Thin-Walled Structures 131 (2018) 88–101

Contents lists available at ScienceDirect

Thin-Walled Structures

journal homepage: www.elsevier.com/locate/tws

Full length article

Dynamic and buckling analysis of composite laminated plates with and without strip delamination under hygrothermal effects using finite strip method

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ARTICLE INFO

Keywords:
Buckling
Dynamic Analysis
Composite plates
Hygrothermal condition
Delamination

ABSTRACT

The effect of hygrothermal conditions such as temperature and moisture on free vibration frequency and buckling load of composite laminated plates was investigated in present article. For this purpose, the effect of changing in material characteristics with changing in temperature and moisture on buckling capacity and natural frequency of plates with different end conditions and biaxial loading was evaluated. In addition, the effect of delamination of layers on buckling load and natural frequency of plate was studied in different situations. The finite strip method was used in present paper to calculate the critical load of plate considering first-order shear deformation theory. In finite strip formulation for evaluating the displacement field of each strip, the trigonometric shape functions were used in longitudinal direction and the Hermitian and linear shape functions were used for out–of–plane and in–plane transverse direction, respectively. The place and dimension of delaminating layers was modelled by separating the adjacent elements and reconstructing the standard, geometric, force and mass matrices, so, the critical load and natural frequency of laminated plates was calculated in different configurations.

1. Introduction

In recent years, composite materials are widely used in several fields of mechanical, civil, automobile and aerospace engineering. High strength to weight, high stiffness to weight ratios, high modulus and good tailoring capability that achieved by combining different materials make composite laminated structures superior to metal structures. Different strain and stress will be induced in composite plates with a change of hygrothermal conditions. With an elevation of temperature and moisture concentrations, the elastic moduli and the strength of composite laminates will degrade. Thus, by changing hygrothermal conditions internal stresses are generated. These stresses induce different deformation and could even cause the failure of the composite plates. Separation of two adjacent plies is one of common types of damages and is usually caused by fatigue loading. Delamination of composite plates in hygrothermal environment can adversely affect the stiffness of laminates.

Tounsi et al. [1] studied the changing in longitudinal modulus as a result of transverse ply cracking in simple cross–ply laminate theoretically with the taking into consideration the decrease of the mechanical properties of material in variation of temperature and moisture. The results showed that the hygrothermal environment had a significant effect on the relative reduction of longitudinal Young's modulus at the higher crack density. Static and dynamic characteristics of thick composite laminates exposed to hygrothermal environment were studied using a realistic higher order theory by Patel et al. [2,3]. It was shown that the shear deformation theory without accounting for the thickness–stretching effect and slope discontinuity in the in-plane displacements may not be adequate for the analysis of fairly thick composite laminates exposed to hygrothermal loading. Naidu and Sinha [4] investigated the nonlinear free vibration behavior of laminated composite shells subjected to hygrothermal environments using the finite element method. A four node quadrilateral plate element based on the global-local higher order theory (GLHOT) was proposed to study the response of laminated composite plates due to a variation in temperature and moisture concentrations by Lo et al. [5]. Also, the effects of temperature and moisture concentrations on the material properties and the hygrothermal response of multilayered plates were studied by them. Zenkour et al. [6] investigated the influence of temperature and moisture on the hygrothermal behavior of laminated composite plates resting on elastic foundations using a refined plate theory. The material properties of the composite were affected by the variation of

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https://doi.org/10.1016/j.tws.2018.06.030
Received 24 October 2017; Received in revised form 12 June 2018; Accepted 21 June 2018

temperature and moisture. Lee and Kim [7] considered the post–-buckling behaviors of Functionally Graded plates (FGP) in hygrothermal environments. For the description of the model, the first order shear deformation theory (FSDT) was used and the Newton–Raphson technique were adopted to analyze the thermal post–buckling behavior of the model. The sinusoidal shear deformation plate theory was presented to study the response of multilayered angle–ply composite plates due to a variation in temperature and moisture concentrations by Zenkour [8]. Natarajan et al. [9] investigated the effect of moisture concentration and the thermal gradient on the free flexural vibration and buckling of laminated composite plates. The effect of a centrally located cutout on the global response was also studied. The analysis was carried out within the framework of the extended finite element method. A progressive failure analysis model involving hygrothermal effects was presented for predicting failure of composite structures in hygrothermal environments by Zhang et al. [10]. The model introduced a constitutive equation accounting for the hygrothermal strains. The delamination buckling behavior of graphene Nano platelets reinforced by 3D fiber–metal laminates was investigated experimentally and numerically by Asaee et al. [11] in which the numerically obtained critical buckling capacities and failure modes were compared to the experimental results.

