Effect of curvature on durable ice-phobic surfaces based on buckling metallic plates
Alasvand Zarasvand, Kamran; Orchard, David; Clark, Catherine; Golovin, Kevin

This publication could be one of several versions: author's original, accepted manuscript or the publisher's version. / La version de cette publication peut être l'une des suivantes : la version prépublication de l'auteur, la version acceptée du manuscrit ou la version de l'éditeur.
For the publisher’s version, please access the DOI link below./ Pour consulter la version de l'éditeur, utilisez le lien DOI ci-dessous.

Publisher’s version / Version de l'éditeur:
https://doi.org/10.1016/j.matdes.2022.110884

Access and use of this website and the material on it are subject to the Terms and Conditions set forth at
https://nrc-publications.canada.ca/eng/copyright
READ THESE TERMS AND CONDITIONS CAREFULLY BEFORE USING THIS WEBSITE.

L’accès à ce site Web et l’utilisation de son contenu sont assujettis aux conditions présentées dans le site
https://publications-cnrc.canada.ca/fra/droits
LISEZ CES CONDITIONS ATTENTIVEMENT AVANT D’UTILISER CE SITE WEB.

Questions? Contact the NRC Publications Archive team at
PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca. If you wish to email the authors directly, please see the first page of the publication for their contact information.

Vous avez des questions? Nous pouvons vous aider. Pour communiquer directement avec un auteur, consultez la première page de la revue dans laquelle son article a été publié afin de trouver ses coordonnées. Si vous n’arrivez pas à les repérer, communiquez avec nous à PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca.
Degradation in system performance due to ice accretion on curved surfaces remains a decades-old challenge. We recently reported that Buckling Elastomer-like Anti-ice Metallic Surfaces (BEAMS) exhibit a low ice adhesion strength and extreme durability in realistic icing conditions. BEAMS consist of thin, flat metal sheets suspended on strips or dots of adhesive, and this partial confinement facilitates buckling of the metal sheet, causing ice to dislodge from the surface at a low applied force. The mechanism of ice detachment from curved BEAMS has not been investigated. Here we study how curvature affects the shear ice adhesion strength of BEAMS, using both glaze- and rime-type ice at \( -20 \) °C. For glaze, it was observed that increasing the radius of curvature increased the ice adhesion strength regardless of whether the curvature was positive or negative. For rime ice a high radius of curvature, \( R = 17.3 \) mm, was used inside an icing wind tunnel. When the compliance of the material used to suspend the metallic sheet was increased, the rime ice adhesion strength was as low as \( \tau_{\text{ice}} \approx 3 \) kPa. Further, the confinement configuration of BEAMS was studied to understand its effect on lateral torsional buckling. Lateral torsional buckling altered the radius of curvature of both the suspension material and metal sheet, initiating cracks due to the unchanged curvature of the accreted ice. Accordingly, the extremely low ice adhesion strength of BEAMS, even on curved surfaces, was due to buckling instabilities either within the thin metal plates or the suspension material. Overall, BEAMS would appear to be a durable, low-ice-adhesion system for curved surfaces in realistic icing conditions.
1. Introduction

Maintaining functionality during exposure to severe icing conditions remains an active challenge due to the detrimental impacts of ice accretion on the performance of engineering structures [1]. This problem exists because structural materials exhibit a very strong bond with ice, often quantified by the surface's shear ice adhesion strength, \( \tau_{\text{ice}} \). For example, engineering materials such as aluminum or steel exhibit high ice adhesion strengths of \( \tau_{\text{ice}} > 1000 \text{ kPa} \) [1,2]. Assuming the size of the interface remains well-below its cohesive length [3], the ice adhesion strength is calculated by dividing the de-icing shear force, \( F \), by the iced area, \( A_{\text{ice}} \). Many active and passive anti-icing solutions have been proposed over the decades to mitigate ice accretion on surfaces. The term ice-phobic was put forth previously to denote, among other things, a surface whose shear ice adhesion strength is \( \tau_{\text{ice}} < 100 \text{ kPa} \) [1,2]. Most of these ice-phobic materials, such as superhydrophobic, elastomeric, or lubricated surfaces, have only demonstrated efficacy on flat surfaces and in relatively mild environments [1,2,4-14]. However, many of the real surfaces subjected to severe ice accretion, for example the leading edges of aircraft wings, transmission cables, or wind turbine blades, are curved [15-18]. The purpose of this work is to understand how surface curvature affects the performance of the recently reported metallic ice-phobic surfaces that are sufficiently durable to survive harsh icing environments, such as flight.

