Review of the Phenomenon of Ice Shedding from Wind Turbine Blades

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ABSTRACT

Wind power is a sustainable source of energy. However, there are certain challenges to be overcome. One of the operational challenges is the phenomenon of ice shedding. Icing happens on wind turbine blades in cold regions. When ice grows to a certain size, it separates from the wind turbine blades resulting in the phenomenon of ice shedding. This phenomenon is of significantly dangerous for equipment and personnel in the region. Ice shedding may happen either because of vibrations or bending in blades. However, it was noticed by operators at Nygårdsfjell wind park, Narvik, Norway that ice shedding is more probable to happen when blades are stopped and turned back on. This observation reveals the fact that bending of blades (from loaded to unloaded positions) allows the ice to separate and hence result in ice shedding. This can be linked to the phenomenon of icing, mechanical and adhesive properties of ice. This paper reviews above in detail.

1. INTRODUCTION

Wind power is an excellent source of renewable energy in areas with sufficient wind resources. Usually, the best locations for wind turbines are on the tops of hills and ridges, where there are lower temperatures. Due to cold climatic conditions, turbine blades are subjected to icing. A number of methods have been proposed and tested for prevention and removal of ice on wind turbine blades, but no solution has been discovered to avoid it completely. The icing on the blades results in the phenomenon of 'ice shedding'.

Ice shedding is the loosening of ice from the blades. It has been reported that ice starts to loosen when its thickness reaches certain size [1]. This depends on weather conditions, turbine dimensions, rotational speed and other potential factors. This phenomenon is extremely dangerous for personnel and structures in the vicinity of the wind turbine. Icing happens on moving blades. When formed, it holds fast on the surface regardless of the inertia of the blade movement. It is reported that when the turbine is stopped and turned back on, a higher rate of ice shedding is observed. It is believed that this could be connected to a number of factors such (1) induced vibration due to the stoppage and (2) bending of the turbine blades (from deformed to undeformed positions).

Wind turbines can accumulate ice under certain atmospheric conditions, such as ambient temperatures near freezing (0°C) combined with high relative humidity, freezing rain or sleet [2]. The accumulation of ice is highly dependent on local weather conditions and the

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turbine's operational state [2]. There are many negative consequences of ice accretion on wind turbines. The icing of the blades can cause a complete loss of power production. According to the survey reported in [3], during 1998 to 2003, due to the low temperature one of the wind parks in Sweden stopped for maintenance 92 times out of a total 1337 times (lost 8022h out of 161523h energy). Most of the lost time (7353h, about 92%) was caused by ice accretion on blades [3]. The icing on the blades of the turbines can disrupt aerodynamics and lead to reduced power production. According to research [4] the increase in the roughness on the blades' surface due to ice accretion may result in higher drag coefficient, resulting in reduced power production. Differences between the ice accretion on individual blades of a wind turbine cause imbalance in the rotor that can induce fatigue in the wind turbine assembly components. Sheets or fragments of ice to loosening and falling make the area directly under the rotor subject to significant safety risks. In addition, rotating turbine blades may propel ice fragments a distance from the turbine that may be up to several hundred meters. Falling ice may cause damage to structures and vehicles and can also cause injury to site personnel and the public unless adequate measures are put in place for protection. Figure 1 shows a piece of ice shed from a wind turbine in Nygårdsfjell wind park [5].

Figure 1: Piece of ice shed from a turbine in Nygårdsfjell wind park, Narvik, Norway [5]

2. WIND TURBINES

Wind power is a source of renewable energy. Wind turbines can generate large amounts of electricity when placed in wind farms onshore or offshore [6]. There are two main kinds of wind turbines; horizontal axis wind turbines also known as 'HAWT' and vertical axis wind turbines also known as 'VAWT' as shown in Figure 2.

HAWT turbines are commonly used for power generation. This project is focusing on HAWT turbines [6].

Figure 3(a) shows wind turbine blades under conditions of almost no wind. At the

time of the photograph, the turbines were rotating but not generating any power. For comparison, a photograph of turbine producing power is shown in Figure 3(b). It can be noticed that wind turbine blade is bent. Wind turbine blade bends when producing power.

