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Three-dimensional semi-analytical model for the static response and sensitivity analysis of the composite stiffened laminated plate with interfacial imperfections

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ABSTRACT

For the stiffened composite laminated plates with interfacial imperfections, the problem of static response and sensitivity analysis was investigated in Hamilton system. Firstly, the meshfree formulation of Hamilton canonical equation for the composite laminated plate with interfacial imperfections was deduced by the linear spring-layer and the state-vector equation theory. And then, based on the equation of plates and stiffeners, governing equation of the composite stiffened laminated plate was assembled by using the spring-layer model again to ensure the compatibility of stresses and the discontinuity of displacements at the interface between plate and stiffeners. At last, a three-dimensional hybrid governing equation was developed for the static response analysis and sensitivity analysis.

To demonstrate the excellent predictive capability of this three-dimensional semi-analytical model, several numerical examples were carried out to assess the static responses and static sensitivity coefficients. Good agreement had been achieved between the predictions and the results of finite element code MSC.Nastran. Extensive numerical results were presented showing the effects of the interfacial stiffness on the response quantities and their sensitivity coefficients. Furthermore, distributions along the thickness direction were also presented for the static responses and the static sensitivity coefficients with respect to the material properties and the shape parameters.

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1. Introduction

The stiffened plates/shells structural system is composed of plate or shell elements, reinforced by a series of stiffeners (or ribs, beams, stringers, etc.) that are attached in longitudinal and sometimes in orthogonal directions. Stiffening of the plate/shell is used to increase its load carrying capacity and prevent buckling especially in the case of in-plane loading. The primary advantage of stiffened constructions lies in the structural efficiency of the system, since great savings or conservation of weight can be attained with no sacrifice in strength or serviceability. Thus, there are wide applications of stiffened plate/shell components in a variety of engineering structures. In aerospace industry, they are used in the construction of aircraft fuselage and wings. Meanwhile, the stiffened plates/shells are also utilized in the construction of bridges, buildings, storage tanks, off-shore structures, and recently in petrochemical processing facilities.

Research into stiffened structures has been a subject of interest for many years. The vibration and stability of stiffened structures is of great interest, since it generally controls the optimum design of the structures in which they are deployed. Also, only a comprehensive and accurate stress analysis can lead a designer to an appropriate selection of the plate thickness distribution and the stiffener dimensions. As a result, a large number of studies on stress analysis, buckling, and vibration of stiffened panels are available in the literature.

Based on energy principles, Kukreti and Cheraghi [1] have presented a procedure to analyze a stiffened plate system supported by a network of steel girders. The beams are assumed to be rigidly connected to the plate. A semi-analytical method for the analysis of bare plates has been extended to the static analysis of stiffened plates by Mukhopadhyay [2]. Both concentric and eccentric stiffeners have been considered. Siddiqi and Kukreti [3] have developed a differential quadrature solution for the flexural analysis of eccentrically stiffened plates subjected to transverse uniform loads. The axial stiffness of the plate and the interaction between the beams and the plate due to the eccentricity are taken into consideration during the analysis of the in-plane forces in the plate. Deb and Booton [4] and Palani et al. [5] have presented respectively linear finite element models based on Mindlin's shear distortion theory and two isoparametric finite element models (the eight-noded QS8S1 and the nine-noded QL9S1) for static and vibration analysis of plates/shells with stiffeners. The boundary element method (BEM) is also developed to model the static and dynamic response of reinforced plate structures [6–10]. Ng et al. [11] have

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studied the suitability of a new method combining the advantages of both the BEM and the finite element method (FEM) to analyze the more complicated problems of slabs and slab-on-girder bridges. This new method is first applied to investigate the conventional plate bending problems.

Due to the complexity of the problem and the many parameters involved, extensive research efforts were devoted over the past years by many researchers to investigate a variety of aspects. Reinforcing the plate/shell with the stiffener elements complicates the analysis, and several assumptions must be made in order to facilitate a solution if the stiffeners are not identical or unequally spaced. And the complication would further increase when analyzing composite laminated plate/shell structures.

Currently, three main approaches can be employed for analysis of laminated structures: equivalent single layer theory (classical laminate theory and shear deformation laminated plate theories) [12–16], three-dimensional elasticity theory (traditional 3-D elasticity formulations and layerwise theory) [17,18] and multiple model methods [19,20]. Since the above theories are established on some hypothesis, the most important of which is the neglect of transverse shear deformations and rotatory inertia, only partial fundamental equations can be satisfied and some of the elastic constants cannot be taken into account. Therefore, the errors will increase as the thickness of plates increases and the stress at interface cannot be exactly calculated. To overcome this difficulty, some refined formulations have been established to take into account, e.g., transverse shear deformations and rotatory inertia [21–23].

In recent years, the state-vector equation in Hamilton system, which is employed in the analysis of control systems of current significance, has attracted the attention of a number of investigators who are interested in the problems of laminated structures [24–38]. In the state-vector equation, two types of variables (i.e., the transverse stresses and displacements) are synchronously considered in the control equation. And the thick plates/shells or the laminated plates/shells problems can be treated without any assumptions regarding displacements and stresses. Due to the transfer matrix technique being employed, the solution provides exact continuous transverse stresses and displacement field across the thickness of laminated structure. Another significant difference from the classical layer-wise methods is that the scale of the final governing equation system is independent of the thickness and the number of layers of a structure. As a result, Qing et al. [39] have developed a novel mathematical model for free vibration analysis of stiffened laminated plates based on the semi-analytical solution of the state space method. The method accounts for the compatibility of displacements and stresses on the interface between the plate and stiffeners, the transverse shear deformation, and naturally the rotary inertia of the plate and stiffeners. Meanwhile, there is no restriction on the thickness of plate and the height of stiffeners. Since the stiffeners are assumed to be rigidly connected to the plate, the bonding imperfection which may be introduced into the interface between the plate and stiffeners cannot be taken into account in this mathematical model.

