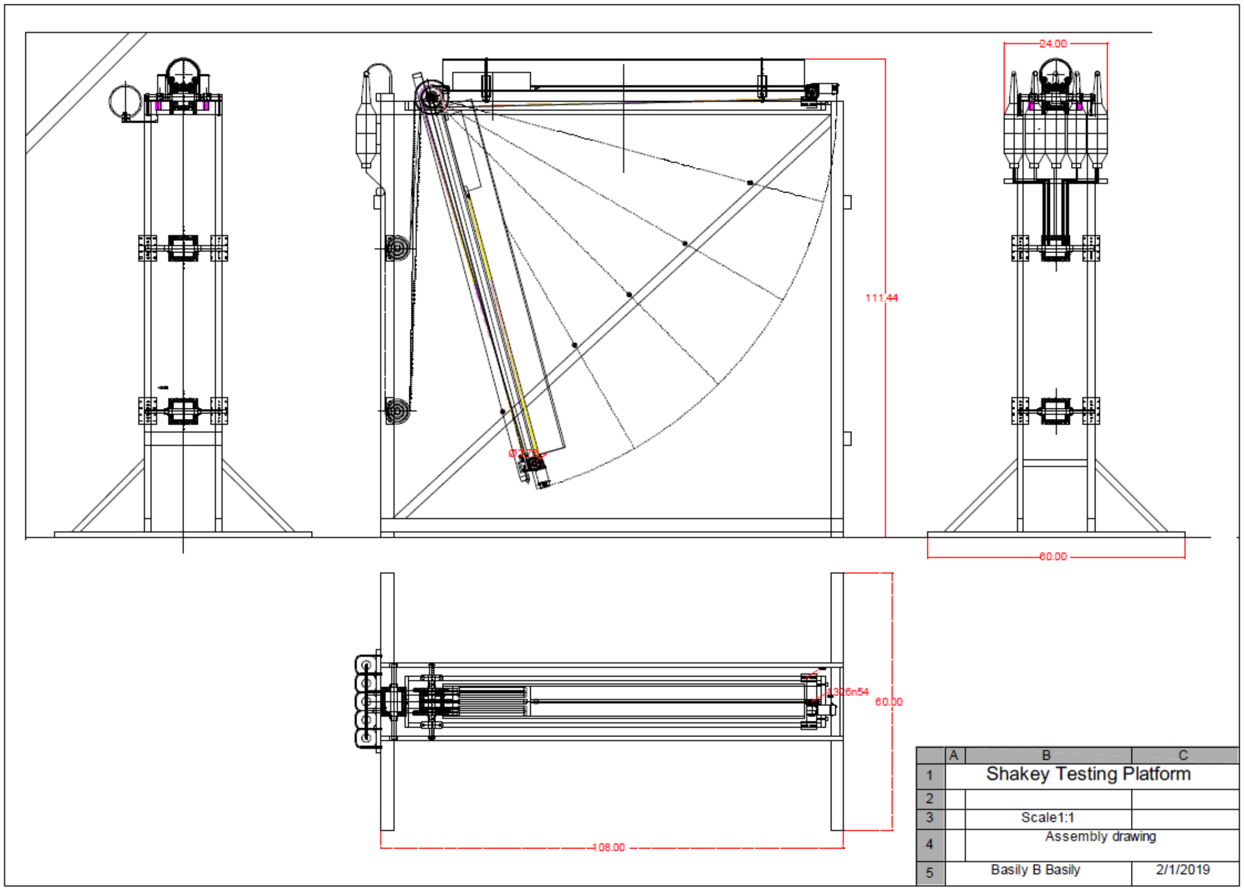

Figure 14 Operating platform design plans

The operating platform to be used with the SHAKEY system was designed with a seven-foot section of 200 mm HDPE pipe commonly used for bridge stay cable sheaths. The proposed operating platform frame was designed with the following capabilities in mind:

- Flexibility to perform tests at different HDPE pipe angles
- Variable speed timing belt with attachment points used to drive prototype deicing device up and down the HDPE pipe
- Variable speed timing switches to offset wait time between cycles at the top and bottom of the pipe when raising and lowering deicing prototype device
- Pully system capable of fully retracting any attached cables used on moving deicing prototype devices
- Optional mounting hardware for an additional 7 ft. side mounted HDPE pipe which could be used for future control deicing tests alongside active testing

