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Vibration and buckling analysis of partially cracked thin orthotropic rectangular plates in thermal environment

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ABSTRACT

An analytical model is presented for vibration of a thin orthotropic plate containing two perpendicular continuous line surface cracks located at the centre of the plate in the presence of thermal environment. Also new configuration of two perpendicular cracks as internal cracks, located along the thickness of the plate is studied by considering appropriate crack compliance coefficients based on line-spring model. Equilibrium principle based on Classical Plate Theory is used to derive the equations of motion for cracked plate, wherein the crack terms are formulated using the line spring model. The moments due to thermal environment are neglected in the results and only uniform heating of the cracked plate is considered. The solution for natural frequencies of cracked plate is obtained by Galerkin's method. A relation for thermal buckling phenomenon for the cracked plate is also formulated. The influence of the lengths of the two cracks and their location along the thickness of the plate on critical buckling temperature and first mode natural frequency is demonstrated. The geometrically linear frequency response relation for cracked plate is formulated using the method of multiple scales. It is thus concluded that the presence of the two cracks affect the critical buckling temperature and natural frequencies.

1. Introduction

As a simplification, composite plates are often modeled as orthotropic. An isotropic plate with unequal stiffening in the two mutually perpendicular directions also makes the plate specially orthotropic [1,2]. During their service life, plates are often exposed to thermal environment resulting in uniform or non-uniform heating which affects its stiffness and thus changing its dynamic characteristics. The reliability of design of orthotropic plate can be greatly improved by the knowledge of dynamic characteristics, especially the vibration characteristics. Aerodynamic heating causing thermal stresses, thus inducing instability is such an example. Murphy et al. [3] experimentally concluded that the fundamental frequency reaches to zero at critical temperature of buckling. Jeyaraj, Chandramouli and Ganesan [4,5] used ANSYS and SYSNOISE to study vibration characteristics of an isotropic and composite plate subjected to uniform temperature rise. They showed that the uniform increase in temperature of the plate decreases its frequency. Baferani and Saidi [6], in their work on thick plates considered thermal and mechanical loads. They concluded that for edge conditions involving combinations of simply supported and fixed edges, the classical plate theory over-predicts and the first order shear theory underestimates the thermal and mechanical buckling forces. Stahl [7] analyzed vibration and stability of cracked rectangular plates. They studied vibration and buckling problem for centrally located crack and crack emerging from an edge. The problems therein (Ref. [7]) were formulated in terms of Fredholm integral equations. They presented results for cracked plates in terms of natural frequencies and mode shapes. Krawczuk [8] studied natural vibrations in rectangular plates with a through crack by formulating a finite element model. They considered the change in stiffness due to the crack and neglected its effect on the mass by assuming the crack to be a line crack. Their results show the effect of the crack location and its length on the fundamental frequencies. Vafai et al. [9] presented instability behavior of simply supported edge cracked rectangular plate in the form of natural frequencies and mode shapes. Their results show the regions of instability, buckling loads for several plate aspect ratios and crack lengths. Many researchers [1,2] have applied the classical plate theory to orthotropic thin plates, although it over predicts the fundamental frequencies. Using the line spring model (LSM) formulated by Rice and Levy [10] based on Classical Plate Theory, Israr et al. [11] devised an analytical model for nonlinear vibrations of cracked isotropic plate considering a partial surface crack located at the centre, parallel to one

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Nomenclature

$2a$	length of crack parallel to x axis
$2b$	length of crack parallel to y axis
d	Distance between the mid-plane of plate and centre of crack depth
L_1	Plate edge length along x axis
L_2	Plate edge length along y axis
h	Thickness of the plate
w	Transverse deflection along z axis
u, v	In-plane deflection along x and y axis respectively
m_y	Bending moment per unit length due to crack length 2a
n_y	In-plane force per unit length due to crack length 2a
m_x	Bending moment per unit length due to crack length 2b
n_x	In-plane force per unit length due to crack length 2b
$n_{xy}=n_{yx}$	In-plane shear force due to crack
T(z)	Temperature at any point along the thickness of the plate
N_x, N_y, $N_{xy}=N_{yx}$	In-plane forces per unit length in an intact plate
M_x, M_y , M_{xy}	Bending moments per unit length
σ_x , σ_y , τ_{xy}	Stresses
ρ	Density of plate material
E_x, E_y	Young' Modulus of elasticity
ν_x, ν_y	Poisson's ratio, orthotropic plate
ν	Poisson' ratio, isotropic plate
α_x, α_y	Coefficients of thermal expansion
P_z	External load
D	Flexural rigidity, isotropic plate
D_x	Flexural rigidity along x direction, orthotropic plate
D_y	Flexural rigidity along y direction, orthotropic plate
B	Effective torsional rigidity, orthotropic plate
D_t	Torsional rigidity
M_T	Moment due to thermal environment, isotropic plate
M_{Tx}	Moment due to thermal environment, orthotropic plate
M_{Ty}	Moment due to thermal environment, orthotropic plate
N_{Tx} , N_{Ty}	In-plane or membrane forces per unit length due to temperature
c_{tb} , c_{tt} , c_{bb}	Crack compliance coefficients for bending-stretching, stretching and bending
g_t , g_b	Shape functions for stretching and bending
T	Rise in temperature above the stress free condition
T_{bcr}	Critical Buckling temperature
$T^*=T/T_{bcr}$	Non dimensional temperature

