Thin-Walled Structures 133 (2018) 96–105

Contents lists available at ScienceDirect

Thin-Walled Structures

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

Full length article

Parametric instability behavior of tow steered laminated quadrilateral plates using isogeometric analysis

V. Khalafi, J. Fazilati*

Aeronautical Science and Technology Dept., Aerospace Research Institute, P.O. Box 14665-834, Tehran, Iran

ARTICLE INFO

Keywords:
Quadrilateral plate
Dynamic instability
Isogeometric analysis
First order shear deformation theory
Variable stiffness composite laminate

ABSTRACT

For the first time, the parametric instability regions of variable stiffness laminated composite quadrilateral plates subjected to uniform in-plane loadings are studied. The static as well as time-varying inplane loadings are assumed distributed throughout the whole geometry. The isogeometric analysis finite element formulation based on non-uniform rational B-splines is developed in order to address the dynamic instability of quadrilateral panels. The problem has been formulated by utilizing the principle of virtual work based on first order shear deformation plate theory. In terms of tow-steered reinforcements, the fiber orientations in every lamina is assumed to change linearly in the panel longitudinal direction. In order to demonstrate the capabilities of the developed formulation in predicting the structural parametric dynamic behavior, some representative results are obtained and compared with those available in the literature. The effects of geometry layout, loading frequency and amplitude, changes in curvilinear fiber orientations, and material orthogonality on the parametric instability regions are studied by applying Bolotin's first order approximation.

1. Introduction

The thin-walled structures are major structural elements especially wherever the stiffness to weight ratio is a main parameter of structural performance. While thin-walled structures are subjected to in-plane harmonic loadings, sort of instability conditions may emerge in accordance with both the amplitude and repetition rate of loading. In other words, there will be some loading frequency-loading amplitude combination sets where the structural instability occurs. The phenomena are called parametric or dynamic instability and aims to characterize those periodic loadings which leads to stable or instable structural behavior. The spread of loadings conditions corresponding to occurrence of instability in the structure postulates the dynamic instability regions (DIR). The excitation conditions may prevalent in case of mechanical and thermal loading conditions as well as in fluid-structure interactions.

The isogeometric finite element analysis (IGA) as firstly proposed by Hughes et al. [1] aims to bridge the gap between geometrical computer aided design (CAD) and the finite element analysis (FEA) models. The fundamental idea of IGA is to adopt the basis functions of CAD into the elemental shape functions of the FEA in order to construct the approximation of the field variables. Many advantages feature from the IGA including maintaining the exact geometry description even in coarse discretization levels and performing of re-meshing process at this level without any further communication with CAD geometry. The formulation is currently outspread to many fields of structural mechanics including fluid–structure interaction, non-linear, and structural analysis [2–4]. Shojaee et al. [5] developed isogeometric finite element method based on classical plate theory for free vibration analysis of isotropic thin flat plates. Yu et al. [6,7] presented isogeometric formulation based on simple first-order shear deformation plate theory (S-FSDT) for free vibration, buckling analysis and geometrically nonlinear analysis of laminated composites and functionally graded plates. They addressed the effects of different boundary conditions, composition, geometry and defects on the mechanical responses of the assumed panels. Valizadeh et al. [8] investigated the bending, free vibration, buckling and flutter analysis of functionally graded plates based on the Reissner-Mindlin theory using IGA method. Hao et al. [9] predicted the buckling strength of Reissner-Mindlin variable-stiffness laminated plates by using IGA method. They provided some comparisons between IGA and FEM approaches. Yu et al. [10] investigated buckling of functionally graded rectangular plates under combined thermal and mechanical loads using isogeometric analysis based on the FSDT. Gu et al. [11] developed a computational framework based on the multi-patch isogeometric analysis that integrates the locally refined B-splines and an adaptive scheme for two-dimensional elasticity problems. A

* Correspondence to: Aerospace Research Institute, Tehran, Iran.
E-mail address: jfazilati@ari.ac.ir (J. Fazilati).

https://doi.org/10.1016/j.tws.2018.09.035
Received 31 July 2018; Received in revised form 12 September 2018; Accepted 20 September 2018
0263-8231/

Nitsche's method is applied to patches coupling between two adjacent patches. Qin et al. [12] studied the static and dynamic characteristics of curvilinearly stiffened plates. The NURBS based isogeometric analysis approach was utilized to analyze the static deformation, the natural frequencies and the vibration behavior of stiffened plates. Furthermore, the large deformation and the large amplitude vibration of the curvilinearly stiffened plates were also studied based on the von Karman's large deformation theory. Xue et al. [13] investigated the free vibration of functionally graded plates considering in-plane material inhomogeneity by using NURBS-based IGA in conjunction with a refined plate theory. The analysis of skew and elliptical plates were performed and the effects of the geometry, boundary condition and material inhomogeneity on dynamic characteristics were discussed. Kiani [14] developed a NURBS-based IGA formulation to analyze the thermal postbuckling of composite laminated plates reinforced with graphene sheets. The third order shear deformation plate theory was utilized. Norouzzadeh and Ansari [15–17] developed FSDT isogeometric analysis method for vibration analysis of nano-beam, nano-plate and nano-shell geometries considering both the nonlocal and surface effects. The traditional composite laminate designs consider any lamina properties to be unchanged throughout the entire ply by employment of straight and uniformly spaced prepreg fibers or woven reinforcements. With the automated fiber placement technology, it is possible to fabricate composite plies with variable and arbitrary oriented fibers within the geometry. As a result of fiber orientation variation, the ply gains variable directional stiffnesses throughout the laminate geometry and may be called as variable stiffness composite laminate (VSCL). A VSCL ply may also be achieved from dissimilarity of either fiber spacing or fiber characteristics. The first reported studies on curvilinear fiber VSCL plates are seems to be the works by Hyer et al. [18] and Gurdal and Olmedo [19]. More recently, Akhavan and Ribeiro [20] studied the free vibration of VSCL plates with curvilinear fibers using the third-order shear deformation theory. Tornabene and co-workers [21] investigated higher-order structural theories for the static analysis of doubly curved laminated composite panels reinforced by curvilinear fibers using the generalized differential quadrature (GDQ) method. They extracted the strain as well as stress distribution through the thickness direction. A review on design for the manufacture of VSCL panels is available in a work by Lozano et al. [22].

