# Bridge ice accretion and de- and anti-icing systems: A review

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# Bridge ice accretion and de- and anti-icing systems: A review

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**Abstract**

Blocks of ice or snow falling from bridge members can cause traffic accidents, direct damages to passing vehicles, and generally place human safety at risk. Consequently, the lack of successful de- or anti-icing measures may result in bridge closure, which leads to traffic hindrance that can in turn lead to severe financial losses. This paper presents a review of the different de- and anti-icing techniques, already developed or in development, which could be applied to bridge cables or pylons. Furthermore, the fundamentals of icing caused by freezing precipitation and in-cloud icing are presented together with the physical mechanisms expected to induce ice shedding.

## 1 Introduction

Atmospheric icing of bridges can result in financial losses for a bridge operator and, more importantly, may put human safety at risk. With the potential of falling blocks of ice or snow frightening drivers or striking vehicles whilst passing over a bridge, traffic safety is not secured until the removal of the accreted ice or snow has been completed. In most cases, all traffic on a bridge has to be suspended until the snow or ice removal operation is completed.

Denmark's Great Belt Bridge has, over the 3-year period 2004-2007, been closed for 12 hours per year because of falling ice, which compared to a total yearly average of 14.3 hours is quite significant (Vincentsen, 2006). Similarly, the Øresund Bridge has had to close 5 times during the past 9 years under similar circumstances. A range of other Northern European bridges such as Uddevalla Bridge in Sweden and both the Severn Bridges in the UK have suffered from similar experiences (Vincentsen, 2006). To secure traffic safety and to reduce long bridge closures, it is important to develop novel measures against ice accretion.

A literature review of existing de- and anti-icing techniques within the fields of bridges, wind turbines, airplanes and power lines has been carried out. Those with the potential to be used on bridges are presented in this paper. Note that the focus here is mainly on cable supported bridges, often using Denmark's large bridges as an example. Also the fundamentals of ice accretion caused by freezing precipitation and in-cloud icing are presented together with the physical mechanisms expected to induce ice shedding.

## 2 Ice Accretion

High levels of humidity, combined with frequent changes between passing cold and warm fronts, results in a high risk of atmospheric icing. Icing typically occurs with very high levels of humidity or direct precipitation, so long as temperatures are slightly below freezing and wind speeds are mild. Icing appears predominately on bridge members that are more than 150 m above sea level.

Furthermore, the duration of an icing event can be important for the development of the ice accretion.

### 2.1 Fundamentals of icing

When natural ice forms on structures the source may either be cloud droplets (fog), raindrops, snow or water vapour. There are three types of ice formation: in-cloud icing, precipitation icing, and hoar frost, where hoar frost is a direct phase transition of water vapour and is usually negligible (Makkonen, 2000).

In-cloud icing can form through both a dry and a wet growth process. The most common type is dry growth which is when there is no liquid layer and the resulting ice is called rime. Rime normally forms on the windward side of the structure and entraps air, lowering its overall density.

Wet growth is when the freezing takes places beneath a liquid layer on the surface of the accretion and the resulting ice is called glaze. Glaze ice has the highest density, with the resulting formation being an evenly distributed ice accretion. Wet growth may also result in the formation of icicles.

Freezing rain also results in the formation of glaze and occurs when warm air aloft melts snow crystals before falling through a freezing layer of air near the ground (Fikke et al., 2007). It may also occur in the case of a rapid air temperature rise where the temperature of the structure is still below freezing. The second type of precipitation icing is wet snow, which is partly melted snow crystals (0-3°C) adhering to the surface of the structure and freezing, as the outer temperature decreases.

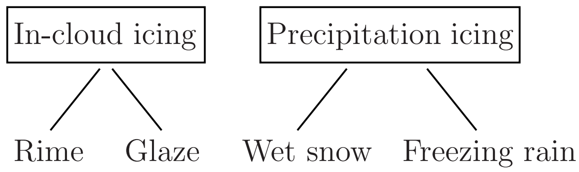


Figure 1: The different types of icing.

### 2.2 Ice shedding

Pieces of accreted ice or snow fall from bridge members when their weight increases beyond a critical limit or when the outer or structural temperature rises.

Three physical mechanisms which induce ice shedding exist: ice melting, ice sublimation, and mechanical ice breaking (Druez et al., 1995).

- In the case of melting ice, the principal characteristic is the air temperature which has to be above 0°C. When melting occurs at the surface-ice interface, ice chunks start falling as a result of wind and gravity forces.
- The sublimation phenomenon occurs at the ice-air interface and results in a rather low rate of ice mass reduction.
- Ice shedding by mechanical breaking is produced by a complex adhesive or cohesive failure.

