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ORIGINAL ARTICLE

Non-linear forced vibrations of variable stiffness plates on elastic supports

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ABSTRACT

The effect of boundary conditions on the vibrations of variable stiffness composite laminates (VSCL) with curvilinear fibers is particularly interesting because fiber orientations at the plate edges and in the plate's domain can differ. Since real boundaries are not the ideal limit cases usually assumed in the literature, a more correct model can be achieved by representing boundaries as elastically restrained edges. This approach is followed in this work, which investigates the combined effect of fiber orientation and boundary stiffness on the geometrically non-linear forced vibrations of rectangular VSCL plates. The boundary stiffness is adjusted using experimental data.

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KEYWORDS

Bi-linear fiber angle; curvilinear fibers; elastically restrained boundaries; forced vibrations; non-linear analysis; variable stiffness composite laminated plate

Acronyms

C	Clamped
CPT	Classical Plate Theory
CUF	Carrera Unified Formulation
F	Free
FRF	Frequency response function
FSDT	First-order Shear Deformation Theory
H	Hinged
R	Elastically restrained boundary or rigid
RFP-Z	Rational Fraction Polynomial in the Z domain
TSDT	Third-order Shear Deformation Theory
VSCL	Variable Stiffness Composite Laminate

1. Introduction

Composite laminates where curvilinear fibers reinforce a resinous matrix offer more design possibilities than their straight fibers counterpart and, consequently, have been the subject of numerous research articles [1–4]. Curvilinear reinforcement fibers lead to a stress-strain relation that varies with the membrane coordinates; for this reason, these laminates are known as Variable Stiffness Composite Laminates (VSCL). Although there are other types of variable stiffness laminates, in the remainder of this paper, VSCL refers solely to laminates with curvilinear fibers.

Curvilinear fibers allow designers to implement panels that have superior strength and critical buckling loads [5–11], or a dynamic response that is more adequate [12–46]. Many researchers, with effective results [2, 47], have considered fibers with linearly varying angles as will be done here. However, alternatives that allow to further expand the design domain have been proposed. For example, Kim et al. [48], Parnas et al. [49] and Coskun and Turkmen [50] employed Bézier curves, Alhajahmad et al. [51] Lobatto–Legendre polynomials, Wu et al. Lagrange polynomials [52], Honda et al. B-splines [14] and cubic polynomials [13, 53]. Montemurro and coworkers proposed representing the fiber paths using B-spline [54] and non-uniform rational basis spline (NURBS) surfaces [11, 54, 55].

Tow placement is the favored technology to place fibers along a curvilinear path, but it has manufacturing restrictions [48]. In this respect, we mention the research of Montemurro and coworkers, who extended to VSCLs, and improved, an optimization strategy designated as multi-scale two-level (MS2L), that is effective on tow placed laminates subjected both to mechanical and manufacturability constraints [11, 54, 56].

Structures with composite laminated panels are often subjected to vibrations [57] and, therefore, there are a few works on vibrations of VSCL. These publications address modes of vibration in the linear and non-linear regimes [12–34], forced vibrations [34–40], buckling and aeroelastic instabilities, and, in some cases, the ensuing oscillations [19, 23, 26, 32, 41–46].

VSCLs find application in structures where low weight is important [58, 59] and relatively large amplitude vibrations may occur. One of the characteristics of VSCL plates is their sensitivity to the fiber orientation at the boundaries [34, 37], which differs from the fiber orientation in the layer's domain. Hence, it is relevant to analyze how boundary conditions interact with the curvilinear fiber path when a VSCL plate experiences geometrically non-linear oscillations.

The infinite stiffness assumed in clamped edges is an idealization that may be far from the true condition. It is also common to assume zero opposition to cross section rotation, as in supports or hinges; however, in practice, some opposition to cross-section rotation is expected. A way

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