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Application of the method of singular integral equations to the failure analysis of impact-damaged thin-walled pressurized structures

Igor Telichev

University of Manitoba, Department of Mechanical Engineering, 75A Chancellors Circle, E2-327 EITC, Winnipeg, Manitoba R3T 5V6, Canada

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ABSTRACT

The present paper is devoted to the application of the method of singular integral equations to modeling of unstable crack propagation in thin-walled metallic pressurized structure subjected to a high-velocity impact. Damage pattern and mechanisms leading to the unstable crack growth are discussed. The critical stress and the critical crack length in the impact damaged structure are calculated by the method of mechanical quadratures. The validity of the developed model is tested by simulating the experimental results and numerical results obtained by other method.

1. Introduction

Foreign object impact represents a serious design concern for thin-walled pressurized structures. Because of the possibility to fail catastrophically when impacted, these items play a central role in determining the survivability of aircraft and spacecraft subjected to impact.

The problem of potential fracture and bursting of thin-walled metallic pressurized structures was extensively examined by the NASA Advanced Fracture Mechanics Group [1–3]. The fracture propagation analysis was conducted analytically using the linear elastic fracture mechanics approach and numerically employing the finite element method and non-linear fracture mechanics technique. Comparison to the experimental data showed that the linear elastic fracture mechanics methods are too conservative and non-linear fracture mechanics approach is required for a more realistic treatment of the problem [1].

The finite element method (FEM) is the most extensively used numerical technique for the modeling of fracture mechanics problems. However, conventional FEM has the drawbacks in modeling the crack propagations since the re-meshing and mesh alignment are required as crack grows. Several approaches have been proposed to address those difficulties either via the mesh-based methods where re-meshing is not required or applying the mesh-free methods. For example, the extended finite element method (X-FEM) enables the geometry of the crack to be independent of the finite element mesh, thus, avoiding the re-meshing procedure [4–6]. There are a number of methods which belong to a family of meshfree methods [7–9] and use a set of nodes scattered within the problem domain instead of meshing. The present paper is focused on the singular integration method (SIEM) which is free of mesh generation. The SIEM technique is a powerful alternative to the finite element method in the non-linear analysis of crack propagation [10–16]. This computationally efficient technique combines both analytic and numerical approaches being, however, limited to problems with relatively simple geometries and loading conditions.

E-mail address: igor.telichev@umanitoba.ca

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Nomenclature

D_{hole}	diameter of the impact hole
D_{crack}	diameter of the impact-damaged zone
$L_{rad.cr.}$	radial crack length
G	shear modulus
E	modulus of elasticity
ν	Poisson's ratio
t_s	specimen thickness
æ	an elasticity constant
σ_y	tensile yield limit
σ_u	ultimate tensile strength
σ_c	critical stress
σ_θ	hoop stress in the vicinity of hole
σ_{pz}	stresses within the plastic zones
p_n	load distribution along crack edges
K_{ic}	fracture toughness at the crack initiation
$K_{c\ max}$	fracture toughness at the maximum load
K_I	stress intensity factor for mode I crack
K_σ	stress concentration factor
COD	crack opening displacement
$CTOD$	crack tip opening displacement
$CTOD_c$	critical crack tip opening displacement
$z = x + iy$	complex variable
Γ	crack contour
$\Phi(z)$	analytic function
$\Psi(z)$	analytic function
$\varphi(z)$	complex potential defined by equation $\Phi(z) = \varphi'(z)$
$\psi(z)$	complex potential defined by equation $\Psi(z) = \Psi'(z)$
P	normal component of traction
T	tangential component of traction
t'_n	load coordinate in the local coordinate system
t_k	crack point coordinate in the local coordinate system
g_k	function of the jump of displacement on the crack contour
z_n^0	complex coordinates of the origins of the local coordinate systems
α_n	inclined angle for the n-th link
L_n	n-th link of polygonal crack
ξ, η	local normalized coordinates
K_{nk}, L_{nk}	kernels of the singular integral equation
M_{nk}	normalized kernel of the singular integral equation
u, v	displacement components
N	number of Chebyshev nodes
T_r	first kind Chebyshev polynomial
w	weight function used in Gauss integration
C_n	constants of integration
τ	time

The primary objectives of the present paper are twofold: (1) to introduce the model of impact damage in the form of a circular hole with two radial cracks as a universal approach which fits all penetration scenarios to replicate the observed fracture behavior of the impact damaged thin-walled metallic pressurized structures and (2) to demonstrate that the application of the SIEM approach allows determining the border between the simple perforation and catastrophic fracture of impact-damaged pressurized structure. The achievement of the above objectives also turns into novelty as to the best of author's knowledge the method of singular equations (SIEM) and proposed model of the impact damage were not previously applied to the analysis of impact-damaged pressurized structures.

The application of the proposed methodology for the design of the pressurized components potentially subjected to foreign object impact (e.g. module of spacecraft, fuselage of aircraft, pressure vessel for oil/gas industry, etc.) enables to control the crack propagation developing the configurations which provide "simple perforation" conditions without bursting.