Figure 2: (a) Horizontal axis wind turbines are also known as 'HAWT' (b) Vertical axis wind turbines are also known as 'VAWT'.

It is known by the operators that stopping a wind turbine, which has ice build-up on the blades and then re-starting it often removes a lot of the ice. This could be due to the significant shift from the loaded blade (2 m deflection) to unloaded blade (zero deflection) and not due to the vibrations from stopping, which the operators thought was the cause [7].

It has been observed that there is an average deflection of about 2 ±0.5 m at the blade tip due to the wind load. The variation of ±0.5 m in the deflection is due to the gusts of the wind. An illustration of this observation is shown in Figure 4 [8].

3. PHENOMENON OF ICING
In the phenomenon of icing, water droplets are cooled below the freezing temperature (0°C) and freeze upon the impact with structure. The key source of ice over wind turbine blades

comes from the atmosphere [9]. To study the ice shedding, it is necessary to understand why atmospheric icing takes place at first. The atmospheric icing is defined as the accretion of ice or snow on structures that are exposed to the atmosphere [10-13]. In general, there are three sources of atmospheric icing such as In-cloud icing, Precipitation icing and Frost icing. In cloud and precipitation, icing creates ice that holds fast to the wind turbine and results in the phenomenon of ice shedding.

(a)   (b)

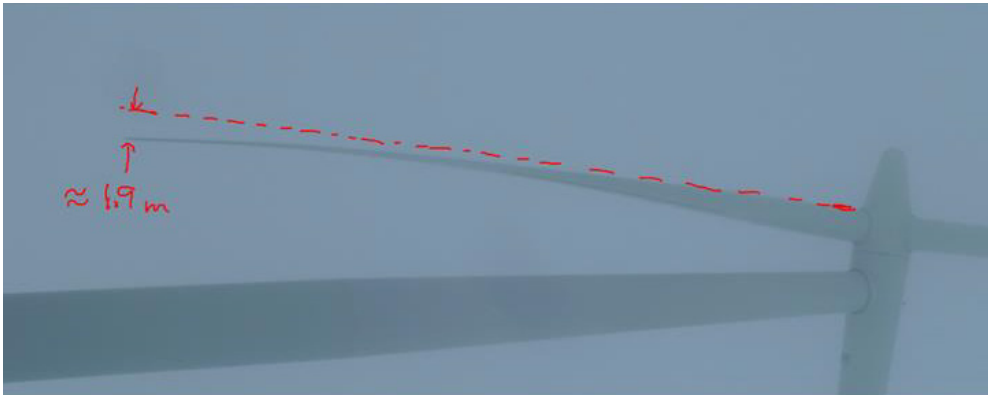Figure 3: Wind turbine blades: (a) under no wind condition, (b) blades are moving and producing power [7]

Figure 4: Demonstration of deflection in the wind turbine blade, the deflection at the tip of the blade is approximately 1.9 m [7].

It happens when super-cooled water droplets hit a surface below 0℃ and freeze upon impact. The droplets temperature can be as low as -30 ℃ and they do not freeze in the air, because of their size. This type of ice accretion may have different sizes, shapes and properties, depending on the number of droplets in the air (liquid water content - LWC) and their size (median volume diameter - MVD), the temperature, the wind speed, the duration, the chord length of the blade and the collection efficiency. There is a continuum of ice accretion appearance from rime at coldest temperatures to glaze at warmest.

The physical properties and the appearance of the accreted ice will vary widely according to the variation in meteorological conditions during the ice growth. [11, 13] give the typical properties of accreted atmospheric ice.

Table 1 Typical properties of accreted atmospheric ice [11, 13]

Type of ice	Density (kg/m³)	Adhesion and cohesion	General appearance	
			Colour	Shape
Glaze	900	Strong	transparent	evenly distributed/icicles
Wet snow	300 to 600	weak(forming) strong (Frozen)	white	evenly distributed/eccentric
Hard rime	600 to 900	strong	opaque	eccentric, pointing windward
Soft rime	200 to 600	Low to medium	white	eccentric, pointing windward

Rime is the most common form of in-cloud icing. It forms through deposition of super cooled fog or cloud droplets. During the icing event, different droplet size and air temperature can give the rime different density and strength, which leads to form two subtypes of rime – hard and soft. Hard rime is harder to move because the higher MVD and LWC cause accretion with higher density. Soft rime appears when the temperature is well below 0°C, and the MVD and LWC are small. It is formed as thin ice with needles and flakes. Soft rime has low density and little adhesion and hence can easily to be removed. Low temperatures and small droplet size typically lead to an ice accretion of low density and low strength.

