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Analysis of laminated composite and sandwich plate structures using generalized layerwise HSDT and improved meshfree radial point interpolation method

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ABSTRACT

This paper presents a generalized layerwise higher-order shear deformation theory for static, free vibration and buckling analyses of symmetric laminated composite and sandwich plates using improved meshfree radial point interpolation method (iRPIM). The approach comes from a layerwise model combined with a generalized higher-order shear deformation theory. In other words, we impose the continuity on the interface of each layer for the in-plane displacements and transverse shear stresses. This yields more adequate solution for sandwich structures which present the significant difference of properties between the core sheet and the face ones. As a result, transverse shear stresses are accurately achieved as compared with the analytical ones. The present iRPIM shows stability and high accuracy with respect to the uniquely proposed correlation function. A simple but effective enforcement based on the concept of the rotation-free of essential boundary conditions yields significant advantage of computations. The numerical results are provided and compared well with other published solutions.

1. Introduction

Materials technology industries have been developed strongly in the 21st century. Herein composite materials play a key role in scientific and technological achievements of disciplines. Composite materials are being applied in various engineering fields such as aerospace, automotive, marine, civil engineering, etc. Formed by combining two or more orthotropic layers with different materials, laminated composite structures achieved better engineering properties than the classical materials, such as high-stiffness, high-strength, lightweight, strength-to-weight ratios, long fatigue life, wear resistance, corrosion resistance, thermal properties, etc. [1]. In addition to other important features of composite structures, sandwich structures are used when stacking two types of laminae, so-called core and face sheets, which have highly different material properties. A good knowledge about their behaviors subjected to loading is really necessary for using them effectively.

In recent decades, several plate theories have been developed to analyze laminated composite and sandwich plates from two original models: equivalent single-layer model (ESL) and layerwise model (LW). Generally, the equivalent single-layer models, which consider the same degrees of freedom for all laminate layers, include classical laminate plate theory (CLPT) [2]. This theory is accurate for thin plates and based on the assumption that the shear deformation effect is negligible. The first-order shear deformation theory (FSDT) [3–5] is suitable for both moderately thick and thin plates, but the shear correction factors cause significant influences on the accuracy of the underlying solution. The higher-order shear deformation theories (HSDTs) [6–8] have been therefore devised. Due to including the high-order contribution of shear deformations, HSDTs do not require shear correction factors. It is evident that the displacements and transverse shear stresses obtained from HSDTs are much better than those of FSDT model. However, it is known for analysis of sandwich plates that the effects of different characteristic material properties through the plate thickness, i.e. between core and face sheets, are large. Hence, the accuracy of the obtained results based on ELS models related to transverse shear stresses and high frequencies is inadequate. Consequently, layerwise theories which impose independent degrees of freedom for each layer have been developed. Among them, the generalized layerwise model proposed by Reddy [9] and the simple expression forms proposed by Ferreira [10] have become popular. For instance,

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the given model in [10] assumed a first-order shear deformation theory for displacement field with independent rotations in each layer and displacement continuity at contact position of the layer interfaces. Hereby, the highly accurate solutions have been achieved. Alternatively, regarding zigzag effects and fulfillment of interlaminar continuity, several other layerwise or zigzag models have been presented by Mau [11], Chou and Carleone [12], Di Sciuva [13], Toledano and Murakami [14] and Ren [15], Tessler et al. [16–18], and so forth. In case of special materials, especially heterogeneous auxetics with negative Poisson's ratio, the influence of auxeticity becomes more noticeable, which needs the elasticity approach instead of employing the approximate plate theories [19], or even the other approached theory such as zigzag theory [20] and global–local zigzag theory [21]. Thanks to the work of Shariayat et al., global–local zigzag theory is also extended to analyze highly sensitive structures like asymmetric orthotropic sandwich plates with single/dual cores [22] or even imperfect laminated and sandwich cylindrical shells [23]. Besides, trigonometric layerwise deformation theories were applied for analyzing composite beams by Shimpi [24] and Arya et al. [25], and then composite and sandwich plates by Roque et al. [26,27]. The special concept of these theories is a combination of HSDTs and LW without requiring additional degrees of freedom while ensuring the continuity of displacement and transverse shear stresses fields at the interface layers.

