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Numerical simulations of ice shedding on single-span models

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***Abstract*— Ice accretion on transmission lines could lead to several mechanical and operational problems. The gravity loads due to heavy ice accretion on overhead lines coupled with wind on iced spans, as well as ice shedding from the conductors could be a source of serviceability problems and structural damage, failure or even cascading collapse of towers in extreme events. Various methods (anti-icing and de-icing techniques) are used to mitigate the aforementioned consequences. One of the methods developed for overhead power line de-icing is based on applying mechanical shocks to iced conductors, taking advantage of the brittle behavior of ice deposits at high strain rates. The empirical development of this method with successful field tests has prompted researchers from UQAC and McGill University to study the problem of sudden ice shedding induced by shock loads in more depth using nonlinear dynamic finite element analysis.**

This work improves on previous computational models for ice shedding with a failure criterion for the ice deposit based on effective plastic strain limits. The new criterion has been verified in models of reduced-scale spans in a comparison with physical tests previously conducted in the CIGELE laboratory at UQAC. In the work presented here, the maximum effective plastic strain failure criterion is applied to a model of a cylindrical ice deposit on a real-scale single span and the results are compared to those obtained from a computational model using a maximum normal stress criterion. ADINA™ is the commercial software used for the nonlinear dynamic analysis of the iced spans subjected to shock loads. The response indicators used in the comparison are the cable tension at mid span and at supports, the conductor's vertical displacement at mid span, and the fraction of ice deposit rupture also called the rate of ice shedding. The results show consistency between the two failure criteria and confirm the improved performance of the new ice failure criterion based on maximum effective plastic strain for real-scale overhead lines. Furthermore, an approach to optimize the conductor mesh size is introduced which can significantly reduce the computational effort in the transient shock analysis of a complex transmission line model comprising multiple spans and supports.

Keywords: Ice shedding, transmission lines, nonlinear dynamic analysis, ice failure criteria.

I. INTRODUCTION

Dynamic analysis of iced power line conductors subjected to ice shedding induced by shock load is complex. The first numerical study to consider ice deposits on the lines explicitly was done by Kálmán [1-3]. The proposed ice failure criterion used in the model was based on the maximum bending stress of an elastic beam ice deposit defined in parallel with each cable finite element. Following this work, Mirshafiei [4, 5] attempted to improve the ice failure criterion to get more realistic results for the actual ice shedding fractions observed in the reduced-scale tests by Kálmán. The new proposed criterion was based on maximum effective plastic strain of ice deposits where a bilinear ice material model was assumed. This new strain criterion was implemented into the finite element models of iced cables subjected to shock loads studied by Kálmán and the numerical results were compared with the experimental results from a reduced-scale model tested in the CIGELE Laboratory at Université du Québec at Chicoutimi (UQAC) [1]. As a result, the strain-based ice failure criterion was validated and yielded to more realistic predictions of ice rupture fractions than the stress-based failure model [4, 5].

As a follow-up, the primary objective of this work is to further validate the effective plastic strain criterion by comparing the results of a real-scale single span model subjected to shock load using both ice deposit failure criteria.

II. MODEL DETAILS

The maximum plastic strain ice failure criterion presented in previous work and validated on a level single-span reduced-scale experimental model [5] is applied to a real-scale single span that has also been studied by Kálmán [1]. An ACSR (Aluminum Conductor Steel Reinforced) cable is used with the properties listed in Table 1. In section III an equivalent ice thickness of 10 mm is modeled as a cylindrical (tubular) ice beam, following the procedure described in [5]. Furthermore, two different triangular pulse loads applied at the mid span are represented in Figure 1 by load amplitudes of 30 kN and 60 kN. The initial sag-to-span ratio and span length are set to 5% and 300 m, respectively.

1500 elements along the span are used to define the appropriate mesh size [1]: this refined mesh is used initially to capture the transient response of the ice deposit and conductor to shock loading. However, as discussed in section IV, a coarser mesh with 300 elements along the span also yields accurate results. Incremental equilibrium for initial static analysis is completed in 5 steps (set to 1 s each) so that dynamic analysis is started at time t = 5 s and continues for a total duration of 6 s. A time increment of 0.1 ms was found appropriate for the mesh selected, while smaller time steps are implemented automatically whenever required in the equilibrium iteration process by activating the *ATS* (automatic time-stepping) option in ADINA [6]. In section IV an equivalent ice thickness of 25 mm is modeled on the same cable with an upward triangular pulse-load of 60 kN with rising time of 1.5 ms applied at mid span. The other model characteristics remain the same as in section II.