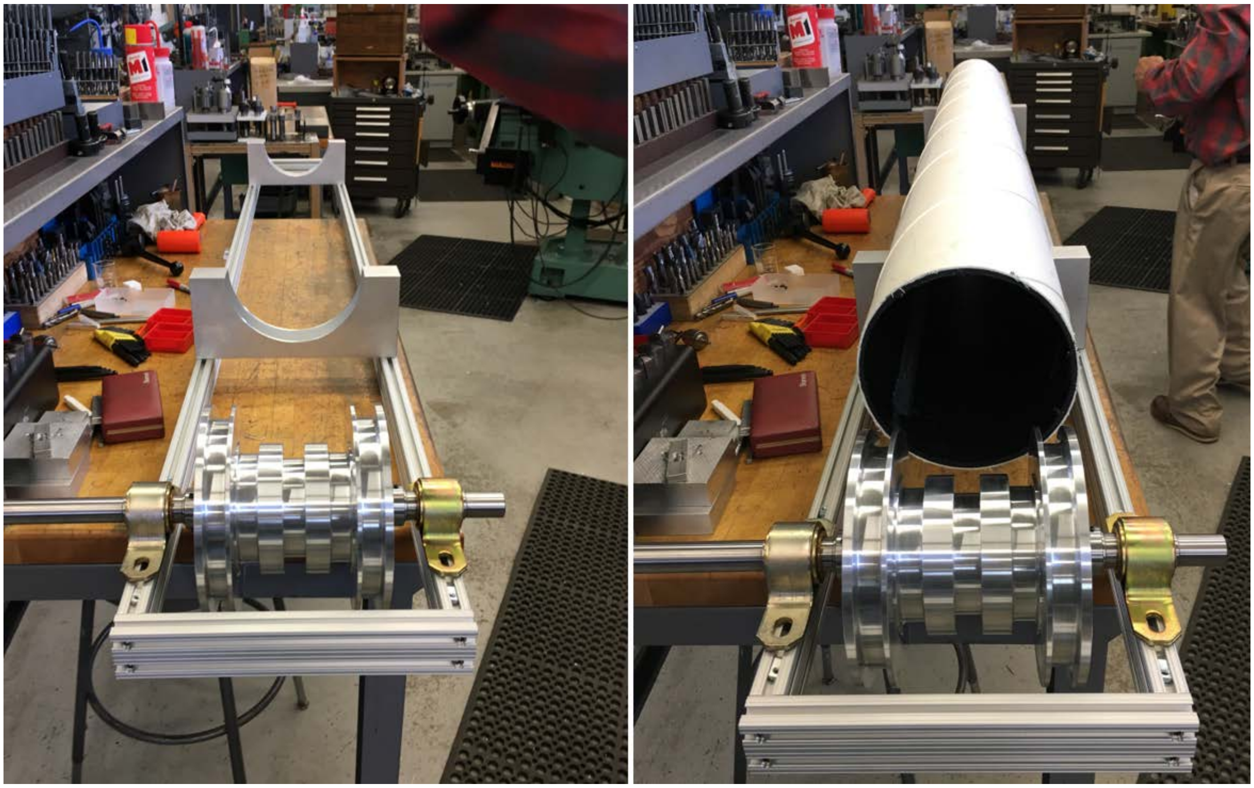

Figure 15 Aluminum machined top section of operating platform with and without 7 ft. HDPE pipe

One of the key features of the operating platform was a pulley system designed to handle cable management for all of the attached vibrator power cables as they moved up and down the section of stay pipe.

Figure 16 Frame fully assembled with cable management pulley system

In order to move the SHAKEY sled along the length of HDPE pipe, a timing belt was used which would allow for precise control over the sled’s position and speed within the section of pipe. The rate of travel that the timing belt was set to was approximately 7 ft/min for testing purposes. While originally a winch system was envisioned for use on a full-scale bridge, a timing belt was ultimately decided to be better for our testing purposes when focusing on the effectiveness of the internal vibrating mass concept which SHAKEY employs.