The finite element method (FEM) has been known as the most popular and powerful tool in engineering field from academic to industrial applications. Because of relying on the mesh discretization, the error of FEM solution is significant when the physical domain has special features such as curved boundary, subjected to concentrated load or distorted meshes, spread and expansion cracks in structures, and so on. Such drawbacks can be overcome by meshless methods. Belytschko et al. [28] proposed a meshless method based on a weak form of a so-called the Element Free Galerkin (EFG) which used the moving least square (MLS) to construct the shape functions. EFG has been extensively applied to a wide class of mechanics problems. It showed the high accuracy of stress discontinuities problems involving volumetric locking [28] and especially for limit analysis problems [29] and so on. However, EFG exhibits some drawbacks such as dissatisfying the Kronecker-delta property and therefore, the essential boundary conditions are violated. One of alternative methods is Point Interpolation Method (PIM), which is based on the Galerkin formulation, was proposed by Liu [30], Liu and Gu [31,32]. The PIM uses polynomial basis shape functions. As a result, the approximated interpolations pass through the function values at each scattered node within the support domain and the PIM shape functions also satisfy the Kronecker-delta property. Furthermore, the other type of PIM shape functions has been extended. It is named as radial basis functions (RBFs) so-called Radial PIM (RPIM) [33,34]. Note that the interpolation coefficients are usually determined if the support domain and the basis function are carefully chosen. Hence, a great advantage of RPIM can overcome the singularity problem of moment matrix so that it can be applied to arbitrary nodal distributions [35].

For linear analysis of composite materials based on layerwise plate theory, many studies have been reported up to date. Typically, with exception of standard FEM, Ferreira et al. successfully developed LW with various methods listed in [10,36], Thai et al. have recently used isogeometric analysis (IGA) [37,38], Roque et al. proposed trigonometric layerwise deformation theories using radial basis functions [26] and multiquadrics [27]. Herein, this paper focuses on the application of RPIM to study static, free vibration and buckling analyses of laminated composite and sandwich plates based on a generalized layerwise higher-order shear deformation theory.

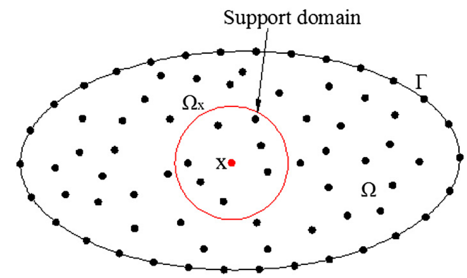

Fig. 1. Domain representation and support domain of 2D model.

The outline of this paper is organized as follows. A brief approach of meshfree RPIM is introduced in the second section. The governing equations using RPIM based on generalized layerwise higher-order shear deformation theory are developed and formulated for laminated composite and sandwich plates in Section 3. Next, in Section 4, various numerical examples for static, free vibration and buckling analyses are considered and compared with other published solutions. At last, the conclusions of this paper are given and discussed in Section 5.

2. A brief of meshfree radial point interpolation method

2.1. Radial point interpolation method

Let us consider a support domain $\mathbf{x}$ that has a set of arbitrarily distributed nodes $P_i(\mathbf{x})$ $(i = 1, 2, \ldots, n)$, as shown in Fig. 1. The approximate function $u(\mathbf{x})$ can be estimated to all values of nodes within the support domain based on Radial Point Interpolation Method (RPIM) by using radial basis function $B_i(\mathbf{x})$ and polynomial basis function $p_j(\mathbf{x})$ [39]. Nodal value of approximate function evaluated at the node $\mathbf{x}_i$ inside support domain is assumed to be u_i.

$$u(\mathbf{x}) = \sum_{i=1}^{n} B_i(\mathbf{x}) a_i + \sum_{j=1}^{m} p_j(\mathbf{x}) b_j = \mathbf{B}^T(\mathbf{x})\mathbf{a} + \mathbf{p}^T(\mathbf{x})\mathbf{b} \tag{1}$$

where a_i, b_j are the coefficients for $B_i(\mathbf{x})$ and $p_j(\mathbf{x})$, respectively. n is the number of scatter nodes in support domain $\mathbf{x}$, m is the number of polynomial basis functions (usually, $m < n$). The terms in Eq. (1) are defined as follows

$$\begin{aligned}
\mathbf{a}^T &= [a_1, a_2, a_3, \ldots, a_n] \\
\mathbf{b}^T &= [b_1, b_2, b_3, \ldots, b_m] \\
\mathbf{B}^T(\mathbf{x}) &= \left[B_1(\mathbf{x}), B_2(\mathbf{x}), B_3(\mathbf{x}), \ldots, B_n(\mathbf{x})\right] \\
\mathbf{p}^T(\mathbf{x}) &= \left[p_1(\mathbf{x}), p_2(\mathbf{x}), p_3(\mathbf{x}), \ldots, p_m(\mathbf{x})\right]
\end{aligned} \tag{2}$$

Radial basis function $B_i(\mathbf{x})$ is a function of distance r_i that has the following general form

$$B_i(\mathbf{x}) = B_i(r_i) = B_i(x, y) \tag{3}$$

where $r_i = \|\mathbf{x} - \mathbf{x}_i\|$ is the distance between the interpolating point (x, y) and the node (x_i, y_i).

In the case of two-dimensional problem, polynomial function chosen from Pascal's triangle is given as

$$\mathbf{p}^T(\mathbf{x}) = \left[1, x, y, x^2, xy, y^2, \ldots\right] \tag{4}$$

To determine the coefficients a_i and b_j, the interpolation is enforced to pass through all n scattered nodal points within the support domain. The interpolation at the kth point has the form

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