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Buckling analysis of unitized curvilinearly stiffened composite panels

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ABSTRACT

Innovative manufacturing technology has led to the fabrication of complex shape and multi-functional structures by using the concept of integrated and bonded unitized structural components. To study the stability behavior of such structural designs, this paper presents an efficient finite element buckling analysis of unitized stiffened composite panel stiffened by arbitrarily shaped stiffeners. A first-order shear-deformation theory is employed for both the panel and the stiffeners. Displacement compatibility conditions are imposed at the panel-stiffeners interfaces. To obviate remeshing when the stiffener shape changes, the stiffeners' geometry and displacement are expressed in terms of those of the panel middle surface through compatibility conditions that make use of the interpolation polynomials employed in the finite element method. To accommodate any shaped stiffeners, a generalized geometry parametrization tool is developed to parameterize the shape of the stiffeners including the stiffener placement and the stiffener geometric curvature. Convergence and validation studies using the present method for the buckling analysis of stiffened isotropic and composite panels are conducted to illustrate the accuracy of the present method. Parametric studies show that the stiffener placement, the stiffener geometric curvature, the stiffener depth ratio (height-to-width ratio) and laminates fiber ply orientation influence both the plate bucking load and the correspond buckling mode shape. The tailoriability of the stiffeners shape and the laminates fiber ply orientation provides an enhanced design space in the structural design for improving the structural stability.

1. Introduction

Unitized structural design has been considered to build a significantly lighter and more environment-friendly aircraft. The design philosophy utilizes the concept of unitized structures; meaning that the stiffening members become integral to the structure, leading to a monolithic construction of aircraft components, which results in a reduced part count [1]. A monolithic construction of the vehicle and a reduced count part for an assembly have made the use of curvilinear stiffening members possible [2]. As a member of unitized structures family, curvilinearly stiffened structures have attracted a number of research studies during the last decade at Virginia Tech. Curvilinear stiffeners/spars/ribs in the aircraft design were found to provide enhanced design space for aircraft wing that resulted in improved structural performance as well as reducing the structure weight because of their curvature in addition to the location and orientation [3–6].

Advanced composite structures are being increasingly employed in the aircraft wing and fuselage design [7]; e.g. there is nearly 50% carbon/epoxy airframe structure in the Boeing 787 and similarly, a significant use of GLAss REinforced (GLARE) panels in the fore-and-aft sections of the Airbus A380 fuselage. The development of manufacturing technique for curved composite panels by using the Integrated Structural Assembly of Advanced Composites (ISSAC) robot at NASA Langley Research Center. Also, the innovative manufacturing technologies of the integrated stiffened composite panel such as through-thickness stitching followed by resin film infusion [8], vacuum assisted resin transfer molding and Pi-joining [7], continuous induction welding [9] and the pultruded rod stitched efficient unitized structure (PRSEUS) concept [10], etc. All of these techniques make it possible to manufacture integrated stiffened composite panel attached by curved composite stiffeners to satisfy various constraints in the aircraft wings and fuselage design.

During the last several decades, an increasing number of research studies on both stiffened isotropic and composite panels have been conducted due to their both high strength-to-weight ratio and the high specific stiffness-to-weight ratio. These stiffened panels are widely being used in the aerospace and many other applications.

Timoshenko and Gere [11] used the classical Ritz method to obtain buckling parameters of a rectangular plate stiffened by longitudinal stiffener(s) under uniaxial compressive load. The stiffener

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was placed concentrically along the panel where the neural axis of the stiffener coincides with the panel middle surface. In their study, the shear deformation and the stiffener torsional stiffness were both ignored in the stiffened panel modeling.

Mukhopadhyay and Mukherjee [12] developed a finite element algorithm for the bucking analysis of a stiffened isotropic panel under uniaxial compression load. The panel and stiffeners in their work were modeled as isoparametric quadratic shell and beam elements, respectively. The advantage of their method was that the stiffeners can be positioned anywhere within the plate through the finite element interpolation and hence need not necessarily be placed on the plate nodal lines. Patel et al. [13] used a similar idea to analyze the buckling and dynamic instability of stiffened isotropic panels. The eight-noded isoparametric degenerated 2D shell elements and compatible three-noded quadratic curved beam elements were used to model panels and stiffeners, respectively. Later, Prusty and Satsangi [14,15] used the same idea as that of Mukhopadhyay and Mukherjee [12] to carry out the structural analysis of stiffened isotropic plates/shells.

Peng et al. [16] used a mesh-free Galerkin method for the stability analysis of stiffened panels using the first-order shear-deformable theory to model the displacements of the plate and stiffeners. In their work, the problem domain was approximated in terms of a set of orderly or scattered points for both the plate and the stiffeners. Tamijani and Kapania [17] used the same approach as in the work by Peng et al. [16] for static and bucking analysis of an isotropic panel stiffened by curvilinear stiffeners. The stiffeners were modeled as 3D curved beams described in the curvilinear coordinate system [3] to capture the stiffener in-plane deformation and bending-twist coupling due to the stiffener geometric curvature. It was found that for a stiffened panel under biaxial compressive loads, the curvilinear stiffener can increase the panel buckling load to a largest value with the least weight penalty than that of using a straight stiffener or a skew stiffener. This work demonstrated the potential advantage of utilizing the curvilinearly stiffened panel in structural design for enhancing panel stability.

