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# Recent developments in finite element analysis for laminated composite plates

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**Abstract**

A review of the recent development of the finite element analysis for laminated composite plates from 1990 is presented in this paper. The literature review is devoted to the recently developed finite elements based on the various laminated plate theories for the free vibration and dynamics, buckling and postbuckling analysis, geometric nonlinearity and large deformation analysis, and failure and damage analysis of composite laminated plates. The material nonlinearity effects and thermal effects on the buckling and postbuckling analysis, the first-ply failure analysis and the failure and damage analysis were emphasized specially. The future research is summarised finally.
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*Keywords:* Laminated composite plates; Free vibration; Dynamics; Buckling; Postbuckling; Failure

## 1. Introduction

Composite laminates have been used increasingly in a variety of industrial areas due to their high stiffness and strength-to-weight ratios, long fatigue life, resistance to electrochemical corrosion, and other superior material properties of composites. A true understanding of their structural behaviour is required, such as the deflections, buckling loads and modal characteristics, the through-thickness distributions of stresses and strains, the large deflection behaviour and, of extreme importance for obtaining strong, reliable multi-layered structures, the failure characteristics. Finite element method is especially versatile and efficient for the analysis of complex structural behaviour of the composite laminated structures. Using finite element method, a significant amount of research has been devoted to the analysis of vibration and dynamics, buckling and postbuckling, failure and damage analysis and etc.

A review of the finite element models developed after 1990 based on the various laminated plate theories for the finite element analysis of composite laminated plates is presented in this paper. The finite element analysis reviewed includes the following categories: free vibrations, damping, and transient dynamic response; buckling and postbuckling; geometric nonlinearity and large deformation analysis; damage and failure. Some of the future research on composite laminated plates is also summarized.

## 2. Laminated composite plate theories

The laminated plate theories are essential to provide accurate analysis of laminated composite plates, and a variety of laminated plate theories have been developed and reported in a large amount of literatures.

A review of various equivalent single layer and layer-wise laminated plate theories was presented by Reddy

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and Robbins [1]. An overall comparison of laminated theories based on displacement hypothesis was presented by Liu and Li [2], including shear deformation theories, layerwise theories, generalized Zigzag theories, and the proposed global–local double-superposition theories. A review of theories for laminated and sandwich plates was presented by Altenbach [3]. A review of displacement and stress-based refined shear deformation theories of isotropic and anisotropic laminated plate was given by Ghugal and Shimpi [4], in which various equivalent single layer and layerwise theories for laminated plates were discussed together with their merits and demerits. A historical review of the zig-zag theories for multi-layered plates and shells up to 2003 were given by Carrera [5]. A review of shear deformation plate and shell theories was presented by Reddy and Arciniega [6], a selective review and survey of the theories with emphasis on estimation of transverse/interlaminar stresses in laminated composites was given by Kant and Swaminathan [7], and a selective literature survey on the free-edge effect since 1967 was given by Mittelstedk and Becker [8].

Generally, the laminated plate theories can be broadly divided into the following two categories:

(a) Equivalent single layer (ESL) theories, including
- Classical lamination theory (CLT)
- The first-order shear deformation theory (FSDT) (referred to as Mindlin Plate theory in some literatures)
- Higher-order shear deformation theories (HSDT)]
- Layer-wise lamination theory (LLT)

(b) Continuum-based 3D elasticity theory

The classical lamination theory (CLT) is based on the Kirchhoff plate theory, it is the simplest theory among others, but the shear deformation effects are neglected. The first-order shear deformation theories (FSDT) provides a balance between computational efficiency and accuracy for the global structural behaviour of thin and moderately thick laminated composite plates, but no accurate prediction for the local effects can be obtained, for example, the interlaminar stress distribution between layers, delaminations, and etc. Various higher-order shear deformation theories have been developed to overcome the limitations in the classical and first-order shear deformation theory, and the free boundary conditions of the transverse shear stresses on the upper and lower surfaces can usually be satisfied. Layer-wise lamination theory assumes a displacement representation formula in each layer. It can predict accurately the interlaminar stresses, however layerwise models are computational expensive since the number of unknown functions depends on the number of the layers of the laminates. The 3D continuum-based theory can predict the interlaminar stress of a composite laminate, but the computational cost using 3D models is a major concern.

## 3. Free vibration and dampling analysis of composite laminated plates

### *3.1. Computational models based on FSDT*

The first-order shear deformation theory (FSDT) has been employed widely to establish finite element models for free vibration analysis of the composite laminated plates. The effects of lamination and extension–bending coupling, shear and twist-curvature couplings on the lowest frequencies and corresponding mode shapes for free vibration of laminated anisotropic composite plates was investigated using a finite element method with quadratic interpolation functions and five engineering degrees of freedom (DOF) [9]. The free and forced vibration response of laminated composite folded plate structures was predicted by a nine-node Lagrangian plate-bending finite element with five engineering DOF per node that incorporated rotary inertia [10]. A nine-node isoparametric plate-bending element was used for the analysis of free undamped vibration of rectangular isotropic and fiber reinforced laminated composite plates [11], and an effective mass lumping scheme with rotary inertia was introduced.

The free vibration analysis of stiffened laminated composite plates was performed using the layered (zigzag) finite element method based on the first-order shear deformation theory [12]. In their work, the layers of the laminated plate were modelled using nine-node isoparametric degenerated flat shell element, and the stiffeners were modelled as three-node isoparametric beam elements based on Timoshenko beam theory. Bilinear in-plane displacement constraints were used to maintain the inter-layer continuity, and a special lumping technique was used in deriving the lumped mass matrices.

A mixed finite element formulation with low-order displacement/strain interpolation for plates and shells was used to study the effect of large spatial rotations on the geometric stiffness for stability analysis as well as inertia operators for vibrations for laminated composite plates and shells [13].

Damping analysis of composite laminated plates has been carried out using the computational models developed based on the FSDT. The effects of transverse shear deformation on the modal loss factors as well as the natural frequencies of composite laminated plates was investigated using a finite element method based on the shear deformable plate theory [14]. The complex modules of an orthotropic lamina were employed to model damping effect. A sandwich composite beam and plate finite superelements with viscoelastic layers were presented for vibration and damping analysis of laminated composite beams or plates [15]. Each layer was considered as simple Timoshenko's beam or Mindlin-Reissner plate finite element. The energy dissipation in the viscoelastic layers was taken into account with complex modulus of elasticity theory, and the method of complex eigenvalues and the energy method were considered for damping analysis. This finite element technique

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