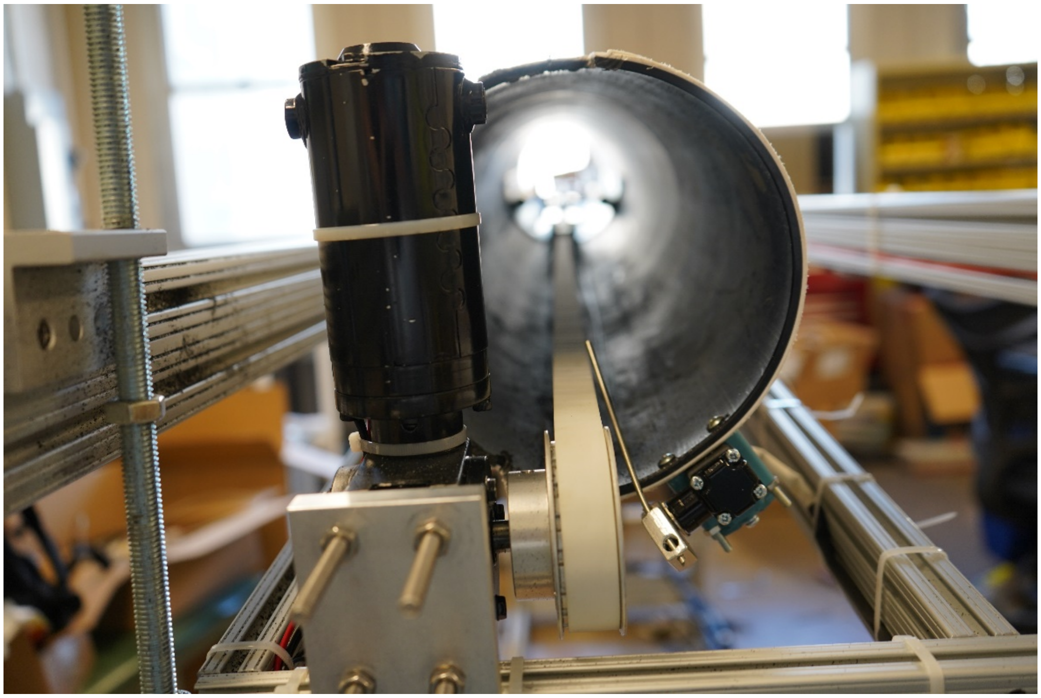

Figure 17 Operating platform timing belt

Operating Platform Spray System

A spray system was also incorporated into the operating platform which would allow the creation of ice formations similar to what is found on full length stay cable sheaths and would potentially come down in the form of ice bombs.

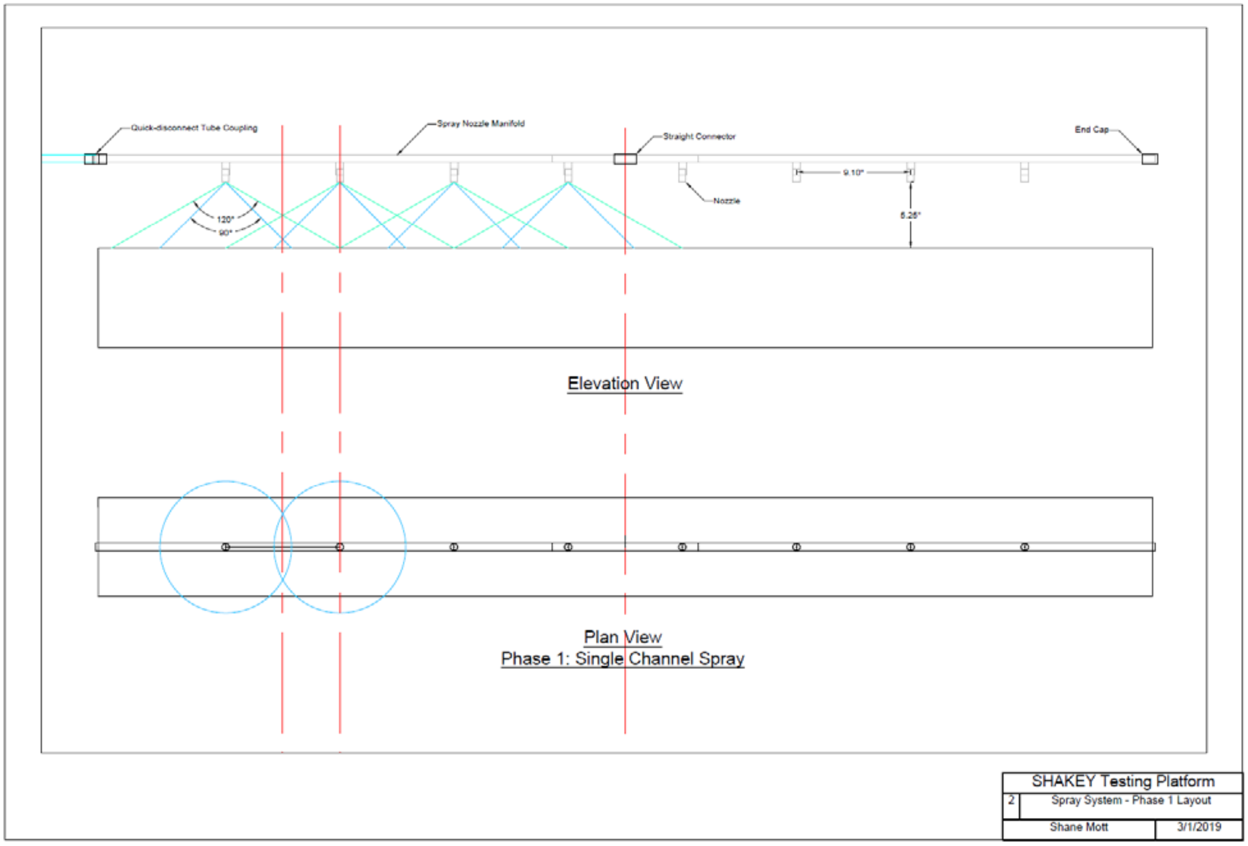

Figure 18 Design plans for ice forming spray system over HDPE pipe

In order to form the most uniform ice thickness within the space available, an assortment of spray nozzles with different spray angles and flow rates were tested at various heights above the HDPE pipe. This spraying when exposed to the freezing temperatures of our testing chamber would aim to replicate ice formed along full scale stay cable sheaths as accurately as possible. The overarching goal of the system was to have the ability to cover a wide range of ice thicknesses relevant to what could be found on a real-world bridge, while at the same time keeping the lens thickness distributed as evenly as possible over the top half of the HDPE specimen pipe section. Interval spraying as well as constant spraying at various freezing temperatures were tested, with constant spraying of water being the more desirable of the two methods when forming ice.