Buckling Elastomer-like Anti-icing Metal Surfaces (BEAMS) have recently demonstrated ice adhesion strengths as low as \( \tau_{\text{ice}} \sim 1 \text{ kPa} \) and high durability [2]. BEAMS consist of suspended thin metal plates where the substrate attachment is sparse, resulting in a surface whose confinement is highly tunable. Using this sparse confinement to control the mechanics of buckling within the thin metal sheets, BEAMS enable crack opening displacements that facilitate interfacial fracture at low applied loads [2]. However, BEAMS has only been studied on flat substrates that exhibit relatively idealized buckling instabilities; similar de-icing performance is not guaranteed on curved structures. Curved elements exhibit higher flexural rigidity than flat sheets, control out-of-plane deformation, increase bending, and increase buckling resistance in thin plates [15-24]. Accordingly, curved BEAMS may exhibit increased sheet buckling resistance compared to flat BEAMS, which could alter their ice detachment mechanism.

Here, we investigated the feasibility of curved BEAMS under realistic icing conditions using both rime- and glaze-type ice. BEAMS were formed in a curved shape with various positive and negative radii of curvature (Fig. 1a). For each type of curvature,
two strategies of ice detachment were explored by applying the de-icing load either to the ice or the BEAMS holder. Negatively and positively curved BEAMS were also numerically investigated to understand the effect of curvature on the ice adhesion strength, as compared to flat BEAMS. A representative numerical study was performed to elucidate how the arrangement and compliance of the BEAMS confinement points can significantly affect the ice detachment process. Further, curved BEAMS performance was evaluated in realistic icing conditions in an icing wind tunnel.

2. Experimental design

2.1. Materials

18–8 stainless steel sheets with a thickness of \( t = 0.05 \) mm (McMaster-Carr), two-part epoxy adhesive (Scotch Weld), VHB double-sided foam tape (RP32, 3M), and Ecoflex 00–30, Mold Max 14NV, and Mold Max 29NV silicone rubbers (Smooth-On) were used as received. Polylactic Acid (PLA) filaments were used for all 3D printed components.

2.2. Evaluation of BEAMS curvature using glaze ice

The higher flexural rigidity of thin curved plates could impact the detachment mechanism of ice adhered to BEAMS [2]. Various radii of curvature were used to investigate its effect on the ice adhesion strength of BEAMS. Additionally, the effects of ice length and width were studied. Two strategies were implemented to apply the de-icing force either to the ice or BEAMS substrate, for both positive and negative plate curvatures (Fig. 1), i.e. four different de-icing configurations were evaluated, denoted Type 1 – Type 4. To facilitate this, four different types of ice/BEAMS sample holders were designed.

For Type 1, a BEAMS sample was wrapped around a semi-cylindrical substrate (positive curvature) and was placed inside a 3D-printed holder, which was then filled with water and frozen (Fig. 1b). To de-ice, the mechanical load was applied to the end of the BEAMS substrate. For Type 2, a substrate with positive curvature was 3D printed and BEAMS was installed on top of it (Fig. 1c). A 3D-printed ice mold matching the curvature (to prevent leakage) was then placed atop BEAMS, filled with water, and frozen. To de-ice, the load was applied to the ice mold. Similar strategies were used to design holders for Type 3 and Type 4, both exhibiting negative curvature (Fig. 1d, 1e). The de-icing force was applied to the ice mold for Type 3, whereas it was applied to the BEAMS substrate for Type 4. Note that the ice was frozen within the underside of the holder for Type 4, which was flipped upside-down before mounting to the Peltier stage (Fig. 1e).