Shi and Kapania [18] studied the buckling and vibrational responses of the curvilinearly stiffened isotropic plate by using the finite element approach. The geometry and displacement of the stiffener were expressed in terms of those of the panel middle surface. In their work, the stiffener element nodes are not necessary to coincide with the shell elements nodes.

Kapania and Raciti [19] summarized various shear-deformable theories for buckling and postbucking analysis of laminated beams and plates. Zhang and Yang [20] presented a detailed review on finite element buckling and post-buckling analysis of laminated composite plates. Reddy [21–23] presented results from various plate theories including, the classical laminate plate theory, the first-order shear-deformable theory and the higher-order shear-deformable theory for buckling analysis of a rectangular laminated panel.

Qatu [24–26] studied both the thin and moderately thick composite curved beams. The rotary inertia and the shear deformation as well as an accurate kinematic relation (consider the term z/R in the beam axial strain) were taken into account in deriving the stiffness matrix. Martini and Vitaliani [27] developed a finite element formulation of an isoparametric skew beam element for curved beams based on Timoshenko's beam theory. Choit and Lim [28] developed a general curved beam element located arbitrarily in space based on the assumed strain functions.

Chattopadhyay et al. [29] used finite element method to study the static deformation of blade-stiffened composite plates under transverse loads, where the composite stiffener was simplified to a 3D composite beam. Several different open cross section shapes of the stiffener were considered. The webs and flanges that constitute the stiffener were modeled as composite beams whose laminates are perpendicular and parallel to the panel middle surface, respectively. Based on this simplification, Kumar and Mukhopadhyay [30] presented a new finite element for buckling analysis of stiffened composite panel under in-plane shear stress. The panel was modeled by combing the Allman's plane stress triangular element and a discrete Kirchoff–Mindlin plate bending element. Similar work [12,30,31] of using 3D composite beam elements to model the composite stiffener can be found, as shown in Chattopadhyay et al. [29], for structural analyses of laminated plates and shells stiffened by straight composite stiffeners. In these works, the average shear modulus in the two orthogonal directions of the stiffener cross section was used for the equivalent stiffener torsional stiffness.

A layerwise (zigzag) finite element formulation was developed by Guo et al. [32] to perform the stability analysis of stiffened composite panels. In-plane displacements are considered in the derivations of the geometric stiffness matrices for both composite panel and stiffeners. The authors claimed that the interaction between the stiffener lateral deflection and the composite panel buckling significantly influences the overall stability of the stiffened composite panel.

Mittelstedt [33] studied the variation of the buckling load and corresponding buckling mode shape with the stiffener height for stiffened composite panels with blade stiffener under in-plane axial compressive and shear loads. The panel buckling load only increases with the stiffener height to one certain value. The critical buckling mode shape also changes with the stiffener height. Mittelstedt concluded that there exists a threshold bending stiffness for the stiffener depending on both the panel and the stiffener bending stiffnesses beyond which the panel bucking load does not increase with the stiffener transverse stiffness. Instead, a local panel buckling mode occurs and becomes dominant and the panel buckling load remains constant as the stiffener transverse stiffness increases.

This research investigates the buckling response of stiffened composite panel with curved composite stiffener when subjected to in-plane shear and axial loads by using the finite element approach. The panels and the stiffeners are composed of advanced composite materials whose constituent layers feature elastic orthotropic properties. Reddy's first-order shear-deformable theory is utilized for modeling both the panel and the stiffeners. To obviate the repeated need for mesh generation of the stiffened composite panels in subsequent shape optimization for optimal stiffener placements, the stiffeners' geometry and displacement are approximated in terms of those of the panel middle surface via finite element interpolation.

The paper is divided into three parts, the first part mainly focuses on the formulations for studying linear bucking analysis of the curvilinearly stiffened composite panels. The next part presents results from a detailed convergence and validation study. Results from buckling analysis of the stiffened isotropic panel with both straight and curvilinear stiffeners and the stiffened composite panel with straight composite stiffeners obtained from the present analysis are compared with both existing solutions and those obtained from commercial FEA software, MSC NASTRAN. The last part conducts the buckling analysis of the stiffened composite panel with arbitrarily shaped composite stiffeners. Several parametric studies are performed to study the influence of the stiffener depth ratio, the stiffener geometric curvature and the stiffener placement on the panel buckling responses.

2. Formulations for stiffened composite panels

2.1. Modeling of a laminated composite panel

Consider a stiffened composite panel as shown in Fig. 1. The middle surface of the panel *Oxy* plane is chosen as the reference