Figure 19 Example image of ice formed by the spray system in one the performance tests

Weather Monitoring System & Predictive Modelling

Alongside the SHAKEY deicing system, testing and development of a weather monitoring system by Pennoni was also employed in this project as a supplement to the active ice shed system. Data collected using each sensor on the weather monitoring station could eventually be used for predictive modeling of when the environmental conditions causing ice bombs to form were met. These predictions could then be used in deciding when the critical times to activate the SHAKEY units on a bridge should be.

The completed weather monitoring system focused on the following variables to help understand what causes ice bomb.

- Environmental Variables include
    - Air Temperature
    - Wind
    - Precipitation
    - Humidity
    - Solar radiation
- Physical Variables include
    - Ice presence
    - Water presence under ice
    - Bridge Temperature
    - Vibration

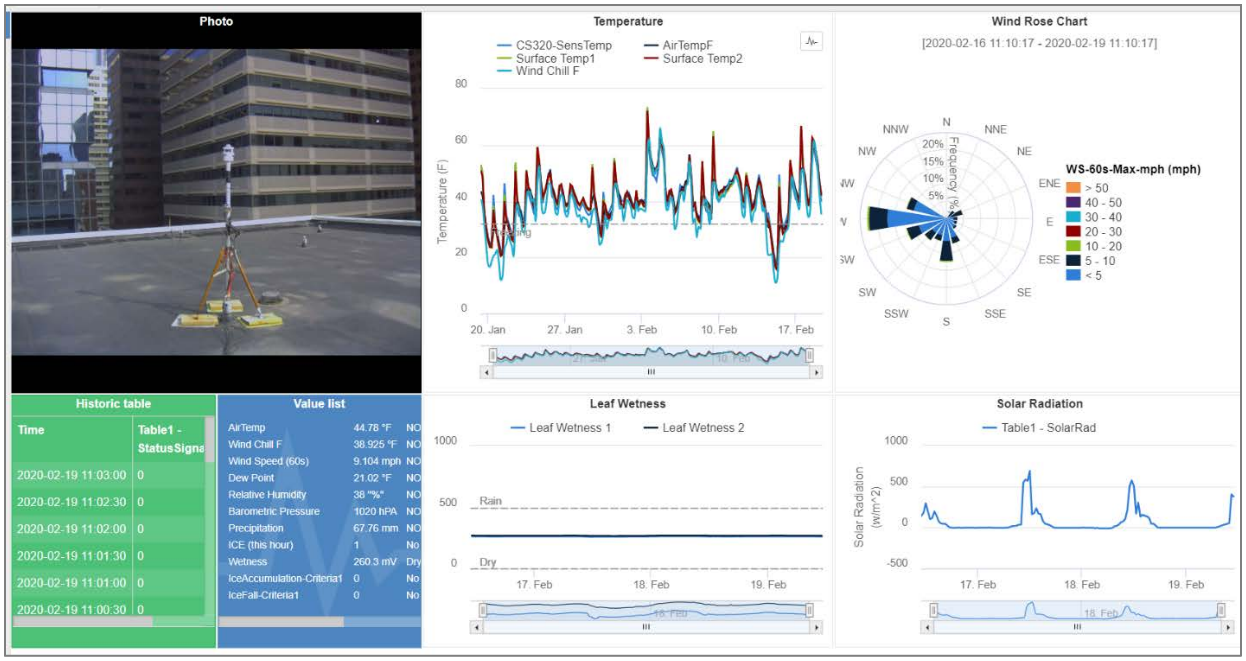

Figure 20 Pennoni eagle.io real-time weather monitoring dashboard

Above is the dashboard page of Pennoni's eagle.io real-time weather monitoring and data logging software. This system is broken down into a variety of weather monitoring sensors relevant to ice formation.

Figure 21 Weather station setup alongside testing frame

Eventual employment of each of these sensors on an at-risk bridge would help to better understand exactly which environmental and physical variables have the highest risk of causing ice bombs to occur and could eventually be used in predicting when to ideally put into action a system like SHAKEY.

Methodology

Testing Environment

The full deicing test system was set inside of an enclosed climate controlled refrigerated area in which ice could be formed. Ambient temperature was set to 15 °F as the spray system turned on during ice formation, and was slowly increased to 50 °F at an average rate of ~1 °F /min once SHAKEY was activated during the ice shed tests. The 50 °F temperature was selected to represent temperatures on the higher end found in areas with at-risk bridges during a wintertime daytime rise in temperature, creating similar conditions which produce ice bombs.