For all four scenarios, de-ionized water was poured into the assembly to cover the curved area of the sample. The edges of all curved sheets were confined with 3 M foam tape. Once the ice of prescribed interfacial area had frozen inside a –20 °C freezer overnight, the sample was quickly transferred to a –20 °C Peltier stage and mounted using the four screw holes shown in Fig. 1. In all cases the BEAMS utilized a stainless steel sheet with dimensions \( L = 60 \) mm, \( W = 40 \) mm and \( t = 0.05 \) mm. In all experiments, the freezing process was completed in the –20 °C freezer, followed by testing on the cold Peltier stage at –20 °C using a force gauge probe at a speed of 100 \( \mu \)m/s. A 3D laser scanning microscope confirmed that the curvature did not affect the surface roughness of any of the BEAMS samples, which was around a root mean squared roughness of 0.9–1.0 \( \mu \)m for the stainless steel sheets used.

2.3. Evaluation using rime ice

Curved BEAMS samples were also evaluated in an icing wind tunnel to study their ability to reduce the adhesion of atmospheric icing such as rime. Parameters investigated included the ice length as well as the compliance and arrangement of the material used to suspend the metal sheet. The Altitude Icing Wind Tunnel (AIWT) at the National Research Council Canada (Ottawa, ON, Canada) was used along with its spin rig apparatus that enables the centrifuge adhesion test to be run on accreted atmospheric ice [2,25]. The icing wind tunnel conditions used are listed in Table 1. Spin rig coupons of different lengths (\( L = 30 \) mm, \( L = 60 \) mm, \( L = 100 \) mm, and \( L = 150 \) mm) were fabricated using a 3D printer (Ultimaker 3) to which BEAMS samples were attached using strips or dots of foam tape. A two-part epoxy adhesive was used to bond the foam tape to the steel sheet and spin rig coupons. In another set of experiments, three different elastomeric materials (Mold Max Ecoflex 00–30, Mold Max 14NV, or Mold Max 29NV) were instead used to make the confinement points (width of 2 mm and thickness of 3 mm).

During each accretion or shedding run, four BEAMS samples were mounted on the retaining arms connected to the rotor. A total of 11 BEAMS samples were fabricated for AIWT testing. For each new sample, first an accretion run was performed for 600 s for each test condition, followed by removal of the sample in order to weigh the accreted ice. After cleaning the sample surface it was re-installed on the spin rig apparatus and ice was again accreted. After the 600 s of accretion, the icing cloud was turned off and the spin rig began to radially accelerate until the ice was shed from the surface. The exact angular velocity at which ice detached from the sample was measured by accelerometers placed in the test section walls, synchronized with the rotational speed of the spin-rig. Considering the mass of the accreted rime ice, \( m_{\text{ice}} \sim 13 \) g, the spin rig arm length, \( r_{\text{arm}} = 185 \) mm, and the angular velocity \( \omega \) at which the ice was shed, the de-icing shear force was calculated as, \( F = m_{\text{ice}} r_{\text{arm}} G \omega^2 \). The ice adhesion strength of each sample was then calculated using \( \tau_{\text{ice}} = F/A_{\text{ice}} \).

3. Numerical characterization

A series of numerical simulations were conducted in Abaqus finite element software to investigate the deformation of curved BEAMS in response to the uniform and non-uniform external loads representative of the loading conditions within the push-off and spin rig experiments. In the first set of analyses, Type 2 and Type 3 curved BEAMS were modeled. The steel sheet was modeled as a deformable shell, whereas ice and the foam tape were modeled as deformable solids. The dimensions of all components in the numerical simulations matched with the actual dimensions used in the experiments. The physical properties of the steel sheet, ice, and foam tape are listed in Table 2. The nonlinear Quasi-Static analysis step was used as a solver. To predict the deformation within the curved sheet, the average de-icing force values recorded during the experiments were applied as distributed pressures on the lateral side of the ice. The tie interaction was used between all components to provide continuity of deformation among all components. A fully-confined boundary condition on the bottom
side of the foam tape was applied in which all translational and rotational degrees of freedom were constrained in the x, y, and z axes. The optimum number of elements was found for each component to minimize analysis time. As a result, a total of 3360 S4R, 4000 C3D8R, and 6330 C3D8R elements were generated for the steel sheet, ice, and foam tape, respectively. Note that the maximum deflection in the steel sheet was recorded according to the last converged increment.