# 3 Prevention and Removal Systems

Ice or snow prevention and removal systems can generally be classified into two categories: Active and passive. Where active systems generally require an external energy supply to operate, passive systems utilise natural forces such as the wind, gravity, incidental radiation, and temperature variations.
Various ideas and designs for different de- and anti-icing techniques have been developed, most of which are listed in reviews by Laforte et al. (1998); Farzaneh et al. (2008); Dalili et al. (2009).
The counter measure techniques identified can be classified as:

- Mechanical methods based on the breaking down of the ice.
- Thermal methods based on the melting of the ice.
- Passive methods based on natural forces.

The preferable solution always lies in passive prevention. When a passive prevention system is not applicable, though, de-icing methods have to be considered. Amongst these, mechanical methods to force ice shedding were demonstrated by Laforte et al. (1998) to require around 100 times less energy than thermal methods.

## 3.1 Mechanical removal

Mechanical ice or snow removal requires that the ice or snow is removed manually or automatically, usually involving the closure of a bridge to traffic. Manual removal is done by physically breaking off the ice or accreted snow. During manual removal, workers have to be lifted in a crane gondola (main towers) or walk on the main cables. However, the work conducted in these heights cannot be secured on days with snowfall or strong winds, which can delay the commencement of snow or ice removal. On the George Washington Bridge, NY, an alternative removal approach is employed, in which the hangers are hit with a baseball bat.
In the case of cables, automatic removal usually involves their forced vibration to break the ice loose. The disadvantage is that thin layers of ice can adhere quite strongly to the surface and may not be brittle enough. Electro-mechanical Expulsion De-icing Systems (EMEDS) use a mechanical force to knock the ice off the surface and depends on very rapid current discharges into electromagnetic coils, giving rise to magnetic fields of like polarity, that result in an electro-mechanical excitation (Al-Khalil, 2007). The electro-mechanical excitation is either generated as surface vibrations or strong pulses to effect de-icing. The utilisation of high voltage in the system, is a potential safety concern. Nonetheless, the system does exhibit advantages over electro-thermal systems, as they require less power.
The Electromagnetic-Impulsive De-Icing (EIDI) system operates by inducing strong and sudden magnetic forces from a high-current DC pulse through a coil, resulting in a rapid acceleration and flexure of the icing surface. This leads to debonding and expulsion of the ice. These systems have been found to operate successfully in the aviation industry, but they typically work with the actuators installed beneath the ice-prone surface. When applied to bridge cables or members this would not be possible without significantly increasing the diameter of the cable or changing the materials used in other bridge members. Therefore, for cable applications, the system is installed as coils along the exterior surface of the cable. To verify the effectiveness of an EIDI system, tests on hangers were performed on the Great Belt East Bridge and described by Vincentsen and Jacobsen (2001). Though it was found

effective at de-icing it also resulted in a quite violent explosion of the ice. With the explosion of ice, a short closure of the bridge was still found to be necessary while the de-icing procedure is performed. The EIDI system was afterwards installed as a pilot project on the top 100 m of the two longest hanger pairs on the Great Belt East Bridge (Laursen, 2004). For three years the system successfully de-iced the hangers, but a sudden extreme icing event, resulting in up to 50 mm of ice thickness, rendered de-icing system ineffective (Laursen and Zwieg, 2007).

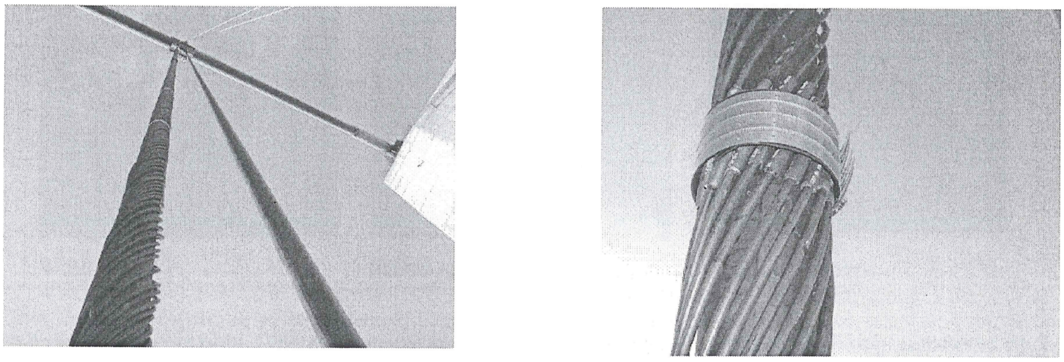

Figure 2: Photo of the EIDI system installed on the top part of hangers next to the pylon on the Great Belt East Bridge after Laursen (2004).