Test chamber environmental testing temperatures:

- Ambient temperature (ice formation) – 15 °F
- Beginning ambient temperature (ice shed) – 15 °F
- Final ambient temperature (ice shed) – 50 °F
- Avg. temperature increase rate (ice shed – 1 °F/min)

Testing Procedure

When determining the thickness of ice to be shed in each trial test, measurements were taken of the ice lens sitting on top of the HDPE pipe. The measurements started at the top of the pipe's outer diameter to wherever the glazed ice covering the pipe ended. Measurements were recorded as a range of the average minimum and maximum ice thicknesses covering the pipe. Ice formation on the top of the sheath varied slightly overall due to the nature of the spray system, which was taken into consideration when determining which values the ice lens thicknesses would fall into for the testing. Areas directly underneath the spray nozzles where ice tended to occasionally artificially accumulate were avoided when measuring the lens thickness.

These thicknesses were estimated visually through the use of corrosion resistant rulers fixed to the top of the cable sheath. Areas of ice directly around these attached rulers were also avoided when estimating average ice thickness since ice would artificially accumulate in these areas as well.

Figure 22 Rulers attached above sheath used to estimate ice lens thickness measurements

The following measurements were used to define the ice thicknesses on each active trial run for SHAKEY.

- 1-7 mm lens thickness = light ice accumulation
- 7-20 mm lens thickness = medium ice accumulation
- 20-30+ mm lens thickness = heavy ice accumulation

The U.S. National Weather Service defines an ice storm as an event when has a minimum of 6.4 mm (0.25 in.) of ice accumulation, which would fall just within the upper limits of our “light” ice accumulation classification. If the ice lens fell between 7-20 mm, the ice thickness was classified as “medium” ice accumulation, and anything in the range of 20-30 mm and over would be considered “heavy”. When comparing this to real world icing events, our medium range of 7-20 mm of ice accumulation would be considered to be on the more severe side, and our heavy accumulation of 20-30+ mm would represent the most extreme weather cases. The spray system utilized in this testing was able to create ice thickness up to 50 mm on top of the HDPE pipe.

Test Plan

The criteria below were used for the planned list of tests at which SHAKEY was to be evaluated. Ice shed performance was tested at both horizontal and angled positions with different ice lens thicknesses.

- Sheath at 0° angle, light ice accumulation (1-7 mm thick lens)
- Sheath at 0° angle, medium ice accumulation (7-20 mm thick lens)
- Sheath at 0° angle, heavy ice accumulation (20-30+ mm thick lens)
- Sheath at 25° angle, light ice accumulation (1-7 mm thick lens)
- Sheath at 25° angle, medium ice accumulation (7-20 mm thick lens)
- Sheath at 25° angle, heavy ice accumulation (20-30+ mm thick lens)

Repeatability of performance at each thickness and angle were also planned, but due to delays in fabrication, as well as mechanical failures which are discussed in more detail later in this report, not all planned repeatability test for each criterion was able to be performed.

When visually assessing the SHAKEY system, the following performance metrics were used to determine how well the system performed:

- Did the deicing system crack the ice lens? If so, was it able to do it one the first pass through?
- If the system cracked the ice lens, did it actively shed the ice as well? How many passes did it take to begin shedding the ice from the stay pipe and approximately how much was shed per pass?
- How well SHAKEY shed the icicles formed underneath the specimen stay pipe

Full shed was considered to be when approximately 90% of the ice had been shed from the sheath. Some tolerances were given due to physical differences on the specimen section of sheath making ice shed more difficult to achieve than it would on a full-sized stay cable, such as the rulers used to measure ice thickness on the top of the pipe giving more surface area for the ice to cling to in some areas.

Data Collection

SHAKEY was evaluated both visually and quantitatively while determining its effectiveness shedding the ice. Bench scales attached to a data acquisition system (DAQ) were used in combination with an ice catching basin that any ice shed would fall into. The ice catching basin would lay directly below the ice covered stay pipe with the DAQ periodically recording the weight of ice being shed by SHAKEY at a frequency of one sample per second (1.0 Hz).   Visual data of the ice shed was also recorded through the use of two weatherproof video cameras.

Figure 23 Ice shed catch basin frame and bench scales (left). Basin sitting on top of scales (right)

The weigh data logged from these bench scales can then be converted to percent ice shed at any point in time once SHAKEY's vibratory sled has been activated, by comparing the cumulative weight the shed ice caught in the catch basin to the overall weight of the ice once it has been fully shed.

Completed SHAKEY Evaluation System

Figure 24 Fully completed SHAKEY system with operating platform and monitoring equipment

The figure above shows the fully constructed cable deicing operating platform with SHAKEY sled, spray system, and weather monitoring station.

The goal of this operating platform was to not only provide a platform for SHAKEY's performance to be evaluated, but to also allow Rutgers to test future cable deicing prototypes on it within the environmental chamber of CAIT's Bridge Evaluation and Accelerated Structural Testing (BEAST) laboratory with some minor modifications.

Below is a brief summary of the testing specifications used for the system

- HDPE pipe length – 7ft.
- HDPE pipe diameter – 200 mm
- Active sled travel speed – 7 ft/m
- Angles tested – 0° to 25°
- Ice thicknesses tested – 0 to 30+ mm
- Number of vibrators active – 3

Findings

SHAKEY was observed to shed the ice just as well at the thickest ice lens thicknesses as it did with the medium thicknesses tested. An example of how the system shed one of the heaviest ice accumulations tested, which had an ice thickness range of 20 to 50 mm is demonstrated in Figures 25-32.