The glaze is a smooth, transparent and homogeneous ice coating occurring when freezing rain or drizzle hits a surface [14]. Glaze has a high density and strong adhesion and is harder to remove than rime. It is often associated with the precipitation. A sample of glaze ice is given in Figure 5 [8]. It is a result of ice shedding from a wind turbine blade.

Figure 5: Glaze ice from a wind turbine blade [8]

Precipitation ice can be snow or rain. The accretion rate can be much higher than in-cloud icing and hence could be more damaging [14]. Precipitation icing may result from two sources 'wet snow' and 'freezing rain'. 'Wet snow' can adhere to a surface when it is liquid at air temperature between 0°C and 3°C. If the temperature is decreasing after wet snow accretion, the snow will freeze. It is due to the snow having some liquid water present, which allows the snow crystals to bind together when they come in contact with the surface. It is easy to remove at first, but can be difficult if it freezes on the surface [10]. When rain falls at temperatures below 0°C, it leads to 'freezing rain'. It often occurs in connection with a temperature inversion where cold air is trapped near the ground beneath a layer of warmer air [13]. It can also occur in the case of a rapid temperature rise where an object still has a temperature below freezing even though the air temperature is above freezing. Ice density and adhesion are high when this phenomenon occurs.

Ice exists in a number of different crystal structures, as well as two amorphous states [15]. The ordinary ice we find in our freezer is hexagonal crystal structure that is called ice-1h as shown in Figure 6. The numbers refer to individual water molecules [16].

4. MECHANICAL PROPERTIES OF ICE

A common experience in handling pieces of ice tells us that ice is a brittle material. Therefore, the mechanical behavior of ice exhibits a similarity to the mechanical behavior of brittle ceramics [17].

The elastic modulus and Poisson's ratio of polycrystalline ice have been measured by subjecting plates of ice to biaxial bending [18]. At a temperature of −10°C for measurements on ice plates that were 0.5 m in diameter, the Young's modulus of ice was reported in the range of 4–9 GPa and Poisson's ratio was 0.29–0.32 [19]. Ice strength depends on the variables of temperature, strain rate, tested volume, and ice grain size.

The average tensile strength of ice from published investigations is 1.43 MPa in the temperature range −10°C to −20°C [20]. Over this temperature range, the compressive

strength of ice ranges between 5–25 MPa [20]. Ice strength depends on the variables of temperature, strain rate, tested volume, and ice grain size.

It is known that the strength of ice increases with decreasing temperature in both tension and compression. As shown in Figure 7, the temperature effect on compression strength is more prominent than in tension strength, which is almost three times more during the temperature 0°C and −40°C [20].
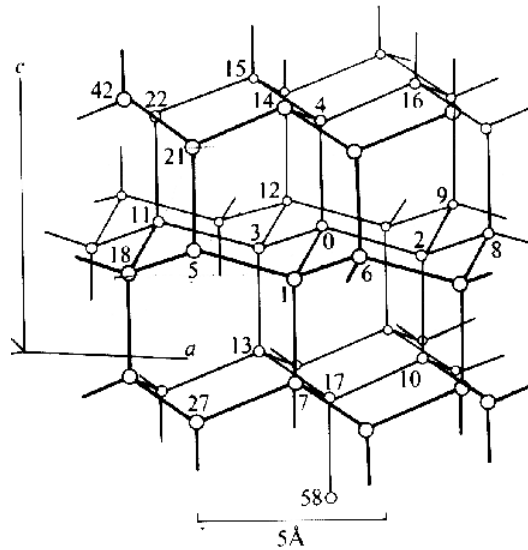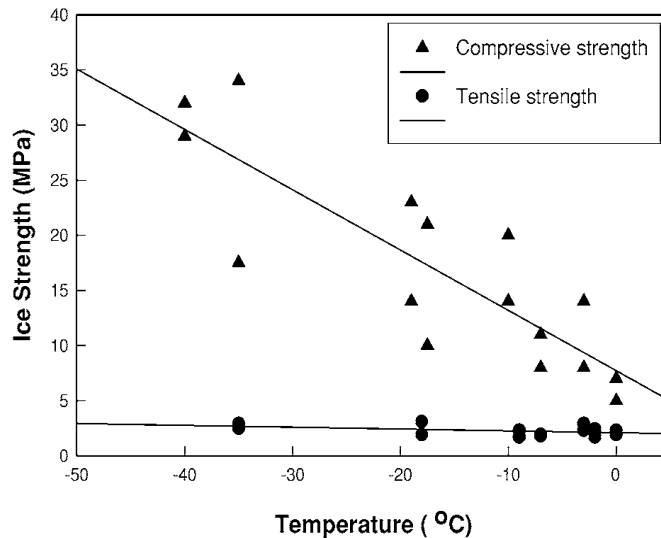

