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Model reduction in thin-walled open-section composite beams using Variational Asymptotic Method. Part II: Applications

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ABSTRACT

This part of the work describes applications of a comprehensive and reliable tool for analysis of thin-walled, open-section composite beams. The developed comprehensive and reliable tool is used for analysis of commonly used cross sections (I-, C-, Z-, and star) of thin-walled open-section composite beams. Usage of VAM renders a rigorous asymptotically correct reduction of the 3-D nonlinear problem to a much simpler 1-D nonlinear problem, with closed-form solutions contributing to rapid yet accurate analysis. This computational efficiency is demonstrated through a Monte-Carlo-type stochastic analysis.

1. Introduction

Thin-walled composite beams are commonly employed in various industries owing to their superior properties, such as high stiffness and strength-to-weight ratios. Despite their superior properties, they exhibit complicated material behavior due to several nonlinear and non-classical effects (such as Trapeze, Brazier, and Vlasov effects) that are commonly observed during operations. Such complicated phenomenon cannot be easily captured by classical tools. Experimental techniques or simple beam models (with assumed factor-of-safety) drives up the overall design and development costs, thus not allowing thin-walled, open-section beams to be exploited to their potential. This necessitates fast yet accurate tools that can be used during preliminary design stages.

Owing to standardization of the Finite Element Method (FEM), 3D FEM solutions can be considered as a basis for comparison for other numerical solution techniques. However, 3D FEM for general design and analysis can be computationally cumbersome and expensive. For example, consider an I-section beam with dimensions 2.5 m in length, 50 mm in breadth and 50 mm in height. The web and flanges each comprise of 16 plies with thickness of each ply being 0.13 mm. Being a bending dominated problem, a FEM mesh with tri-linear displacement elements (or linear 8-noded hexahedrons) can result in numerical problems such as locking. Thus, an ideal element for meshing could be the tri-quadratic displacement elements (or quadratic 20-noded hexahedrons). Considering two elements along the thickness of the beam results in 406,908 elements (C3D20 from Abaqus) and 2,198,658 nodes. Consideration of solid elements with 3 degrees of freedom (dof's) or unknowns per node implies 6,595,974 dof's or unknowns. Now, if the problem is multi-physics in nature, including more dof's per node, such as temperature or non-local damage, this would drastically increase the size of the problem. Solving such systems can require parallel computing facilities, parallel solvers etc alongside long computational time for each simulation. Computing on 32-processors (single-node) of a Xeon E5 cluster and using approximately 250 GB of memory will require more than 96 h of computing time. In contrast, comparable results can

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be computed using a reduced-order model obtained from the VAM (i.e., the framework that is the subject under discussion in this paper) in less than a minute on a simple Dual Core laptop.

In addition, laminated composites have inherent uncertainties originating both in their manufacturing processes as well as service lives and their properties generally have significant scatter around the mean value. Thus, the uncertainties in material and geometric properties must be considered in the analysis. Almost all previous approaches in the literature that employ VAM for dimensional reduction simplify the problem by considering the uncertain parameters as deterministic and account for uncertainties using empirical safety factors in design. Exceptions include works of Li [37] and Murugan et al. [39]. However, the conventional deterministic approach is not appropriate for realistic applications. Thus, it is required that the deterministic design be expanded to account for these uncertainties. A simple Monte-Carlo evaluation of even small sample sizes of few tens of samples could be infeasible using 3D FEM solutions.

Alternatively, there have been several approaches and tools developed for analysis of thin-walled, open-section beams including for post-buckling behavior. Most common ones include analytical beam theories (generally restricted to isotropic materials) or FEM-based beam models such as generalized beam theory. Yet, most of these models are not always directly capable of capturing all the nonlinear and non-classical effects that arise in thin-walled beams. Thus, the current work is motivated by the need for a general purpose tool to capture the overall behavior, including non-classical effects of thin-walled, open-section composite beams in a fast yet accurate manner. This is partly because it is feasible in the asymptotic framework to obtain approximate closed-form solutions. This work is implemented using MATLAB (and compatible for usage with open-source SciLab) to visualize non-classical, nonlinear effects and to enable multi-objective tailoring of composite beams with varying layups. In this work, the applicability of the developed theory to a wide variety of commonly favored aerospace structures (with cross sections such as I-sections, T-sections, X-sections, Z-sections, cruciforms, and stars), all of which may be constructed as an assembly of strip-like beams, is demonstrated. This work also considers the random nature of material properties, and the probabilistic perspective provided by the current model enables one to quantify some of the many inherent uncertainties in composite beams.