An alternative electro-magnetic de-icing system is the Eddy Current De-icing Strip (EDS), which use induced eddy currents acting on the iced surface to effect de-icing (Shin and Bond, 1993; Zieve et al., 1991). With EDS, the impulse coils are built thin and flexible with printed circuit board technology (Ingram et al., 1998). This allows the application to be significantly less flow intrusive (Adams et al., 1992).

The last of the electro-mechanical systems is piezoelectric de-icing using a piezoelectric covering material. The piezoelectric material converts an available electrical alternating current into mechanical force by realignment of its crystalline structures. This realignment causes the material to expand and retract in continuous motion and, thereby, insures that ice formation will be prevented, or rapidly removed. To the authors' knowledge, neither this nor EDS have ever been applied to bridges.

Other possible mechanical solutions (which have not been applied to bridge cables) include the ROV de-icer (Fig. 3), developed for overhead lines (Farzaneh et al., 2008), or a mobile pulley system, manually pulled whilst going down the cable removing the ice accretion (Laforte et al., 1998).

The two last mechanical techniques that should be mentioned are the Pneumatic Impulse Ice Protection (PIIP) and the Small Tube Pneumatic (STP). Both utilize inflatable rubber bladders, such that when they expand, ice is sheared, cracked, and flaked off. These types of de-icing methods have been successfully employed on aeroplanes, although they are prone to damage from weather and foreign objects. Generally, their durability falls far short of the systems using metals.

## 3.2 Thermal systems

A range of different thermal applications exist, as these systems are reliable and simply work by heating the ice prone surfaces to sufficiently to prevent the formation of ice or to generate de-icing. As might be understood, the systems generally consume copious amounts of energy when operating.

Electrical resistance heating systems use resistive elements embedded within thin sheets of material placed over and/or under the ice-prone surfaces. When electricity is applied to these heating mem-

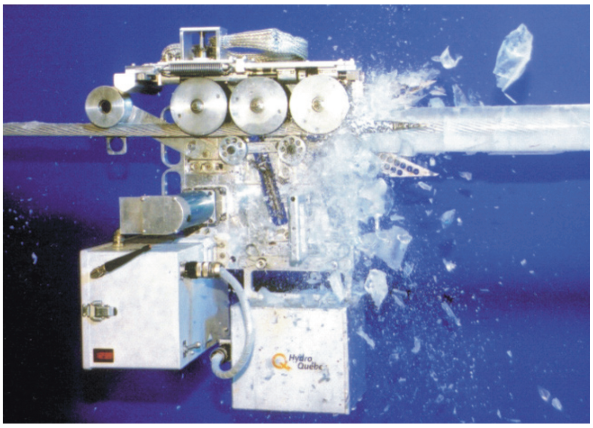

Figure 3: Prototype of the ROV de-icer after Leblond et al. (2002).

branes or elements, they generate heat to melt the ice (Ingram et al., 1998).
Field tests on bridge pylons by Numata and Kitada (2008) examined the performance of three types of heaters: the aluminium foil heater, the sheet heater, and heating tubes. Although the aluminium foil heater was the simplest to apply and found to give the highest temperatures with the least amount of power, it still had a very large energy consumption.
Instead of electrical heating, an indirect heating method can be applied using warm air to heat the ice prone areas so as to melt the ice or prevent it from forming. This method was applied to the Uddevalla Bridge, Sweden where a high-pressure system pushed warm air through a small opening in the cable protecting pipe and therefore kept the whole cable strand at temperatures above freezing (Kuhn, 2006). The cable heating system was successful, but the total energy demand was exceptionally high.
Another thermal de-icing method uses far-infrared radiation. When transmitting energy by means of electromagnetic waves or rays, the energy travels in straight lines from the heat source and, without significantly heating the air it passes through, reaches the object to be heated. This method could be employed when trying to reach inaccessible ice-prone bridge areas. Nevertheless, not withstanding the high energy demand, tests conducted with a mobile infrared de-icing system also found the method to be quite time consuming (Ruggi and Pole, 1998).
The most cost effective of the thermal solutions seems to be the Pulse Electro-Thermal De-icing (PETD) method which uses short pulses of electricity applied directly to the ice-material interface. To apply heat directly at the interface the surface needs to be covered with a thin electrically-conductive film. The film is then heated with a milliseconds-long pulse creating a thin melt-water layer causing the ice to drop off. Because only a micrometer-thin layer of ice is melted, PETD achieves a quite good energy efficiency compared the other thermal methods. The PETD system has been installed on part of the Uddevalla Bridge (Fig. 4) where both a cable stay and part of the pylon was covered in a PETD foil. To avoid having a negative effect on the conductivity the foil needed to be mounted in one piece which was successfully installed using a robe access method (Kuhn, 2006). To the authors' knowledge the system is still effective in keeping the Uddevalla bridge clear of ice.