The structural members including beams, plates and shells are often subjected to periodic in-plane loads and become dynamically unstable for certain combination of load amplitude and the excitation frequency of the structure. A comprehensive study on the parametric instability behavior of various elastic systems has been carried out by Bolotin [23]. Patel et al. [24] presented dynamic instability analysis of laminated composite plates supported on elastic foundations subjected to periodic in-plane loads using finite element method. Wang and Dawe [25] have developed a Bezier-spline version of finite strip method (FSM) under the assumptions of first order shear deformation plate theory (FSDT) in order to deal with the problem of parametric dynamic instability of flat thin-walled composite rectangular plates. Dey and Singha [26] presented dynamic stability analysis of simply supported composite laminate skew plates using a four-noded shear flexible high precision plate-bending element. The influence of a variety of parameters including skew angle, thickness-to-span ratio, fiber orientation and static in-plane load on the dynamic instability response was studied. Ovesy et al. [27] developed a layer-wise spline finite strip method (FSM) based on FSDT and analyzed the parametric instability problem of laminated rectangular plates containing through the width delamination. Dynamic instability analysis of VSCL panels has been received attention, just recently. Loja et al. [28] presented dynamic instability analysis of VSCL rectangular plates under the assumptions of classical plate theory using Rayleigh-Ritz method. The influence of different material and geometrical parameters on dynamic instability response of such geometries was investigated. Samukham et al. [29] investigated dynamic instability behavior of VSCL rectangular plates based on FSDT under periodic axial compression using finite element method. Fazilati and his co-authors [30–33] developed a FSM formulation based on higher order shear deformation theory and investigated the behavior of parametric stability of laminated flat rectangular and skew plates as well as cylindrical shell panels. Conventional as well as variable stiffness composite laminates has been considered along with different geometrical defects including cutout and delamination. A IGA linear flutter calculation of finite square and skew VSCL laminated plates inside the yawed flow is recently performed by the authors [34].

In this paper, the problem of dynamic instability of arbitrary quadrilateral flat panels subjected to in-plane time-harmonic mechanical loadings are investigated. The laminate plies are assumed to be variable stiffness due to curvilinear fiber placement that changes linearly in the panel longitudinal direction. The IGA formulation is developed and adopted based on FSDT assumptions. The effects of through the thickness rotational inertia terms are also taken into account. The problem governing equations are derived through the principle of virtual work. The dynamic behavior including natural frequencies as well as instability load-frequency margins are extracted utilizing the Bolotin's first order approximation followed by a standard eigenvalue procedure. To show the accuracy and effectiveness of the formulation, some representative problems are numerically studied and compared to those available in the literature. To the best of the author's knowledge, this is the first investigation on the problem of dynamic instability of quadrilateral panels using IGA.

2. Derivation of the formulation

A quadrilateral flat laminated panel is considered as depicted in Fig. 1. The laminated panel is assumed made from a number of plies reinforced by curvilinear (linearly changed) continuous fibers. A typical laminate with length a, width b, and a Cartesian coordinate system located on the mid-plane of the undeformed laminated plate is considered as illustrated in Fig. 1. (u,v,w) are the displacement of the plate in the Cartesian (x,y,z) directions. The angle set (Φ_1,Φ_2) characterizes the quadrilateral assumed geometries. In certain cases, the panel geometry may represent a rectangular plate ($\Phi_1 = \Phi_2 = 0$), a skew plate ($\Phi_1 = \Phi_2 \neq 0$) or a symmetric tapered one ($\Phi_1 = -\Phi_2 \neq 0$). Fig. 2 illustrates some different quadrilateral geometries corresponding to the driving angle set.

A uniform longitudinal time-harmonic in-plane loading is assumed. The loading is consisted of a non-changing (static) component and a harmonically time-changing (dynamic) component which are indicated using $_s$ and $_d$ subscripts, respectively. The loading as a function of the

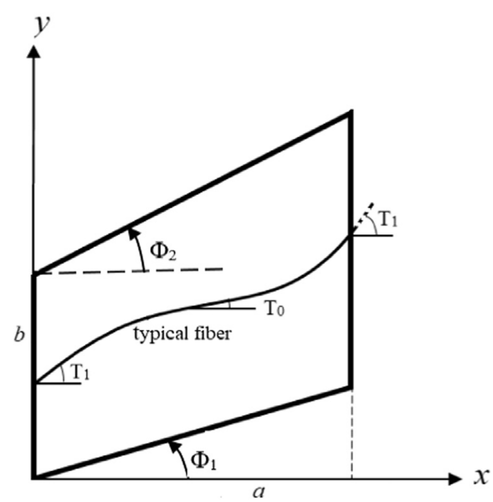

Fig. 1. Typical quadrilateral plate geometry with the characteristic angle set (Φ_1, Φ_2) and a VSCL ply fiber path.