Figure 6: The structure of ice-Ih [15].

Figure 7: Tensile and compressive strength of ice as a function of temperature [20]

Schematic stress-strain curves. I, II, and III denote low, intermediate, and high-strain rates as shown in Figure 8. The arrows indicate either ductile (horizontal) or brittle (vertical) behavior. At low rates of deformation, cracks do not form, and the material is ductile (curves

I). At high rates, cracks do initiate, and the material is brittle (curves III) and independent of the stress state. At intermediate strain rates, cracks also develop, and the material is brittle under tension (curve II-Tension) but ductile under compression (curve II-Compression). The ductile-brittle transition occurs at lower strain rates under tension because the applied stress opens the cracks directly. Under compression, the required tensile stress is generated locally through crack sliding. Note that the compressive stress-strain curve at intermediate strain rates displays a peak owing, we believe, to crack-induced localized flow [15].
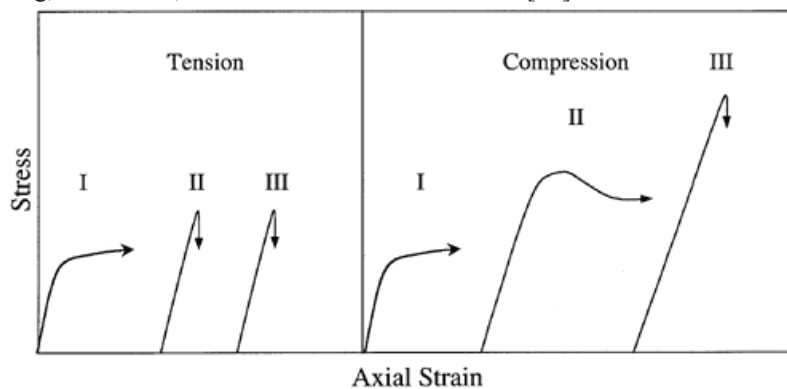

Figure 8: Schematic stress-strain curves [15]

The tensile and compressive strengths of fresh-water ice of about 1 mm grain size vs. strain rate are shown in Figure 9.

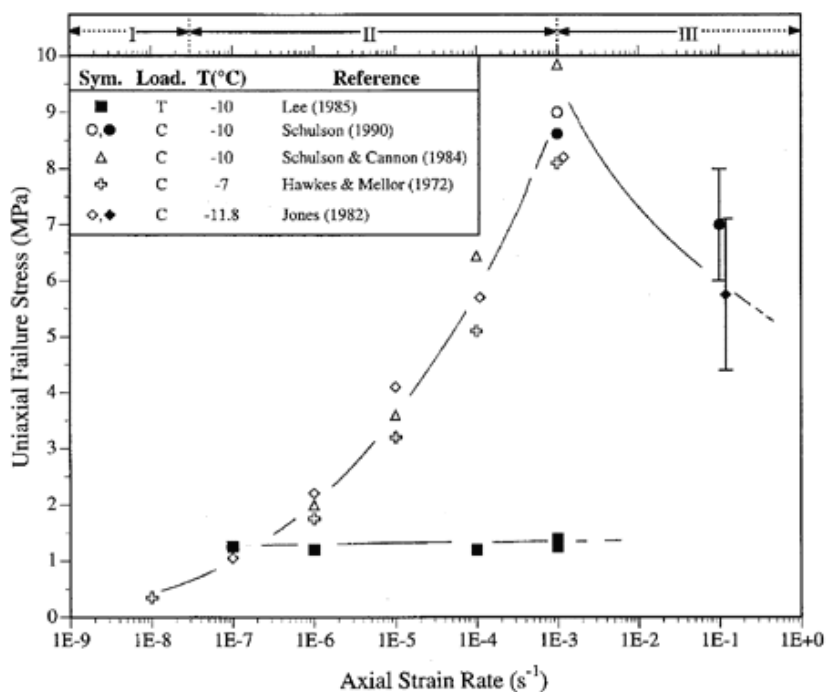| Sym.	Load.	T(°C)	Reference
■	T	-10	Lee (1985)
O,●	C	-10	Schulson (1990)
△	C	-10	Schulson & Cannon (1984)
⊕	C	-7	Hawkes & Mellor (1972)
◇,◆	C	-11.8	Jones (1982)