Representative BEAMS spin rig experiments were also simulated considering a rotational body force applied on BEAMS. In these models, the steel sheets were modeled using 3502 S4R elements as deformable shells, and the ice, elastomeric strips, and foam tapes modeled as deformable solids with 2565, 2240, and 9632 C3D8R elements. Similar to the push-off modeling, the tie constraint was utilized between the surfaces of the steel sheets, elastomeric strips, ice, and foam tape. The Quasi-Static solver considering nonlinear geometry was used in all spin rig simulations. The angular velocity at which ice was experimentally shed from the BEAMS sample was used in the numerical simulations.

4. Results and discussion

4.1. Curved BEAMS performance using glaze ice

BEAMS with various positive and negative radii of curvature were first fabricated in order to understand the influence of curvature on the resultant ice adhesion strength (Fig. 2a-d). Increasing the radius of curvature resulted in lower ice adhesion strengths, converging to $\tau_{\text{ice}} \approx 20$ kPa for both positive and negative curvatures. This asymptotic ice adhesion strength matched that of flat BEAMS, as expected given that flat surfaces can be thought of as ones possessing an infinite radius of curvature. For the smallest radius of curvature, $R = 12.5$ mm, ice fractured adhesively from Type 1 BEAMS (Fig. 2a), whereas cohesive fracture was observed for the negative curvature Types 3 and 4 BEAMS (Fig. 2b, c). For $R = 12.5$ mm, relatively higher ice adhesion strengths of $\tau_{\text{ice}} \approx 120$ kPa and $\tau_{\text{ice}} \approx 140$ kPa were recorded for Types 3 and 4, respectively (Fig. 2b, 2c). Increasing the radius of curvature to $R = 25$ mm sharply decreased the ice adhesion strength to $\tau_{\text{ice}} \approx 20$ kPa for Type 1 BEAMS, whereas for negative curvature the decrease was gradual. Ice was removed at $\tau_{\text{ice}} \approx 60$ kPa and $\tau_{\text{ice}} \approx 120$ kPa, for Types 3 and 4 BEAMS, respectively, at $R = 25$ mm, and this only decreased to $\tau_{\text{ice}} \approx 50$ kPa for $R = 60$ mm (Fig. 2d).

For flat BEAMS, the effect of ice geometry (width or length) has been previously investigated. The ice adhesion strength of flat BEAMS was shown to be invariant to ice length but decreased substantially with the width of ice [2]. The length and width of the ice adhered to curved BEAMS was also varied to understand if these trends were affected by curvature. At a constant positive radius...
of curvature, $R = 60\, \text{mm}$, the ice adhesion strength of Type 1 BEAMS was measured for lengths of ice from $a_L = 30 - 150\, \text{mm}$. The width of ice was similarly varied from $s_{aw} = 10 - 40\, \text{mm}$ for Type 2 BEAMS. Much like flat BEAMS, no statistically significant difference was observed in the ice adhesion strength of curved BEAMS when increasing the length of ice ($\tau_{\text{ice}} \approx 20\, \text{kPa}$, Fig. 2e). However, dissimilar to flat BEAMS, no change in the ice adhesion strength of curved BEAMS was observed for increasing widths of ice ($\tau_{\text{ice}} \approx 24\, \text{kPa}$, Fig. 2f). This is likely because increasing the width of ice also increases its confinement in the radial direction, resulting in a higher detachment force for higher iced areas.