However, various interlaminar debonding like microcracks, inhomogeneities and cavities may be introduced into the bond in the process of manufacture or service. During the service lifetime, these tiny flaws can get significant. To avoid the local failure of bond or the whole collapse of structure, therefore, the effect of imperfect interfaces on the structural behavior should be accurately evaluated. In recently years, Chen et al. [40–43] have used the analytical methods and numerical methods to research the problem of interfacial imperfection for composite laminated plates in Hamilton system.

In present work, the static response analysis and static sensitivity analysis of composite stiffened laminated plates with interfacial imperfections are investigated by the spring-layer model, meshfree method and the state-vector equation theory. A hybrid governing set equation of the composite stiffened laminated plates with bonding imperfection is deduced for the response and sensitivity quantities. One of the main advantages of the hybrid governing set equation is that the discontinuity of displacements and the compatibility of stresses on the interface between the plate and stiffeners are accounted. The present three-dimensional semi-analytical model with no initial assumptions regarding displacement and stress accounts for the transverse shear deformation and rotary in the governing equations. Furthermore, by using this hybrid governing equation in the response analysis and sensitivity analysis, the convoluted algorithm can be avoided in sensitivity analysis, and the response quantities and the sensitivity coefficients can be obtained simultaneously.

2. Mathematical model of stiffened laminates with bonding imperfection

2.1. Meshfree formulation of Hamilton canonical equation for composite laminated plates

Consider a continuous function $u(\boldsymbol{x})$ defined on a 2D domain Ω in which there is a set of suitably located nodes. An interpolation of $u(\boldsymbol{x})$ in the neighborhood of a point $\boldsymbol{X}_Q$ using RBFs and polynomial basis is written as [44]

$$u(\boldsymbol{x}) = \sum_{i=1}^{n} R_i(\boldsymbol{x})a_i + \sum_{j=1}^{m} p_j(\boldsymbol{x})b_j = \boldsymbol{R}^{\mathrm{T}}(\boldsymbol{x})\boldsymbol{a} + \boldsymbol{p}^{\mathrm{T}}(\boldsymbol{x})\boldsymbol{b} \tag{1}$$

with the constraint

$$\sum_{i=1}^{n} p_j(\boldsymbol{x})a_i = \boldsymbol{p}_m^{\mathrm{T}}(\boldsymbol{x})\boldsymbol{a} = \boldsymbol{0}, \quad j = 1, 2, \ldots, m \tag{2}$$

here, $R_i(\boldsymbol{x})$ is a radial basis function associated with node i (i. e., for the modified multiquadrics (MQ) used in this present work, $R(\boldsymbol{x}) = \left[r_i^2 + (\alpha_c d_c)^2\right]^q$, where α_c and q are shape parameters, and d_c is a characteristic length that relates to the nodal spacing in the local support domain of the point of interest $\boldsymbol{x}$, usually the average nodal spacing for all the nodes in the local support domain); n is the number of nodes in the neighborhood of $\boldsymbol{X}_Q$, $p_j(\boldsymbol{x})$ is a monomial in the space coordinates $\boldsymbol{x}^{\mathrm{T}} = [x, y]$; m is the number of monomial basis functions (usually $m < n$); $a_i(\boldsymbol{x}_Q)$ and $b_j(\boldsymbol{x}_Q)$, which varies with the point $\boldsymbol{X}_Q$, are coefficients for $R_i(\boldsymbol{x})$ and $p_j(\boldsymbol{x})$, respectively.

In utilizing radial basis functions, several shape parameters need to be determined for good performance. In general, these parameters can be determined by numerical examinations for a given type of problems. For example, Wang and Liu left the parameter q open to any real variable, and found that $q = 0.98$ or 1.03 led to good results in the analysis of two-dimensional solid and fluid mechanics problems in the Lagrangian system [45,46]. In the present work, the optimum values of the shape parameters are obtained by repetitious numerical experimentation for the present three-dimension model. We adopt the optimum values of shape parameters for the MQ determined as $\alpha_c = 0.03$ and $q = 1.03$.

Requiring that the function $u(\boldsymbol{x})$ given by Eq. (1) equals its value at n nodes in the vicinity of the point $\boldsymbol{X}_Q$, we get a set of simultaneous linear algebraic equations for the coefficients $a_i(\boldsymbol{x}_Q)$ and $b_j(\boldsymbol{x}_Q)$. If the constraint (2) is satisfied at the same time, a linear equation group including $n + m$ equations can be obtained for the coefficients $a_i(\boldsymbol{x}_Q)$ and $b_j(\boldsymbol{x}_Q)$. With the solution of this linear equation group, Eq. (1) can be written as follows:

$$u(\boldsymbol{x}) = \boldsymbol{\Phi}^{\mathrm{T}}(\boldsymbol{x})\boldsymbol{U}_s = \sum_{i=1}^{n} \phi_i u_i \tag{3}$$

where $\boldsymbol{\Phi}^{\mathrm{T}}(\boldsymbol{x}) = \{\phi_1(\boldsymbol{x}), \phi_2(\boldsymbol{x}), \ldots, \phi_n(\boldsymbol{x})\}$ is the RPIM shape function with respect to displacement volume of the field node [44]. $\boldsymbol{U}_s = [\,u_1 \quad u_2 \quad \cdots \quad u_n\,]$ is the values at the field node.

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