Figure 9: Tensile and compressive strengths of equiaxed and randomly oriented fresh-water ice of about 1 mm grain size vs. strain rate [21].

The tensile strength of ice decreases with the increase of grain size as shown in Figure 10. The given data of ice is recorded at a constant strain rate of $10^{-5} \cdot s^{-1}$ and temperature of -10°C.
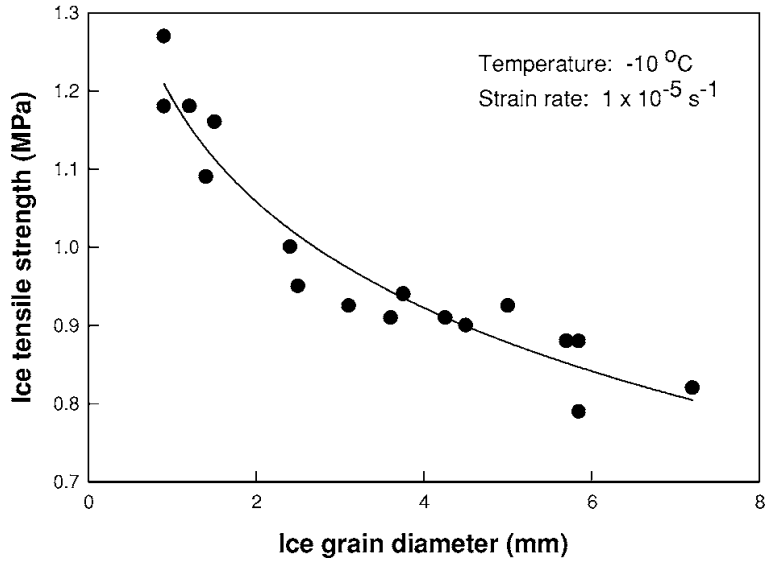
Figure 10: Tensile strength of ice as a function of grain size [21]

The tensile strength of ice decreases with increasing test specimen volume [22], as shown in Figure 11. Volume effects on the strength of brittle materials are usually described by a Weibull statistical distribution approach [23].
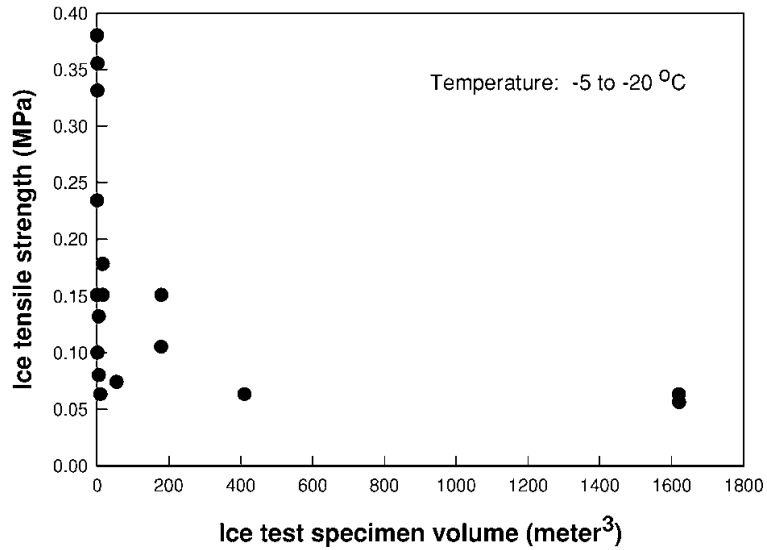
Figure 11: Tensile strength of ice with specimen volume [22]

