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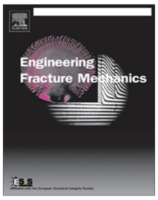

Bulging factor of a longitudinal crack in pressurized cylindrical shell with a reinforcing layer

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ABSTRACT

Bulging factor expressions for a longitudinal crack in a pressurized cylindrical shell with a reinforcing layer are developed. In this study, a parametric finite element model was constructed, validated (based on experimental data) and used to simulate various shell configurations. A Python script automates the execution, data collection and calculation of the bulging factor for 2592 configurations using the commercial code ABAQUS. Candidate expressions for the bulging factor are selected based on physical arguments and fitted using stress displacement data obtained previously; several expressions were found to be in good agreement with finite element data.

1. Introduction

Fuselage structures in ageing aircraft are known to be vulnerable to cracks in their skin as well as reinforcing members such as stringers and frames. For this reason such structures are designed with a failsafe or damage tolerant approaches. However, despite such precautions catastrophic failure in fuselages of ageing aircraft has been recorded in civil and military aviation [1]. This is due to a phenomenon known as widespread fatigue damage where multiple independently initiated cracks grow to critical lengths and link up to form a super crack that would cause significant reduction in the residual strength of the fuselage structure [2]. Wu et al. have proposed a solution to mitigate the stress field around the crack tip in the objective to increase fatigue life of the panel section [3]. This solution consists in applying a layer of rigid foam to the inner side of the fuselage panel section. The added foam would provide additional reinforcement and attenuate the stress field near the crack tip. Experimental studies were conducted by Bakuckas et al. [4] and Lazghab et al. [5] showed that this solution could increase fatigue life by 161%. A numerical study conducted by Lazghab et al. [6] showed that the bulging factor could be reduced by as much as 45%.

Abbreviations: MCCI, Modified Crack Closure Integral; SIF, stress intensity factor; MPC, multi-point constraints; SG, strain gage; FEA, finite element analysis.

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Nomenclature

a	half length of the crack in the shell (mm)
a_0	initial half crack length in the shell (mm)
A_i	parameters to be determined from data fitting procedure
d_F	depth of the crack in the reinforcing layer (mm)
e	characteristic element length (mm)
e^*	critical characteristic element length (mm)
$\hat{\mathbf{e}}$	unit vector in a reference frame (–)
E_S	elasticity modulus of the shell material (GPa)
E_F	elasticity modulus of the reinforcing material (GPa)
$\mathbf{F}$	force vector at the crack tip (N)
F_a	total axial force applied to the shell section (N)
G_I	strain energy release rate (N mm/mm^2)
K_I^S	stress intensity factor in the shell for mode I (N/mm$^{3/2}$)
K_I^P	stress intensity factor in the plate for mode I (N/mm$^{3/2}$)
L_{stiff}	stiffener spacing in a stiffened shell (mm)
L_θ	length of shell section along tangential direction (mm)
$\mathbf{M}$	moment vector at the crack tip (N mm)
N_i	ith node number
p	internal pressure (MPa)
R_S	radius of the shell (mm)
$\mathbf{r}$	nodal rotation vector (rad)
t_S	thickness of the shell (mm)
t_F	thickness of the reinforcing layer (mm)
$\mathbf{u}$	nodal displacement vector (mm)
β	bulging factor in bare cylindrical shell (–)
β_F	bulging factor in reinforced cylindrical shell (–)
χ	stress state biaxiality ratio (–)
η	non-dimensional parameter (–)
γ	correction factor expression (–)
λ	non-dimensional parameter (–)
ν_S	Poisson's ratio for the shell (–)
σ_t	tangential stress (MPa)
σ_a	axial stress (MPa)
σ_S^Y	yield limit of shell material (MPa)

Superscript and subscripts

0	initial
I	mode I crack opening
F	reinforcing layer
S	shell
P	plate
θ	tangential component
r	radial component
a	axial component
$stiff$	stiffener
X, Y, Z	components in the XYZ reference frame
X', Y', Z'	components in the $X'Y'Z'$ reference frame

The bulging factor is a parameter defined as the ratio of the stress intensity factor (SIF) of a through crack in curved shell to the stress intensity factor of the same crack in a flat plate of the same thickness as the shell as given in Eq. (1) and under the stress conditions shown in Fig. 1.

The bulging factor accounts for the difference in stress states near the crack tip of a crack in a flat plate and a crack in a curved shell. It has been treated extensively in the literature, a few representative works are [6–13]. Generally the stress conditions near the crack tip in a curved shell are more severe than its counterpart in a flat plate. They are caused by the coupling between bending and membrane strains generated by the additional pressure loading. The bulging factor is a