III. COMPARISON OF STRESS AND STRAIN ICE FAILURE CRITERIA

Figure 2 shows the schematic finite element model and a summary of the results is presented in Table 2. This table lists the number of ice elements remaining attached to the cable (n), the rate of ice shedding (RIS) – in effect this is the fraction of the ice that is fractured, the initial amplitude of the transverse wave displacement induced by the shock load on the conductor at mid span (IWA), the maximum dynamic cable tension at mid span (MT) and at the support (MTS), as well as the maximum cable jump at the mid span (MD). Displacements are calculated with respect to the static profile of the fully iced cable.

TABLE 1. CABLE CHARACTERISTICS

Property	**Conductor**
Name Code	CONDOR
Type	ACSR
Diameter (mm)	27.8
Total cross-sectional area (mm^2)	455.1
Young's modulus of the cable composite (GPa)	68.95
Mass per unit length (kg/m)	1.522
Weight per unit length (N/m)	14.93
Rated tensile strength (kN)	127

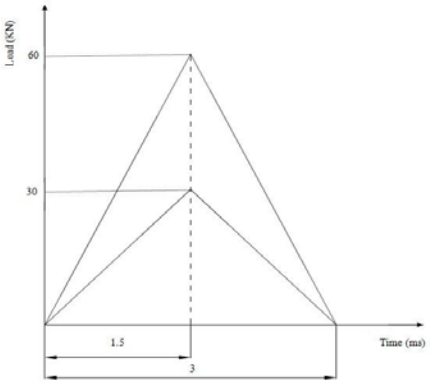

Figure 1. Pulse Load Characteristics

As indicated in Table 2, the pulse load with 60 kN amplitude triggers 100% ice failure in both failure criterion scenarios. However, the 30 kN pulse load carries less energy and the predicted RIS is of 83% (252 of the total 1500 ice beam elements remained attached) with the proposed plastic strain criterion, while only 49 elements remained attached when the stress criterion was used. The other results such as MT, MTS and MD are close in both ice failure scenarios with slight differences, since as soon as different ice-beam elements drop off the span, each scenario evolves in a slightly different manner. However, in both cases, the shock load of 60 kN generated additional cable tension at the excitation point that exceeded the rated tensile strength of the conductor, which cannot happen in reality. Therefore, to avoid damaging the cable, it may be necessary in practice to apply successive lower amplitude shock loads at a given point along the span or at two or more points. These simulations show that it is feasible to implement the new strain-based failure to real scale problems and they could serve to plan and optimize emergency field interventions.

IV. FINDING THE OPTIMUM MESH SIZE FOR AN ICED SPAN

This section discusses a procedure to determine the optimum mesh size to use in ice-shedding simulations for real-scale conductors subjected to shock loads. The maximum plastic strain criterion is used in the models.

A. Eigenvalue and FFT analysis of the iced cable with 1500 elements

In this example, a 300-m CONDOR span with an equivalent ice thickness of 25 mm under the upward 60 kN pulse-load (see Fig. 1) at mid span is modeled to validate the proposed refined mesh size (1500 elements) in section III. The natural frequencies and mode shapes of the fully iced cable model are calculated and compared with the analytical solution [7] for ideal elastic catenaries; results of the four lowest frequency modes are listed in Table 3.

The frequencies are identical in all cases except for the 2nd symmetric mode; this discrepancy is explained by the fact that the iced-cable model comprises ice beams and cable truss elements and therefore cannot deflect as an ideal catenary shape. To verify this, the model was made anew by using increased density cable truss elements with the same mesh size to account for the added mass of ice, and the natural frequencies were the same as predicted with Irvine's theory.