Overall, this work provides an effective mathematical tool for analysis of open-section thin-walled composite beams and could assist in composite tailoring of a variety of layups and cross-sectional shapes. This also accounts for the generality of the layup and random fluctuations of input parameters, thus providing a reliable and computationally efficient probabilistic model. Also considered is the generality of the shape as well as the number and orientation of the strips forming the open-section beam. This renders the tool versatile for composite tailoring of almost all commonly employed forms of open-section beams. In this work, the developed tool will be demonstrated for applicability for different cross sections and validated with results from the literature and 3-D FEM.

2. Review of earlier works

This section provides a brief literature review of tools developed (including FEM-based beam models, analytical approaches) to model thin-walled, open-section beams. There have been many studies, particularly pertaining to civil engineering applications, where thin-walled members are used in steel structures and concrete bridges. For practical purposes, isotropic material models are generally assumed in the analysis and design of these structures. Some of the main issues addressed in these works include those pertaining to effect of distortional loading and cross-sectional warping [10], and are based on or follow the ideas expressed by Vlasov [54]. Several analytical and finite element formulations, such as [1,4,59,32], have been developed based on the work of [54]. Along the same direction, [34] considered a FEM formulation to account for warping effect through a Total Lagrangian formulation, while [44,51] considered higher-order terms stemming from the rotation matrix.

One of the common approaches has been to formulate beam elements in an FEM framework. Giavotto et al. [22] applied discretization of displacement fields using planar elements, and this methodology was further applied in cross-sectional analysis [5], optimization [9,7], and fracture [8] of wind turbine blades made of composite materials using the open-source code BECAS. The idea was also further applied by Høgsberg and Krenk [29] for moderately thin-walled cross sections using higher-order isoparametric elements into a Matlab-based FEM framework called BeamSec. In spite of the discussion regarding the generality of the developed formulations, the ability of the methodology to capture the nonlinear and non-classical effects in thin-walled open-section beams is yet to be demonstrated. Similar higher-order isoparametric elements have been developed in several works, like [50,47,38], with a goal to accurately capture torsion and shear fields.

Another method had been the generalized beam theory approach for FEM models. Original equations developed by Schrad [46] were valid for small deformation and moderate rotation. This has been further extended by Silvestre and Camotim [48] to provide a nonlinear GBT formulation and by Basaglia et al. [2] for moderate to large rotation – thus making it feasible for post-buckling analysis for arbitrary load conditions.

Some of the latest works using FEM for modeling thin-walled composite structures include series of papers by Genoese et al. [21,20], Garceaa et al. [19], Gabriele et al. [18], Nguyen et al. [40]. Genoese et al. [21] proposes a mixed linear model based on Hellinger-Reissner mixed variational principle for heterogeneous materials, including warping and section distortions. In addition, Blasques et al. [6] demonstrate methodology for the usage of constraint equations to impose free and restrained warping conditions and the same has been used in this work.

There have been several other isolated works studying thin-walled, open-section beams using FEM-based beam models under various subtopics, such as symmetric, fiber-reinforced laminates [3,58], optimization [30,15,52,53,11], torsional analysis [35,31,55,13], distortion mechanics [49,23], shear deformability [16], and general nonlinear elements [24,42,56]. There have been several analytical solutions as well but mostly addressing isotropic materials. Lee and Lee [36] develop an analytical approach to capture the flexural-torsional behavior of thin-walled, open-section composite beams and demonstrated its application to I-section beams. But none of the other known works address the issues concerning composite or anisotropic materials.

In recent years the Variational-Asymptotic Beam Section (VABS) analysis, originally developed by Cesnik and Hodges [12] and Yu et al. [62] based on the principles of Variational Asymptotic Method (VAM), has been widely used for modeling composite structures. Yu et al. [63] discuss the history and capabilities of VABS, which was validated for different classes of beams. Kovvali and Hodges [33] extend VABS functionalities to model pretwisted and curved beams comparing the results with commercial software with regard to both the dynamic behavior (resulting natural frequencies) and static deflections. Yu et al. [61] discuss the recent updates to VABS which include consideration of the effects of applied loads in cross-sectional analysis and constraints on warping based on 1-D displacements and rotations. Lately, VABS is also available as a cloud-variant on cdmhub.org.

VABS already treats nonlinear and non-classical effects in thin-walled open-section composite beams using VAM but implemented in a FE framework. In other words, VABS already treats the Vlasov and Trapeze effects that are of importance in thin-walled open-section beams. However, unlike analytical solutions discussed here, VABS uses FE-based method for the cross-sectional analysis. In addition, VABS requires a separate 1-D tool (like GEBT) for usage of cross-sectional results to obtain actual beam deflections and rotations. A discussion of the start-of-the-art in nonlinear composite beam modeling can be found