In general, deflection in curved elements highly depends on the direction of the applied force. Curved elements exhibit higher flexural rigidity and deflect less compared to flat sheets, in the case of a normal force applied toward the center of curvature. Moreover, curved surfaces show higher resistance against deflection in the direction opposite the applied force. To investigate why BEAMS with negative and positive curvatures exhibited different ice adhesion strengths, two numerical simulations were carried out (Fig. 3). Type 2 and 3 BEAMS were used as representative cases to study the deformation contour within the steel sheet in response to a unit displacement, $U = 1\, \text{mm}$. Similar to flat BEAMS, displacing the lateral side of the ice generates a moment that induces tension and compression on the front and rear edges of the ice, respectively. Positively and negatively curved BEAMS respond differently to this generated moment.

For Type 2 BEAMS, the positive curvature prevents deflection in the tension zone, while the rear edge of the ice is free to deflect, maximally displacing $U = 1.1\, \text{mm}$ (Fig. 3b). Accordingly, the rotational axis of the ice, i.e. the line at which the curved sheet has the least tendency to deflect, is along the front edge of the ice in Type 2 BEAMS (Fig. 3b). Deformation within the compression zone alters the radius of curvature of the sheet, but the ice maintains its curvature due to its higher flexural rigidity. This will initiate delamination at the rear edge of the ice and propagate an interfacial crack toward the front edge. The maximum displacement occurring at the rear edge will also facilitate this crack opening (Mode I) fracture mechanism.

In contrast, for Type 3 BEAMS the rear edge (compression zone) of the ice acts as a fully-confined line (Fig. 3d). The small deformation in the compression zone results in an axis of rotation near the rear edge of the ice. Moreover, the maximum deflection of the ice is 20 times lower in Type 3 BEAMS, compared to Type 2. It was previously shown for flat BEAMS that confining the compression side of the ice results in higher ice adhesion strengths by preventing crack opening, as compared to confinement within the tension zone [2]. Similarly, Type 3 BEAMS show higher ice adhesion strengths than Type 2 BEAMS. Overall, the numerical analysis indicated that the ice adhesion strength of BEAMS, regardless of curvature type, is highly dependent on the sheet deformation in the compression zone.

### 4.2. Curved BEAMS performance using rime ice

Type 2 BEAMS ($R = 17.1\, \text{mm}$) was also evaluated using realistic rime icing conditions in the Altitude Icing Wind Tunnel (AIWT). Four different BEAMS samples, fabricated utilizing two to five strips of elastomers as confinement, were used for the spin rig test. Optical images of the BEAMS spin rig samples are shown in Fig. 4a. A 2D schematic of the BEAMS samples with their conical spin rig coupon shape is shown in Fig. 4b. For flat BEAMS, previously it was demonstrated that energy release due to buckling causes crack opening displacement at the ice/metal interface, followed by a clean ice shed [2]. However, the critical buckling force for curved plates is an order of magnitude higher due to the increased flexural rigidity of the sheet. Unexpectedly, low ice adhesion strengths, $\tau_{\text{ice}} < 3\, \text{kPa}$, were still observed for all Type 2 BEAMS samples investigated (Fig. 4c). This value is five-times lower than the glaze-type ice adhesion strengths measured using the push-off test for flat BEAMS, $\tau_{\text{ice}} \approx 10 - 15\, \text{kPa}$ (Fig. 4c). While the type of ice may have contributed to this counter-intuitive result, typically rime has higher adhesion than glaze due to its more porous, less dense structure [26]. To explain this observation, numerical simulations were again carried out for representative experimental cases.

### 4.3. Lateral torsional buckling in elastomers

Another series of numerical simulations was performed to study the icing of Type 2 curved BEAMS and the spin rig results. While rime was evaluated experimentally in the AIWT, its porous and variable structure is significantly challenging to simulate accurately. Accordingly, in the simulations, glaze ice was used to simplify the deformation analysis. Similar to the experimental program, two to five strips of elastomers with width and thickness.
of 2 mm and 3 mm, respectively, were used as confinement points. These elastomeric strips were aligned perpendicular to the centripetal force applied during the rotational acceleration. A schematic of the simulated spin rig apparatus is shown in Fig. 5a.