Considering that 1500 elements make for a very fine mesh to capture the successive ice shedding of adjacent ice chunks, other coarser meshes are studied in this section to find out the optimum mesh size. The first step is to examine the frequency content of the calculated cable response using Fast Fourier Transform (FFT) analysis on the 1500-element mesh model.

The time history of the cable tension at the right support is illustrated in Figure 3: the maximum tension is 61.4 kN and it oscillates about its initial value of 38 kN. Figure 4 shows the amplitude of the discrete Fourier transform of this cable tension time history. The dominant frequencies are at the low end (below 1 Hz) of the spectrum, coinciding with the lowest few in Table 3, and there is another peak with less energy near 9.8 Hz. In fact, the shock load generates longitudinal stress waves (in addition to transverse waves) that propagate back and forth along the span at an approximate speed of 4.5 km/s [8]. This fundamental longitudinal (axial) vibration of the iced cable, evaluated at 9.77 Hz, creates the high frequency oscillations of the cable tension in Fig. 3.

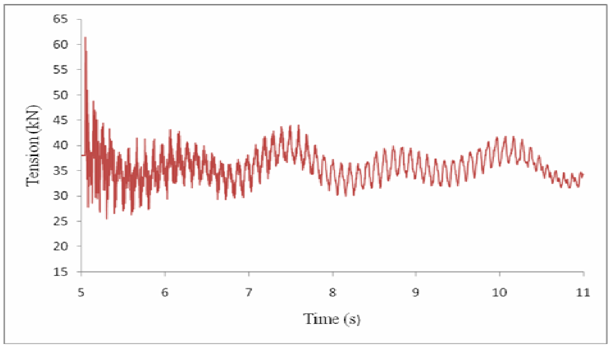

Figure 3. Cable tension at the right support

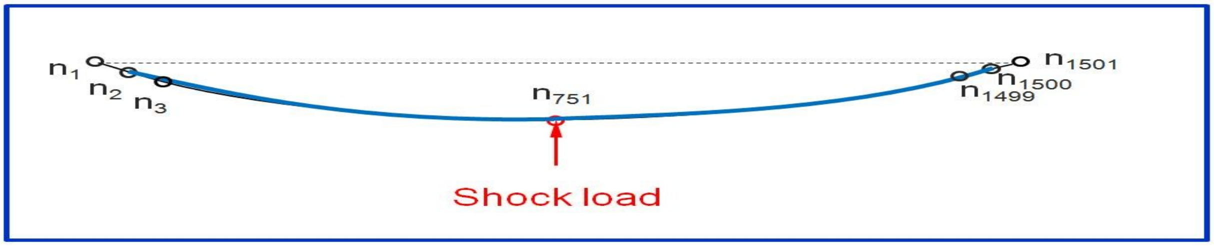

Figure 2. Finite element model

TABLE 2. RESULTS OF TWO ICE-SHEDDING SCENARIOS OF AN ACSR CONDUCTOR

Span (m)	**Shock Load (kN)**	**Maximum normal stress criterion**						**Maximum effective plastic strain criterion**					
		n	***RIS (%)***	***IWA (m)***	***MT (kN)***	***MTS (kN)***	***MD (m)***	***n***	***RIS (%)***	***IWA (m)***	***MT (kN)***	***MTS (kN)***	MD ***(m)***
300	60	0	100	0.24	131.8	57.2	0.803	0	100	0.22	131.6	56.9	0.805
	30	49	96.7	0.10	76.6	29.1	0.480	252	83.2	0.10	75.8	32.1	0.580

TABLE 3. NATURAL FREQUENCIES AND MODE SHAPES OF ICED SPAN

Mode	**Finite element model (Hz)**	**Irvine's theory (Hz)**
1st asymmetric	0.27	0.27
1st symmetric	0.39	0.38
2nd asymmetric	0.55	0.55
2nd symmetric	0.66	0.55

