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Probabilistic model of the growth of correlated cracks in a stiffened panel

G.Q. Feng, Y. Garbatov, C. Guedes Soares *

Centre for Marine Technology and Engineering (CENTEC), Instituto Superior Técnico, Technical University of Lisbon, Av. Rovisco Pais, 1049-001 Lisboa, Portugal

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ABSTRACT

The objective of this paper is to develop a probabilistic model for a stiffened panel subjected to correlated growth of cracks in the stiffener and plate elements. The geometry functions of the correlated cracks in the plate and in the stiffener are defined based on the stress intensity factors calculated by finite element analysis. A validation of the stress intensity factor and the geometry function calculation has been performed for an isolated crack in a plate with a central/edge through thickness crack. The Paris–Erdogan law is used to predict the crack propagation. Monte Carlo simulation is employed to define the statistical descriptors of the crack growth in the stiffened panel under different correlation functions and a probabilistic model of crack size as a function of time are presented adopting a truncated normal distribution to describe the probability density function of the crack size in the plate and in the stiffener. A procedure for the development of a probabilistic crack growth model for a stiffened panel has been proposed, allowing for the existence of multiple cracks both in the stiffeners and in the plate and accounting for the correlation between them. The developed probabilistic model may be used for fatigue crack growth analysis and is suitable for reliability assessment of a stiffened panel subjected to correlated crack growth.

1. Introduction

Fatigue as a mode of structural failure is well known problem to ship owners and designers. Very intensive work have been performed to analyse fatigue failures in [1] and at the same time new requirements for new structural designs have been established for ship structures including hot-spot and notch approaches. The analysis of the local hot spot stresses becomes a routine practice and many reports can be found in the literature, as for example in [2–4].

The direct fatigue analysis of marine structures addresses several steps of calculations: wave-induced load, structural response analysis, and the Palmgren–Miner or fracture mechanics approach. The Palmgren–Miner approach is more oriented to design formulations that predict the strength as a function of the number of cycles at various stress levels. The fracture mechanics approach is oriented to predict the behaviour of cracked structural elements in conditions of crack growth.

Once the expected stress ranges, including concentration factors, have been determined for any structural detail, fatigue damage calculations can be undertaken. The standard approaches to perform this is to use the Palmgren–Miner linear damage summation approach to evaluate the cumulative damage over the period selected, which is normally taken as the design lifetime of the structure [5].

The fracture mechanics approach assumes the existence of an initial crack. This approach can be used for the assessment of crack propagation life from the initial crack size to a final size as well as a critical crack size. The crack propagation assess-

* Corresponding author.
E-mail address: guedess@mar.ist.utl.pt (C. Guedes Soares).

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Nomenclature

Ux	translation along x axis
Uy	translation along y axis
Uz	translation along z axis
a	crack size
Y	geometry correction function
K	stress intensity factor
ΔK	stress range intensity factor
σ	axial tensile stress
$\Delta\sigma$	axial stress range
w	breadth of plate
L	length of plate
k	percent of the size of crack in respect to the breadth of plate
j	percent of the size of crack in respect to the height of stiffener
C, m	material parameters in the Paris–Erdogan equation
$a(t)$	crack size as a function of time
a_0	initial crack size
a_c	critical crack size
N	number of cycles
v_0	mean zero up-crossing rate
t	time
T_p	time of crack propagation to critical crack size
A, B	coefficients in the new geometry correction function
Z	vector of random variables
μ_Z	vector of mean values of random variables
C_Z	covariance matrix of the random vector
M	dimension of the distribution
Z_i^D	random crack size in the plate or in the stiffener
$\mu_{Z_i^D}$	mean values of random crack size in the plate or in the stiffener
$C_{Z_i^D}$	covariance matrix of random crack size
ρ	coefficients of correlation of the crack sizes in plate and stiffener
$E\,[\cdot]$	mean value of variable
$\sigma^2\,[\cdot]$	variance of variable

ment as defined by the fracture mechanics approach is based on the Paris–Erdogan crack propagation law [6], which is a function of the stress range intensity factor.

The recent increase in the use of high tensile steel applications in shipbuilding practice can be followed by increased risks of early and costly fatigue failures. The stiffened panel has been widely used in ship structures because of its lightweight and high strength and stiffness.

Poe [7] studied the fatigue crack propagation in stiffened panels used in the aircraft structures. Rates of fatigue crack propagation were measured in fatigue tests of stiffened panels composed of bolted and integral stringers. The crack growth in the stiffened panels was predicted with the calculated stress intensity factor. Fatigue tests were conducted on unstiffened panels to find out the relationship between the stress intensity factor and the crack growth rate. The author showed that the bolted stringers reduced the crack growth rate significantly below that for an equally stressed unstiffened panel, whereas the integral stringers had no significant effect. Much effort has also been undertaken in the fatigue crack propagation of repaired stiffened panel [8] with bonded patches, which have been the primary focus of most of previous studies in aerospace structures.

Rather few studies have been conducted on welded stiffeners that are found in ship structures. Watanabe et al. [9] conducted an earlier work studying the crack growth in a welded stiffened panel typical of ship structures. However, the investigation was limited to one configuration. Petershagen and Fricke [10] performed several fatigue crack growth experiments on stiffened panels and reported that stiffeners with cut-outs such as drain holes were ineffective in slowing down an approaching crack compared to solid stiffeners.

Dexter and Pilarski [11] conducted a series of experiments to study the propagation of large fatigue cracks in welded stiffened panels. The experiments confirmed that the cracks propagate in a stable manner in redundant stiffened panels and showed the effects of welding residual stress, the presence of transverse butt welds and stiffener details such as drain holes on the growth rate of these cracks. Dexter and Pilarski [12] made an analysis of crack propagation in welded stiffened panels. The Green function was used to calculate the stress intensity factor accounting for residual stresses and confirmed by finite element analysis of linear-elastic fracture mechanics. The crack propagation in box girder with welded stiffeners was predicted by applying the Paris law.