of the edges of the plate and concluded that the natural frequencies go on decreasing as the crack length increases. The authors established the geometric nonlinearity due to presence of crack in the frequency response relation and demonstrated its effect for three different boundary conditions of support. Ismail and Cartmell [12] developed an analytical model for vibration analysis of an isotropic rectangular plate considering various angular orientation of a partial surface crack. Sahin et al. [13], formulated a finite element scheme for studying thermal buckling behavior of anti-symmetric composite plates with angle crack. They concluded that the critical buckling temperature decreases due to presence of a through crack. Also the angle crack affects the critical buckling temperature more than the horizontal crack. Natarajan et al. [14], using finite element formulation for free flexural vibrations of a functionally graded plate containing a through crack showed that the natural frequency decreases with increase in temperature and crack length. Huang et al. [15], considered through cracks for 3D vibration analysis of functionally graded rectangular plates. Recently they (Ref. [16]) presented interpolation functions in the application of moving least squares method for vibration of cracked plate. Bachene et al. [17], presented approximate solutions for cracked plates using the extended finite element method. Viola et al. [18], applied differential quadrature finite element method to study the vibrations of thick composite plate with crack and extended it to plates of arbitrary shapes. Natarajan et al. [19], formulated the extended finite element method proposed in Ref. [18], for cracked functionally graded plates using 20 degrees of freedom for a 4 node quadrilateral plate element. Recently Natarajan et al. [20] presented vibration and buckling of laminated composite plates with centrally located cutout considering the effect of moisture content and thermal gradient. They applied the extended finite element method in their formulation accounting transverse shear deformation and used an enriched shear-flexible 4-noded quadrilateral element. The authors also (Ref. [21]) studied buckling of functionally graded plates with discontinuities like and cracks and cutouts by employing the extended finite element method. The authors (Ref. [21]) deduced that the buckling load reduces with the increase in crack length, radius of cutout and gradient index. Natarajan et al. [22] also studied the static bending, free vibration thermal and mechanical buckling of functionally graded plates using cell based smoothed finite element method. They employed the first order shear deformation theory for plate kinematics and suppressed the shear locking by discrete shear gap method. The authors presented parametric results for the global response as affected by aspect ratio, skewness and gradient index. Brighenti [23] studied the effect of through crack length and orientation on buckling load of rectangular plates considering different boundary conditions and Poisson's ratio in their finite element formulation. They considered compression for buckling, tension for fracture and concluded that the presence of crack affects the buckling load. Brighenti [24] studied the buckling of elastic thin cracked plates under tensile, compressive and shear forces. He formulated an accurate finite element model and presented results for buckling collapse as affected by centrally located crack length, boundary conditions and orientation. Recently Joshi et al. [51], presented an analytical model for vibration of isotropic plates containing two partial cross cracks at the centre. The authors also considered the effect of location of cracks along the thickness in their results for fundamental frequencies.

Thermal buckling of composite plates is one of the recent areas of interest (Refs. [29–33]) and modeling of plates with defects like hole or crack is one of the currently developing areas of research. The defects in the form of crack(s) or hole(s) affect vibration characteristics. Literature (Refs. [12,13,25,26–28,34,35–39]) shows that the natural frequencies of plate depend on several factors such as length of surface or through crack, plate geometry, and orientation of crack. Thus it is important to analyze the effect of internal crack and thermal environment on the vibration characteristics of cracked orthotropic plate.

Plates under normal conditions contain inherent microscopic flaws, initial geometric distortion, voids or cracks, these defects can be on the surface or internal [40]. The literature shows that the presence of crack affects vibration and buckling behavior of plates. Also there may be interaction between such cracks. In order to develop theoretical understanding of such cracks on vibration and buckling and to develop an analytical model, the present work considers a theoretical case of two perpendicular cracks at the centre of the plate. Also to the best of author's knowledge, the literature lacks in results for thermal buckling of partially cracked orthotropic plates. The present work addresses this by proposing an analytical approach which has obvious advantages such as being very fast, ease of parametric study, improving physical understanding of the problem and efficient computation time when compared to finite element models.

The present work proposes an analytical model for vibration analysis of thin orthotropic cracked plate in thermal environment. The two perpendicular surface cracks located at the centre of the plate, are in the form of continuous lines. One crack is parallel to x axis and the other is parallel to y axis. New location of the two perpendicular

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