Accelerating the rotor with an angular velocity of \( \omega \), a centripetal force of \( F = m_\text{rotor} \omega^2 \) was applied to the ice, BEAMS sample, and spin rig coupon. As a result of the eccentricity of this applied force on the accreted ice, a moment was generated on both the ice and elastomeric strips and the tension/compression resulting from the generated moment on the ice are also shown. c, Schematic side view of the elastomeric strips and the non-uniform centripetal force distribution. T = Tension and C = Compression. The elastomers are shown in blue and for simplicity the steel sheet is not shown. d, Confinement condition in each elastomeric strip. Confinement at the interface of the foam tape and elastomeric strips prevents warp and twisting of the elastomers by the non-uniform centripetal forces.

Fig. 4. Evaluation of curved BEAMS performance using rime- and glaze-type ice. a, Fabrication process of BEAMS spin rig coupon. b, Schematic of confinement arrangements for BEAMS samples in spin rig and push-off tests. c, Comparison of the ice adhesion strength of flat BEAMS and curved BEAMS consisting of strips of elastomers using the push-off and spin rig instruments.

Fig. 5. Ice detachment mechanism in BEAMS spin rig coupons. a, Schematic of centripetal force distribution during spin rig experiment. b, Force distribution on spin rig coupon, BEAMS sample, and accreted ice due to the centripetal force. The non-uniform centripetal force on the elastomeric strips and the tension/compression resulting from the generated moment on the ice are also shown. c, Schematic side view of the elastomeric strips and the non-uniform centripetal force distribution. T = Tension and C = Compression. The elastomers are shown in blue and for simplicity the steel sheet is not shown. d, Confinement condition in each elastomeric strip. Confinement at the interface of the foam tape and elastomeric strips prevents warp and twisting of the elastomers by the non-uniform centripetal forces.
Fig. 6. Lateral torsional buckling in the elastomeric confinement strips of BEAMS. a, 3D deformation contours in the five elastomeric strips as a result of the centripetal force. The undeformed condition of the strips is shown by the meshed contours. b, Side view of the deformation contours for the five elastomeric strips. c, The change in the radius of curvature for BEAMS consisting of two elastomer strips. For the elastomer strip experiencing the lower centripetal force (Strip 1), expansion occurs underneath the accreted ice and contraction occurs at ice-free areas. For Strip 2, compression occurs in the elastomer underneath the ice, resulting in bulging of the elastomer under areas where no ice accreted.

Fig. 7. Cross-sectional profile of BEAMS with 2 – 5 strips of elastomers underneath. A comparison of the cross-sectional profile of the deformed and undeformed steel sheet directly above the elastomeric strips for, a, two strips, b, three strips, c, four strips, and d, five strips. The coordinate systems were identified for each layer separately to obtain a non-tilted profile.
BEAMS. This moment induced tensile and compressive force components on the ice (Fig. 5b). Moreover, the centripetal force increases with the radius of rotation, \( r_{\text{arm}} \), and the wedge shape of the spin rig coupon results in a non-uniform centripetal force on the BEAMS and ice (Fig. 5c).

A side view schematic of the force distribution on the elastomeric strips is shown in Fig. 5c. For BEAMS consisting of five strips, the highest tensile and compressive forces are applied on the elastomeric strips closest to and farthest from the center of rotation, respectively, while the transition from tension to compression occurs on the strip at the middle due to negligible pressure from the ice. The non-uniform centripetal force on the side of each elastomer causes lateral displacement. This complex force distribution, in addition to the fully-confined conditions at the interfaces above each elastomer, results in lateral torsional buckling in the elastomers. In this regard, the lateral centripetal force causes lateral bending while the longitudinal forces (tension/compression) resulting from the ice generate torsion in the elastomeric strips. Note that, unlike flat BEAMS, the buckling observed here is within the elastomeric supports rather than the metallic sheet.

