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Experimental determination of mode I stress intensity factor in orthotropic materials using a single strain gage

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ABSTRACT

This paper presents a robust technique for experimental determination of mode I stress intensity factor in orthotropic materials using only a single strain gage. Theoretical foundation and finite element based analysis leading to the selection of the angular orientation and position of the strain gage for accurate estimation of K_I in orthotropic materials is presented here. Applicability of the proposed method has been established through experiments conducted on edge-cracked carbon-epoxy laminates. Results show that the present single strain gage experiments yield accurate values of K_I when strain gage locations are selected as per the criteria set by the proposed approach.

1. Introduction

The stress intensity factor (SIF) is an important parameter in linear elastic fracture mechanics (LEFM) and is extensively employed for the analysis of engineering components having cracks. Analogous to isotropic materials, the concepts of LEFM have been used in the analysis of fracture of composites [1–4]. However, unlike isotropic materials where a crack grows perpendicular to the direction of maximum tension, in orthotropic composites, direction of crack growth depends upon the strength of the materials and the state of stress [5]. Based on the dimensional and or assembling requirements, many a times presence of crack like defects in a structural components made of orthotropic laminates cannot be avoided. Unfortunately, these are also the potential sites from where intra-laminar and inter-laminar defects like debonding, delamination and matrix cracking initiate [6–8] during service. Whether such a crack will at all grow and lead to the initiation of the delamination and matrix cracking, could be assessed by comparing the stress intensity factor (SIF) with the critical SIF. Therefore, determination of SIFs for an existing crack in laminated composites is extremely important to assess the propensity of delamination initiation from such cracks. Hence, SIF which is a parameter independent of crack growth direction finds significant importance in fracture analysis of such materials.

In applying LEFM to orthotropic materials to prevent fracture, it is therefore important to determine accurate value of SIF. As a result, large numbers of analytical, numerical and experimental techniques have been proposed to determine SIFs in such materials. Among different available approaches, experimental determination of the SIF plays an important role in complex situations [9] and are also required to validate the theoretically or numerically determined SIFs thus aiding to their correct application. In recent years, piezoelectric sensors are also used for in-situ measurement of SIFs and simultaneous detection of crack tip location by solving an inverse problem for the structural health monitoring under fatigue loading [10–12]. In experimental fracture mechanics, strain gage based techniques for the determination of SIFs are quite popular

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Nomenclature

a	crack length
b	width of the plate
C	constant
h	height of the plate
L, T	principle material directions (Longitudinal and Transverse)
r	radial distance from the crack tip
x, y	x and y coordinates of a point
α, β	parameters dependent on material properties
θ	angular coordinate
σ	nominal stress
ϕ	orientation angle of strain gage
a_{11}, a_{12}	material properties depending on Young's modulus, Poisson's ratio and shear modulus
a_{16}, a_{22}	material properties depending on Young's modulus, Poisson's ratio and shear modulus
A_n, B_m	coefficients of series type complex analytical functions for mode I
E_i	Young's modulus along i^{th} direction $(i = L, T)$
G_{LT}	shear modulus in $L - T$ plane
K_I	mode I stress intensity factor
F_I	normalized mode I stress intensity factor
$r_{\max}$	upper limit for gage locations
$r_{\min}$	minimum radial distance
ε_{aa}	normal strain in the positive direction of θ and ϕ
$\nu_{i,j}$	Poisson's ratio of orthotropic composite material $(i, j = L, T)$
2D	two dimensional
DS	Dally and Sanford
FEA	finite element analysis
Q8	eight node isoparametric quadrilateral element
QPE	quarter point element
SDZ	singularity dominated zone
SIF	stress intensity factor

due to their ease of operation, cost effectiveness and ability to measure strains in the high strain gradient zones compared to other methods such as photo elasticity [13], caustics [14,15] and DIC (Digital Image Correlation) [16]. However, the degree of accuracy of SIF values determined using strain gage techniques can get affected to a great extent owing to strain gradient effects due to finite size of gages and three dimensional effects near the crack tip.

The single strain gage technique for determination of K_I proposed by Dally and Sanford [17] (DS technique) for isotropic materials was the first method of its kind that was based on strong theoretical foundation to take care of the aforementioned difficulties. The DS technique (where a single strain gage placed sufficiently away from the crack tip at certain orientations can accurately measure the mode I SIF) has been widely employed [18–21] in various contexts due to its ease of implementation and robustness.

The ease of implementation of strain gage methods in isotropic materials has motivated other researchers to develop strain gage based applications for estimation of SIF in orthotropic materials. However, none of the available strain gage based determination of SIF for orthotropic materials [22–25] has exploited the advantages of the DS technique [17]. Shukla et al. [22] reported determination of K_I using single strain gage in orthotropic materials, based on a two parameter strain field series around the crack tip instead of a three parameter series as proposed in DS technqiue [17] thus, significantly reducing the range of radial distance for pasting a strain gage. Cerniglia et al. [23] employed an overdeterminstic method using many strain gages for determination of SIFs. Khanna and Shukla [24,25] also a developed a single strain gage technique for determination of mode I dynamic SIF in orthotropic composites based on two parameter strain series and established that the SIF values determined by pasting strain gages in the singularity dominated zone (SDZ) is agree well with those obtained using photoelastic technique. Apparently, the strains measured within such a small zone as the SDZ would be tarnished by 3D effects [26]. Recently, Chakraborty et al. [27] presented a theoretical development of extending the DS technique [17] to orthotropic materials.

In any strain gage based application, the gage(s) positioned at a given location (r, θ) with certain orientations (ϕ) (Fig. 1) gives strain readings which when equated with the appropriate analytical strain series, gives the values of fracture parameters as per requirement. A prior knowledge of the angular location and orientation (defined by θ and ϕ) with respect to the crack axis and radial location (r) from the crack tip is essential to ensure correct determination of SIF values. The angular positions of the strain gage are decided by the selected truncated strain series. However, an important factor influencing the accuracy of experimentally determined SIF is in deciding the radial location where the strain gage is to be pasted for accurate measurement of K_I. The strain gage should not be placed very close to the crack tip, where the strain readings may be affected by 3D effects and large strain gradients caused by averaging error due to finite size of the gage [17,22]. Further, it should not be

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