5. ADHESIVE PROPERTIES OF ICE

There is no direct correlation to calculate the ice adhesion force [24]. However, researchers have given number theories [25, 26]. The theories divide the force of adhesion into four categories such as electrostatic adhesion, diffusive adhesion, mechanical adhesion and chemical adhesion. In electrostatic adhesion, the interface between the material and the ice adhere due to the transfer of electrical charges between them [27, 28]. In diffusive adhesion, material and ice adhere because the molecules at the surface diffuse across the interface into the matrix of the each other [29, 30]. In mechanical adhesion, material and ice adhere because water flows into the microscopic pores of the substrate and freeze, thereby, forming an interlocking mechanism of adhesion. As shown in Figure 12, a droplet of water in depression solidifies and expands, hence pushes apart the sides of the depression generating a grip [31]. Therefore, surface roughness has a significant effect on ice adhesion. For example, ice adhesion on the surface of stainless steel, in general, is up to 1.65 MPa, while the ice adhesion on the polished stainless steel is only 0.07 MPa [24].
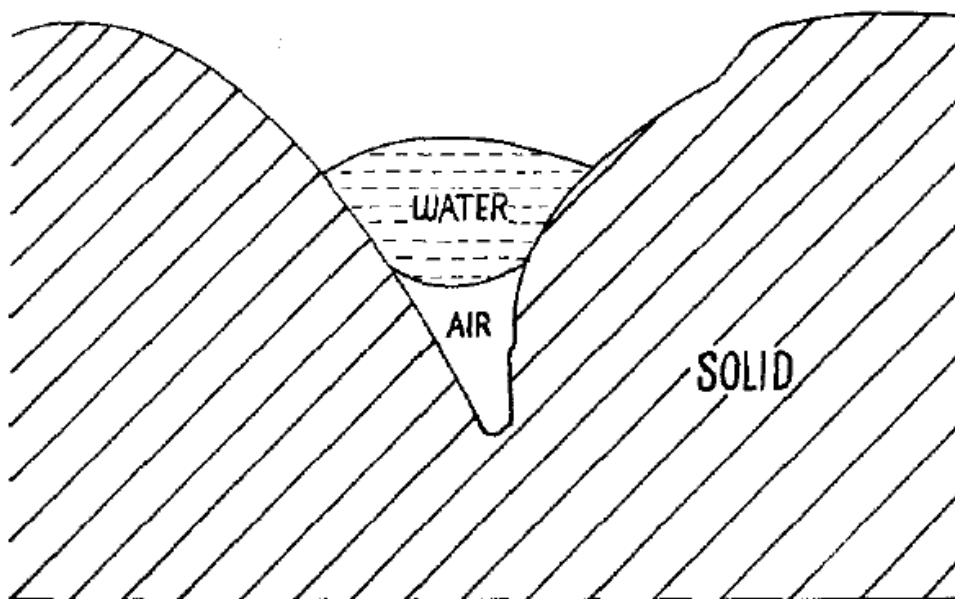

Figure 12: A water droplet in the micro-depression of solid surface [31]

In chemical adhesion, materials and the ice adhere because chemical bonds are formed between them at the interface. A number of different types of chemical bonds can be formed [32].

6. CONCLUSION

Ice shedding is a concerning phenomenon for wind turbine operations in cold regions. The phenomenon of ice shedding is of significant risk to personnel and equipment in nearby areas of wind turbines. The phenomenon of ice shedding is associated with mechanical failure of ice. This can be associated with bending in wind turbine blades since ice shedding is more

prominent once iced turbine blades are stopped and turned back again. For building an understanding of the phenomenon of ice shedding, it is vital to understand the mechanical and adhesive properties of ice.

ACKNOWLEDGEMENT

REFERENCES:

[1]   Scavuzzo, R. and M.L. Chu, Structural properties of impact ices accreted on aircraft structures. 1987: National Aeronautics and Space Administration.