A finite element formulation was presented for the analysis of the composite plates with multiple delaminations by some researchers. Free vibration tests had been conducted to study the effect of low velocity impact induced damage consisting of inter–laminar delamination accompanied by matrix cracking on the natural frequencies of thin composite laminated circular plates by Hou and Jeronimidis [12]. Alnefaie [13] developed a 3D finite element model of delaminated fiber reinforced composite plates to analyze their dynamics behavior. Natural frequencies and modal displacements were calculated for various case studies with different dimensions and delamination characteristics. Li et al. [14] presented a nonlinear analysis model of fatigue delamination growth for piezoelectric elasto–plastic laminated beams under hygrothermal conditions. Free vibration of delaminated multilayer beams was analyzed by Della and Shu [15]. Both the free mode and constrained mode analyses in the study of delamination vibration was used. In addition, for three–layer beams with double delaminations, the lower and upper bounds of the natural frequency was obtained by assuming a totally free and totally constrained deformations of the delaminated layers. A novel analytical model was developed by Szekrényes [16] to solve the problem of free vibration of delaminated composite beams. The beam with a single delamination was modelled by six equivalent single layers by establishing the kinematic continuity in the un–delaminated portion of the system. Also, he presented the problem of free vibration of delaminated composite beams by showing the existence of parametric excitation, bifurcation and stability [17]. A numerical finite element study on the strain energy release rate distribution along delamination front in mechanically coupled laminated composites deformed was done by Samborski [18] in accordance with the DCB test configuration as described in the ASTM Standard. Also, Kormaníková and Kotrasová [19] presented a mixed–mode delamination of laminate plate made of two sub–laminates with opening and sliding load mode as failure model. The failure model was implemented in FEM code to calculate the mixed–mode delamination response based on interface techniques.

Kumar et al. [20] discussed the presence of open–mode delamination mode shape for large delaminations within the first three natural frequencies. Layerwise plate theory of Reddy, extended for the analysis of delaminations, was studied by Marjanović and Vuksanović [21] as a basis for development of enriched finite elements. The effects of plate geometry, lamination scheme, degree of orthotropy and delamination size or position on dynamic characteristics of the plate were presented and the results of natural frequencies, mode shapes and critical buckling loads for intact and damaged plates were compared. Shankar et al. [22] studied an analysis of delaminated composite plates under hygrothermal environment with eight–noded serendipity element with five degrees of freedom per node for the finite element formulation. The non–linear hygrothermal and mechanical buckling responses of functionally graded sandwich plates resting on elastic foundations were presented by Radwan [23]. The effects of temperature rise, moisture concentration, parameters of elastic foundation, aspect ratio of the plate and the inhomogeneity parameter on the critical buckling load was investigated in Ref. [23]. Emam and Eltaher [24] presented an investigation into the buckling and post–buckling of composite beams in hygrothermal environments. Their results show that the buckling load was decreased by increasing the temperature, while the post–-buckling load was increased.

The delamination in the composite plates can be generally classified into strip, edge, circular, elliptical, and rectangular types; however, the strip delaminations are generally occurred under in–plane loading [25]. The effect of strip delamination and hygrothermal conditions did not consider, simultaneously, in previous researches by 2D analysis. According to modelling the strip delamination in composite plates, in present study, the finite strip method is used for evaluating the critical load and natural frequency of laminated plates without and with strip delamination as a numerical method. The ordinary finite strip method was employed by authors and other researchers for analysis of composite [26], viscoelastic [27–29] and micro plates [30,31]. In ordinary finite strip method, the in–plane internal forces was assumed to be constant at all points along the external load, while, in present method the in–plane internal forces are calculated by pre–buckling analysis at all points to achieve the more accurate results. The present paper is organized into the following sections. In Section 2, the kinematic of deformation is explained using finite strip method and the constitutive equations relating the components of stress and strain are expressed in the integral forms. After that, the standard finite element procedure, based on virtual work is employed to derive force vector, standard and geometric stiffness and mass matrices for a strip. In Section 3, the numerical results are presented for evaluating the implementation of the model and the accuracy of results. Finally, some concluding remarks are presented in Section 4.

2. Finite strip formulation of laminated plates

A laminated plate with m number of layers which is subjected to moisture and temperature is considered. The length, width and total thickness are represented by a, b and h, respectively, and the global coordinate system of the laminated plate is (x, y, z) as it is shown in Fig. 1. The first–order shear deformation theory has been incorporated for the analysis. Displacement field, based on the first–order shear deformation theory for a laminated composite plate is given by Eq. (1).

$$\begin{aligned} u(x, y, z, t) &= u_0(x, y, t) + z\theta_x(x, y, t) \\ v(x, y, z, t) &= v_0(x, y, t) + z\theta_y(x, y, t) \\ w(x, y, z, t) &= w_0(x, y, t) \end{aligned} \quad (1)$$

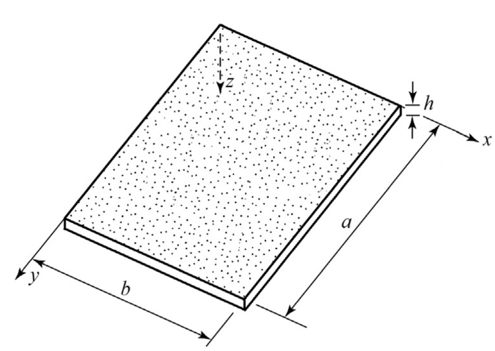

Fig. 1. Geometry and coordinate system of laminated plate.