Although the system shed the ice well at thicker ice accumulations, it struggled to shed the thinnest ice layers that fell within the 1 to 7 mm range. As the ambient temperature would rise from 15 to 50 °F, the water layer that began to form beneath the ice and between the lens and stay sheath began to cause the cracked sections of ice to "stick" to the sheath on these lighter accumulations. It seemed that there was not enough weight for gravity to allow for these pieces of ice to drop from the pipe even after they had been cracked and shaken loose by the deicing system.

Visual Demonstration of How SHAKEY Sheds Ice

The set of figures below gives a visual example of the active SHAKEY system shedding the formed ice. Each of the figures show one full cycle of the active vibratory sled which consists of one pass up and down the length of the specimen stay cable sheath. The following test was performed at a 25° sheath angle and demonstrated heavy ice accumulation with a lens thickness ranging from 20 to 50 mm along the top of the sheath.

This visual ice shed demonstrated in the following figures (Figures 25-32) was on the extreme end of the largest ice thicknesses tested, and was indicative of how the other ice layers shed at each angle with the exception of the thinnest layers as mentioned previously.

Figure 25 Example ice shed at 25° sheath angle, heavy ice accumulation - 0 cycles

Figure 26 Example ice shed at 25° sheath angle, heavy ice accumulation - 1 cycle

As the active vibratory sled moves through the stay pipe in Figure 26, the ice lens directly around that area begins to crack, and all icicles that had formed underneath the specimen pipe as well as the majority of the adjacent ice on the bottom half of the sides are shed.

Figure 27 Example ice shed at 25° sheath angle, heavy ice accumulation - 2 cycles

Figure 28 Example ice shed at 25° sheath angle, heavy ice accumulation - 3 cycles

Figure 29 Example ice shed at 25° sheath angle, heavy ice accumulation - 4 cycles

Figure 30 Example ice shed at 25° sheath angle, heavy ice accumulation - 5 cycles

Figure 31 Example ice shed at 25° sheath angle, heavy ice accumulation - 6 cycles

Figure 32 Example ice shed at 25° sheath angle, heavy ice accumulation - 7 cycles