The torsion of the elastomers also results in warping at the interface of the elastomer/foam tape at the back edge of the coupon (backside of the leading edge). Because the elastomer/foam tape interfaces are assumed to be fully-confined, deformation caused by the elastomer warping is prevented (Fig. 5d). The high Poisson ratio of the elastomers (\( \nu = 0.48 \)), in addition to this warping prevention at the elastomer/foam tape interface and the compression at the sheet/elastomer interface beneath the ice, results in elastomer bulging under the ice-free areas (Fig. 6a, 6b). Initially, ice is accreted in the shape of the undeformed curved sheet and accordingly the elastomers, steel sheet, and ice all have the same radius of curvature everywhere. However, the deformation induced by the lateral-torsional buckling in the elastomeric strips alters the sheet's radius of curvature, whereas the relatively thick ice maintains its curvature due to its higher flexural rigidity (Fig. 6c). This change in radius of curvature under the ice occurs regardless of the number of elastomeric strips. For example, a change in the radius of curvature in the steel sheet of BEAMS consisting of two elastomeric strips is shown in Fig. 6c, with the front edge under tension and rear edge under compression.

For the case of lateral torsional buckling of the elastomeric supports of curved BEAMS, the delamination mechanism depends on whether one is considering the tension or compression zones. In the tension zone, the rigidity of ice causes the elastomer to expand. However, the flexural rigidity of the steel sheet is substantially larger than the elastomer, resulting in large deformation of the elastomer at point \( a \) (Fig. 6c). At the same time, the high Poisson ratio of the elastomer causes compression in the areas where ice is not adhered to the steel sheet (for example, between points \( b \) and \( d \) or \( c \) and \( e \) in Fig. 6c). This change in the radius of curvature initiates a crack at points \( b \) and \( c \) of the steel sheet/ice interface, which then propagates toward point \( a \). In the compression zone, ice compresses the steel sheet and elastomer at point \( a \). In contrast to the tension zone, the steel sheet then bulges in the ice-free areas to compensate for this compression. The change in the radius of curvature caused by this bulging will initiate a crack at point \( a \), which will propagate along the interface towards points \( b \) and \( c \). Note that the direction of crack propagation under each elastomer depends on whether they are located in tension or compression zones. This change in the radius of curvature was observed in all cases of BEAMS with two to five strips of elastomers (Fig. 7).

Increasing the number of strips decreases the change in the radius of curvature in BEAMS. However, elastomer deformation will serve as a crack initiation site at the ice/metal interface above each strip. This numerical result was corroborated by the spin rig experiment measurements, where a higher number of strips results in lower ice adhesion strength (Fig. 4c). For BEAMS with two elastomer strips, we also conducted a numerical simulation increasing the width of the strips from 1 to 4 mm. As expected, sheet deformation is reduced as the elastomer strip width increases, as the critical buckling stress of a column scales with its width.

5. Conclusions

In this study, the performance of curved BEAMS was investigated using glaze- and rime-type ice. A decrease in radius of curvature of the steel sheet increased its flexural rigidity, resulting in significantly higher ice adhesion strengths. This was observed using four different ice holders specifically designed to evaluate curved BEAMS with positive and negative curvatures, where the applied load either impacted the BEAMS holder or ice. Overall, a negative radius of curvature doubles the ice adhesion strength of BEAMS compared to a positive radius of curvature, because it prevents deformation in the compression zone and acts as a fully-confined support. However, regardless of the higher flexural rigidity, curved BEAMS show promisingly low ice adhesion strengths when evaluated in realistic icing conditions using rime. The use of elastomeric strips underneath the steel sheet increases the compliance of the confinement points ten times, resulting in lateral torsional buckling of the elastomeric strips. Unlike flat BEAMS, buckling of the confinement points, in addition to their high Poisson ratio, substantially alters the radius of curvature of the steel sheet above each elastomeric strip, initiating crack opening at the ice/steel sheet interface. Accordingly, a higher number of elastomeric strips should result in lower ice adhesion strengths, and this was validated using spin rig experiments in an icing wind tunnel.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We acknowledge that this work was conducted at the University of Toronto, on the traditional land of the Huron-Wendat, the Seneca, and the Mississaugas of the Credit. The authors thank the Department of National Defence for sponsoring the research, through project CP-3237, as well as the Canada Foundation for Innovation, under grant 41543.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.matdes.2022.110884.

References


C. Santaputra, M.B. Parks, W.W. Yu, Local Buckling of Curved Elements, International Specialty Conference on Cold-Formed Steel Structures (1986).