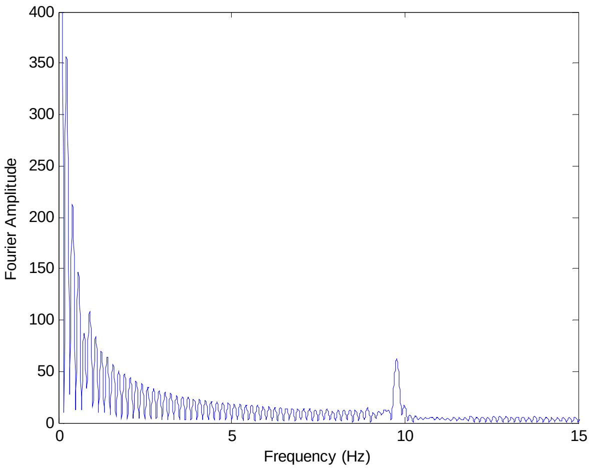

Figure 4. FFT spectrum of cable tension at the right support

B. Eigenvalue and FFT analysis of the iced cable with 300 elements

Several scenarios with coarser mesh sizes such as 30, 100, 200, 300, 600 and 900 elements were studied to find out the optimum mesh size of a 300-m level span of CONDOR cable with an ice thickness of 25 mm. In conclusion, the 300-element case was chosen as optimum. This selection is based on different numerical performance criteria: having mode shapes, frequencies up to 10 Hz and cable responses identical to that of refined mesh (1500 elements) and also having an acceptable level of normal stress (below 0.15 MPa) in the ice elements after the initial static analysis; i.e. in the range of the refined mesh which is under the yielding threshold value. Meshes that are too coarse impose too much bending in the ice deposit beams defined between adjacent cable nodes. The time history of the cable tension at the right-end support and its corresponding FFT amplitude spectrum obtained for this optimum mesh size are illustrated in Figure 5 and Figure 6, respectively. In addition, a comparison between the refined and optimum mesh frequencies is shown in Table 4 which confirms the accuracy of the 300-element mesh.

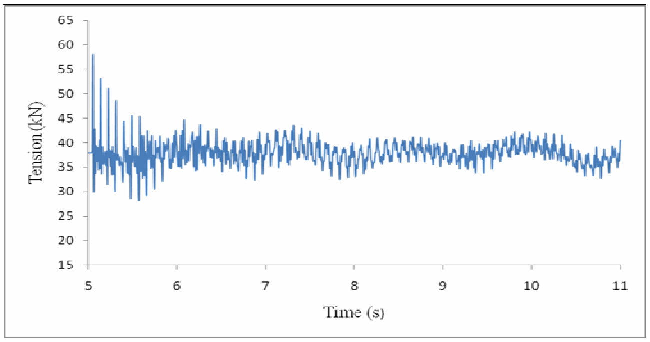

Figure 5. Cable tension at the right support

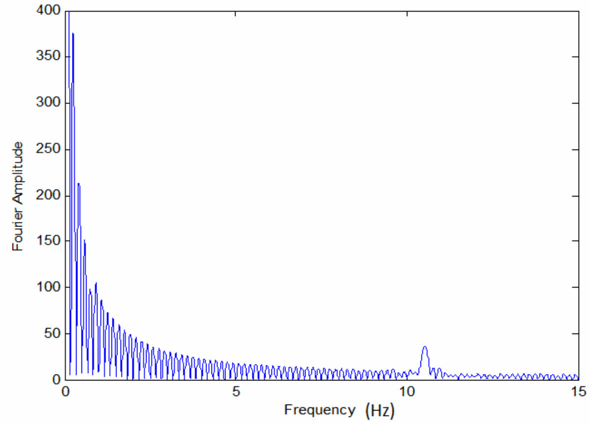

Figure 6. FFT spectrum of cable tension at the right support

TABLE 4. COMPARISON OF NATURAL FREQUENCIES (IN HZ) OF 300 AND 1500 ELEMENT MODELS

Mode	**Mesh size**	
	1500 elements	***300 elements***
1st asymmetric 1st symmetric	0.27 0.39	0.27 0.39
2nd asymmetric 2nd symmetric	0.55 0.66	0.55 0.66
	...	
33rd asymmetric 33rd symmetric	9.8 10.0	9.7 9.9

V. CONCLUSION

Numerical studies have shown that it is feasible to implement the new ice failure criterion based on maximum effective plastic strain to single-span real scale overhead lines. Furthermore, an optimum mesh size was found which will significantly reduce the computational efforts in a complex transmission line model with iced conductors subjected to ice shedding induced by shock loads.

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