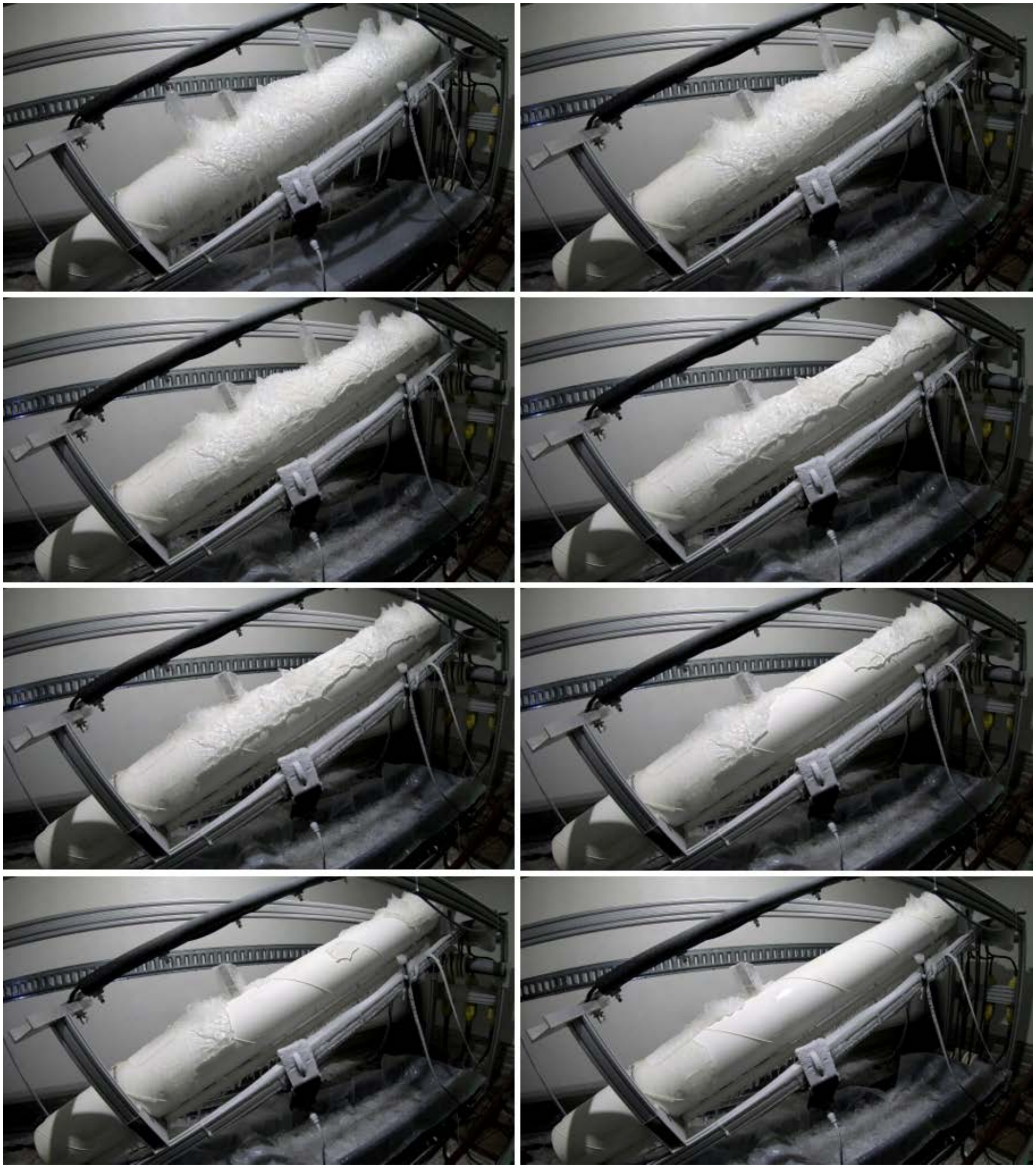

Figure 33 All of the 25° sheath angle, heavy ice accumulation, testing cycles shown together sequentially

Pictured above in Figure 33 is a side by side visual comparison of the SHAKEY system shedding ice over the seven cycles (14 passes) starting with SHAKEY in the inactive, stationary position. Out of all cycles shown in the above figure, there were some notable stages in the shedding which were also demonstrated in the other tests performed at a medium to heavy ice accumulation regardless of angle. These notable cycles include the following:

- **First pass**: Ice lens begins to crack, all icicles formed under the specimen pipe as well as the majority of ice on the bottom half are shed
- **Second pass**: The majority of additional cracking happens here
- **Intermediate passes**: mechanical vibrations from the system shake loose remaining loose sheets of ice

Table 1 below shows the accompanying weigh data to the test performed in Figure 33 showing percent total ice shed after each pass up or down the stay sheath.

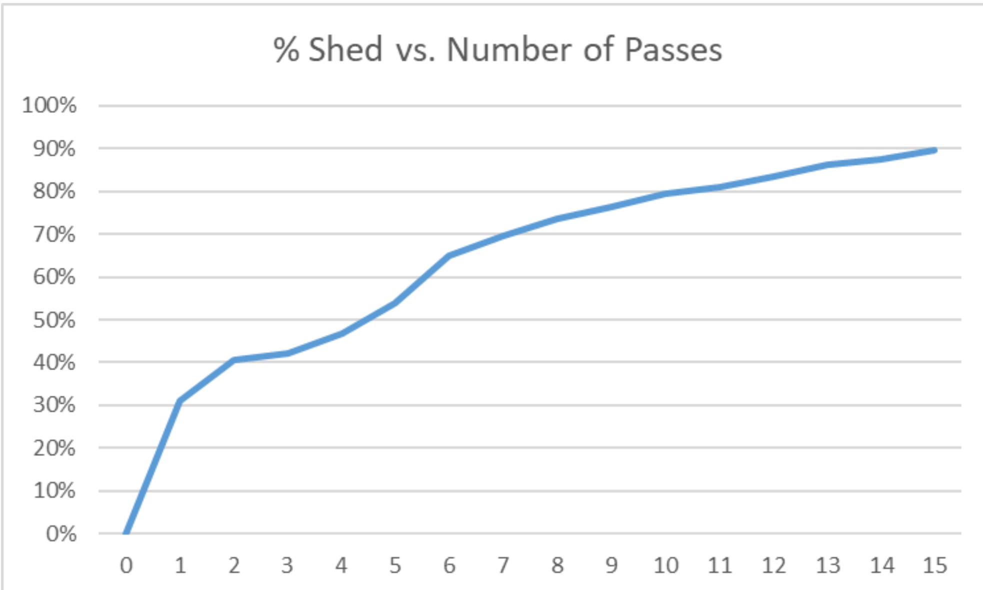

Table 1 Weigh data showing % shed vs. # of passes for 25° sheath angle, heavy ice accumulation

The quantitative weigh data taken from the bench scales at 25° sheath angle and heavy ice accumulation shown in Table 1 above shows a sudden spike in total shed weight after the first pass with the percent shed slowly tapering off for each subsequent pass after. This data coincides with the visual observation of SHAKEY cracking and shedding a large portion of the ice during the first active run.

Observed Performance at Different Angle and Lens Thicknesses

The table below outlines the observed performance of SHAKEY at each angle and lens thickness tested.

