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Probabilistic fracture mechanics analysis of spalling during edge indentation in ice

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ABSTRACT

The design of marine structures for ice environments requires ice load estimates, which are greatly influenced by fracture and associated scale effects. During edge indentation of natural ice, fracture processes are highly influenced by variability associated with flaw structure and contact conditions. A probabilistic framework is the most appropriate for modeling such interactions. In the present analysis, a probabilistic fracture mechanics model has been developed to model localized fracture events for ice specimens with ice edge taper angles ranging from 0° to 45°. Crack instability criteria have been formulated for compressive and tensile states of stress. This approach varies from traditional probabilistic failure models which assume that zones of compressive stress have zero failure probability and include only tensile zones in the calculation of failure probability. For compressive edge loading, experimental results indicate that local edge fractures (spalls) are most likely to emanate from regions of the ice where cracks would be subjected to axial compression and lateral tension. Compressive contact loads required to propagate fractures from zones of bi-axial tension or bi-axial compression were found to be considerably higher and are much less probable. Estimates of the mean pressure required to trigger a fracture event as a function of ice thickness were generated for thicknesses in the range of 0.2–2.0 m. These results demonstrate that observed scale effects in ice pressure data can be explained by probabilistic aspects of fracture. Simulations of fracture probabilities as a function of loading eccentricity confirmed that extreme loads of interest in engineering design are most likely to correspond to high pressure zones located near the center of thickness of the ice sheet. Results indicate that fractures occur more readily for flat ice edges and higher pressures are required to propagate fractures for edges with more highly tapered edges. This result provides a theoretical basis to explore the interplay between fracture and crushing, both of which occur during compressive ice failure: fractures create tapered edges that localize contact in manner that supports crushing; crushing, over several cycles, flattens the ice edge in a manner that in turn promotes fracture. While the application presented here is focused on ice mechanics, the analysis methodology could readily be applied to other brittle materials.

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Nomenclature

E	elastic modulus
ν	Poisson's ratio
K_{Ic}	mode I fracture toughness
σ_{ij}	stress tensor
ε_{kl}	strain tensor
C_{ijkl}	stiffness matrix
$X(t)$	autoregressive random series
$U(t)$	background random noise
$B_x(\tau)$	covariance function
σ_P^2	variance
τ	lag distance
$\rho(t)$	correlation coefficient
c	characteristic correlation length
σ_G^2	variance of global pressure
σ_L^2	variance of local pressure
T	averaging distance
$\gamma(T)$	variance reduction function
c_1, c_2	characteristic correlation lengths (composite correlation method)
q_1, q_2	weighting factors (composite correlation method)
γ_1, γ_2	variation reduction factors (composite correlation method)
$\mu_{L,i}$	mean local panel pressure for the *i*th panel
$\sigma_{L,i}$	standard deviation of the local pressure for the *i*th panel
α_L	pressure coefficient for the event maximum method
C	coefficient of power law for mean pressure
D	exponent of power law for mean pressure
E	coefficient of power law for standard deviation of pressure
F	exponent of power law for standard deviation of pressure
T_i	random strength of the *i*th element
$F_T(t)$	strength distribution function
W	event that the weakest link fails
$F_W(\sigma)$	failure probability of the system
v_0	reference volume (for Weibull function)
$m(\sigma)$	material function (for Weibull function)
α_W	Weibull shape parameter
σ_W	Weibull scale parameter
σ_0	Weibull constant (here lower limit on strength)
$\langle R \rangle$	expected specimen strength
σ_R	standard deviation of strength
s_1	constant corresponding to probability of exceedence
E_1	extreme pressure
a_s	spall depth based on idealized geometry
b_s	spall distance from center of indentation
$2q$	width of contact zone
ω	effective taper angle of ice edge (in degrees)
P_0	reference state (maximum peak pressure)
$\overline{P}_c$	mean contact pressure (over contact area)
$\overline{P}_h$	overall mean pressure (over nominal area)
F_{TOT}	total force on specimen
$\overline{P}_{h,50}$	mean overall pressure corresponding to 50% probability of spalling
σ_x	stress component in *x*-direction
σ_y	stress component in *y*-direction
τ_{xy}	shear stress component
σ_1	maximum principal stress
σ_2	minimum principal stress
θ_p	principal angle
$\sigma'(x_i)$	normalized stresses at *i*th element
$\sigma(x_i)$	stresses at *i*th element
r	reference stress value (scalar)
σ'_{ij}	normalized stress tensor