[2]   Morgan, C., E. Bossanyi, and H. Seifert. Assessment of safety risks arising from wind turbine icing. in EWEC-CONFERENCE-. 1997. BOOKSHOP FOR SCIENTIFIC PUBLICATIONS.

[3]   Ronsten, G., Svenska erfarenheter av vindkraft i kallt klimat nedisning, iskast och avisning. Elforsk rapport, 2004. 4: p. 13.

[4]   Jasinski, W.J., et al., Wind turbine performance under icing conditions. Journal of Solar Energy Engineering, 1998. 120(1): p. 60-65.

[5]   Homola, M.C., Atmospheric icing on wind turbines. Department of Technology, 2011: p. 152.

[6]   Tong, W., Wind Power Generation and Wind Turbine Design. 2010: WIT Press.

[7]   Xue, H., Ice Shedding Processes, in Department of Engineering Design. 2015, UiT-The Arctic University of Norway.

[8]   Homola, M., Impacts and Causes of Icing on Wind Turbines. 2005, Narvik University College.

[9]   Wahl, D. and P. Giguere, Ice Shedding and Ice Throw–Risk and Mitigation. General Electric Wind Application Engineering Group of GE Energy, 2006.

[10]   1Boluk, Y., Adhesion of freezing precipitates to aircraft surfaces. 1996.

[11]   Fikke, S., et al., Cost 727: atmospheric icing on structures. Measurements and data collection on icing: State of the Art, Publication of MeteoSwiss, 2006. 75(110): p. 1422-1381.

[12]   Richert, F., Is Rotorcraft icing knowledge transferable to wind turbines. BOREAS III. FMI, Saariselkä, Finland, 1996: p. 366-380.

[13]   12494, I., Atmospheric icing of structures. 2001.

[14]   Oblack, R. Glaze Ice definition. 2015 [cited 2015 26-08-2015].

[15]   Schulson, E.M., The structure and mechanical behavior of ice. JOM, 1999. 51(2): p. 21-27.

[16]   Hobbs, P.V., Ice Physics. 2010: OUP Oxford.

[17]   Schulson, E.M., Brittle failure of ice. Engineering Fracture Mechanics, 2001. 68(17–18): p. 1839-1887.

[18]   Gold, L.W., On the elasticity of ice plates. Canadian journal of civil engineering, 1988. 15(6): p. 1080-1084.

[19]   Voitkovskii, K., The mechanical properties of ice. 1962, DTIC Document.

[20]   Haynes, F.D., Effect of temperature on the strength of snow-ice. 1978, DTIC Document.

[21]   Currier, J. and E. Schulson, The tensile strength of ice as a function of grain size. Acta Metallurgica, 1982. 30(8): p. 1511-1514.

[22]   Dempsey, J., et al., Scale effects on the in-situ tensile strength and fracture of ice. Part I: Large grained freshwater ice at Spray Lakes Reservoir, Alberta, in Fracture Scaling. 1999, Springer. p. 325-345.

[23]   Weibull, W., A statistical theory of the strength of materials. 1939: Generalstabens litografiska anstalts förlag.

[24]   Kulinich, S. and M. Farzaneh, Ice adhesion on super-hydrophobic surfaces. Applied Surface Science, 2009. 255(18): p. 8153-8157.

[25]   Landy, M. and A. Freiberger, Studies of ice adhesion: I. Adhesion of ice to plastics. Journal of colloid and interface science, 1967. 25(2): p. 231-244.

[26]   Houwink, R. and G. Salomon, Adhesion and adhesives, Vol. 1. 1965, Elsevier, New York.

[27]   Seidler, P., New theories of adhesion of high polymers. Adhaesion, 1963. 7: p. 503-512.

[28]   Krotova, N., et al., Investigation of various types of adhesion bonds. 1965, DTIC Document.

[29]   Voiutskii, S.S., Autohesion and adhesion of high polymers. 1963.

[30]   Wake, W., Theories of adhesion and uses of adhesives: a review. Polymer, 1978. 19(3): p. 291-308.

[31]   Bikerman, J.J., The Science of Adhesive Joints. 2013: Elsevier Science.

[32]   Adhesion Science and Engineering: Surfaces, Chemistry and Applications. 2002: Elsevier Science.