Sheath Angle	Ice Accumulation	Lens Thickness (mm)	Visual Assessment	
			First Pass	Subsequent Passes
0	light	1-7	Lens cracked, ice shed began starting with all icicles underneath sheath and partial shed from lower sides	Lens cracking continued each pass, ice shed of thinner lens sections struggled to fall
0	medium	7-20	Lens cracked, ice shed began (~1/3 total ice shed) starting with all icicles underneath sheath and partial shed from lower sides	Lens cracking continued each pass, ice shed continued from sheath sides then top of sheath
0	heavy	20-30+	Lens cracked, ice shed began (~1/3 total ice shed) starting with all icicles underneath sheath and partial shed from lower sides	Lens cracking continued each pass, ice shed continued from sheath sides then top of sheath
25	light	1-7	Lens cracked, ice shed began starting with all icicles underneath sheath and partial shed from lower sides	Lens cracking continued each pass, ice shed of thinner lens sections struggled to fall
25	medium	7-20	Lens cracked, ice shed began (~1/3 total ice shed) starting with all icicles underneath sheath and partial shed from lower sides	Lens cracking continued each pass, ice shed continued from sheath sides then top of sheath
25	heavy	20-30+	Lens cracked, ice shed began (~1/3 total ice shed) starting with all icicles underneath sheath and partial shed from lower sides	Lens cracking continued each pass, ice shed continued from sheath sides then top of sheath, full shed observed

Table 2 Observed performance at each angle and lens thickness

Although SHAKEY was able to be tested at the critical ice thicknesses and angles, not all desired repeatability tests as well as sheath angles tested were able to be performed due to mechanical failure of the vibrator attachment pieces as well as delays in the fabrication process. While SHAKEY's core concept of using internal vibrating masses to remove ice through mechanical vibrations was capable of effectively cracking and shedding medium to heavy ice accumulations, there were issues of durability in the design of the vibrator attachment pieces failing due to vibration fatigue. The four screws fixing the nose blocks and tail attachment pieces to the sled would slowly begin to fatigue and eventually shear off, allowing the vibrators attached to the aluminum sled to separate themselves. Overall, the way SHAKEY shed ice from each cable stay test remained fairly consistent throughout the different angles and ice lens thicknesses.

When it comes to evaluating the overall effectiveness of the ice shedding capabilities of the deicing unit, having the sheath angle set to 25 degrees and exposed to the heaviest ice accumulation that would realistically be seen on a full-sized bridge as demonstrated in the findings above, seems like the best benchmark when gauging performance. 25 degrees from horizontal would represent the flatter angles of cable stays, and should theoretically make the ice shed more difficult than the more vertical stays due to the lack of help from gravity. Additionally, the natural oscillations found in in the full-length cable sheaths on cable-stayed bridges as well as environmental factors such as wind were absent from these tests. Both of which should only aid in the shedding of any ice covering the sheath once sufficiently cracked by SHAKEY's vibrations.

Conclusions

Overall the core concept employed by SHAKEY, using mechanical vibrations internally on HDPE stay pipe sheaths, works well at shedding ice formed around the pipe, and the system shows promise in helping to solve the current ice bomb problem. The system was found to do particularly well in shedding medium to heavy ice accumulations ranging from 7 to 30+ mm.

In its current design form, there are some issues of durability that need to be addressed in order to overcome the mechanical failure of certain components caused by vibration induced fatigue. The current attachment pieces used on the prototype to hold each vibrator in place on the travelling sled are not adequate when it comes to resiliency to this fatigue. This issue should be able to be alleviated through a redesign of how the vibratory units are attached to the sled in the future.

Summary of Conclusions:

- SHAKEY's core concept of using internal mechanical vibrations to shed ice accumulated on stay cable sheath's works
- The system is most effective at shedding medium to heavy ice thicknesses
- Durability of the system in its current design form needs to be addressed

Recommendations

A redesign of the configuration between the sled and vibrators and how they are currently coupled together is recommended in order to alleviate the durability issues between the connection points between the two components failing. Eliminating the use of commercial vibrators and the need for connection pieces altogether through a more streamlined chassis with internalized vibrators built into the sled portion of the unit may be beneficial.

More focus on deployment of prototype units on a full-sized bridge is also recommended, with a focus on maintenance and power delivery in particular. Access to SHAKEY units for routine maintenance and repair from inside the sheath as well as estimates of how often each unit will need to be serviced should be looked into further. More extensive research on how power delivery and cable management of all attached cables both driving and powering the vibratory sled on a full-sized bridge should also be performed.

While the system excelled at shedding ice thicknesses from medium and heavy ice accumulations, more testing is recommended with a focus on the thinner ice layers formed around the sheath to see exactly at which point the system struggles to shed this ice, and if ice at this thickness is even a concern. Further testing with the SHAKEY unit operating alongside steel wire strands added inside the HDPE operating platform sheath would be useful as well. An additional phase of testing with the recommended updated design and more of a focus on the items talked about in this section would be beneficial.

Summary of Recommendations:

- Redesign of sled and vibrators recommended to increase durability
- Further research on deployment of deicing units on a full-sized bridge needs to be done
    - Access to units for routine maintenance and repairs
    - Power delivery and cable management of cables driving and powering SHAKEY
- Second phase of testing with new design recommended with a focus on the thinner ice accumulations as well sled operation alongside steel wire strands within the sheath

References

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