### 3.3 Passive Anti-Icing/Snowing

There is no known passive anti-icing method that completely hinders the formation of ice. Generally, the purpose of passive systems is to help limit the problematic effects of ice. Some of the known

Figure 4: Photos of the PETD system installed on the Uddevela Bridge after Kuhn (2006).

methods include:

- Thermal absorbent coating: can only be effective when there is a sufficient level of incidental radiation (Laforte et al., 1998).
- Hydrophobic coatings with characteristic adhesion and surface tension: provide only some effectiveness in wet snow conditions (Laforte et al., 1998).
- Solid icephobic coatings: still have ice adhesion forces ten times greater than what is necessary for ice to attach/detach under gravity or wind loading.
- Viscous products and anti-icing greases: have a limited duration of protection, as they lose their efficiency under the effects of precipitation. Furthermore, they can form a potential risk to the environment.

A newly developed material is the black-coloured coating StaClean, purported by the manufacturer to be non-wetting, slicker than Teflon, and highly impact and abrasion resistant (Dalili et al., 2009). When applied to wind turbine blades it was found effective at reducing icing issues even though the black colour had no affect on surface temperatures.
Another type of anti-icing coating based on the sol-gel technology was tested through application on the main suspension cable of the Great Belt East Bridge (Laursen and Zwieg, 2007). The tests were unsuccessful and further development of the coating is ongoing. Rather than completely preventing the formation of ice, a more realistic goal might be to focus on the production of durable, industrially viable coatings (Nadine and Volkmar, 2009).
For cable bands and selective other bridge members, a passive method other than the aforementioned coatings might be a covering (Numata and Kitada, 2008). Fig. 5 shows a prototype cover consisted of a simple square blanket with eyelets that was found through field testing to mitigate snow accretion.
Finally, an interesting passive anti-snowing technique is a specially developed lattice fence which has been verified effective in trapping accreted snow at the upper parts of the bridge members and preventing it from falling in chunks (Takemoto et al., 2006).

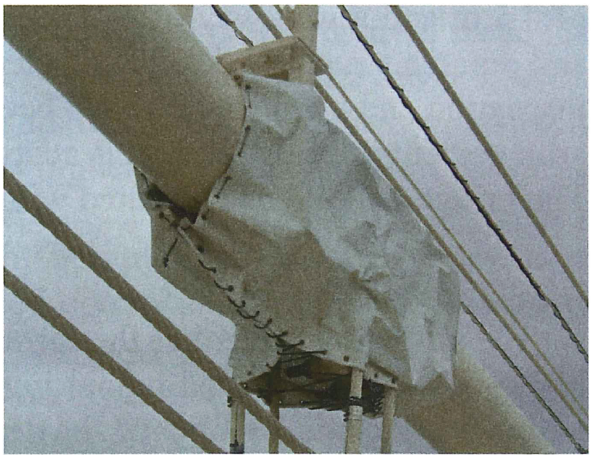

Figure 5: Cable band cover installed on Hakucho Bridge after Numata and Kitada (2008).

# 4 Conclusion

Overall only a limited amount of work has been undertaken to improve the safety of bridges prone to ice and snow accretion. To secure traffic safety and to reduce long bridge closures, it is important to develop novel measures against ice accretion to mitigate the risk of falling ice and snow.
It is found that the preferable passive anti-icing/snowing methods have still not been developed enough to effectively mitigate ice and snow accretion. The effective full-scale application of these methods seems out of reach at the moment.
Among the mechanical techniques, the Electromagnetic-Impulsive De-Icing (EIDI) systems appear the most promising. When installed on the Great Belt Bridge hangers it proved effective over a period of three years against diverse light to medium cases of icing, although it failed against a sudden heavy icing event.
The many different thermal applications simply heat the ice prone surface and, as such, tend to be very reliable and generally seem to work. Nevertheless, they consume very large amounts of energy. The only thermal technique that achieves reasonably good energy efficiency is the Pulse Electro-Thermal De-icing (PETD). The method uses short pulses of electricity applied directly to the ice-material interface and therefore only has to melt a micrometer-thin layer of ice. The system has been installed on the Uddevalla Bridge and seems very promising.

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