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Vibration prediction of thin-walled composite I-beams using scaled models

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ABSTRACT

Scaled models of large and expensive structures facilitate in understanding the physical behavior of the large structure during operation but on a smaller scale in both size and cost. These reduced-sized models also expedite in tuning designs and material properties, but also could be used for certification of the full-scale structure (referred to as the prototype). Within this study, the applicability of structural similitude theory in design of partially similar composite structures is demonstrated. Particular emphasis is placed on the design of scaled-down composite I-beams that can predict the fundamental frequency of their corresponding prototype. Composite I-beams are frequently used in the aerospace industry and are referred to as the back bone of large wind turbine blades. In this study, the governing equations of motion for free vibration of a shear deformable composite I-beam are analyzed using similarity transformation to derive scaling laws. Derived scaling laws are used as design criteria to develop scaled-down models. Both complete and partial similarity is discussed. A systematic approach is proposed to design partially similar scaled-down models with totally different layup from those of the full-scale I-beam. Based on the results, the designed scaled-down I-beams using the proposed technique show very good accuracy in predicting the fundamental frequency of their prototype.

1. Introduction

The certification process for a wind turbine blade starts with coupon testing of the materials that are used in the manufacture of the blade and is finalized with full-scale testing of the blade. Coupon testing is relatively quick and cost-effective, but it is not fully representative of the structural integrity of the blade. In contrast, full-scale testing is time consuming and very expensive (e.g. hundreds thousands of dollars). As blade lengths continue to increase, the logistics of full-scale testing become more challenging and the test time increases as the resonant frequency of the blade decreases. Therefore, the total time for doing a specific number of fatigue cycles increases. Subcomponent testing can bridge the gap between coupon and full-scale testing of the blade. If meaningful scaled-down models can be designed that are representative of their parent components in the full-scale blade, then blade certification can be expedited and the confidence of blade manufacturers for introducing new materials (e.g. bio-based resins) into the industry can grow.

Interest and activity in the testing of wind-turbine-blade subcomponents has gained momentum in recent years and this interested has led to a number of case studies of a variety of parts of utility-scale wind turbine. Mandell et al. [1] tested composite I-beams with flanges and shear webs out of components which are used in the cross section of wind turbine blades. Stiffness and strain measurements that were observed in a four-point bending test of the beams were in agreement with predictions from simple beam theory and finite element analysis. Cairns et al. [2] studied the root section of the blade where the root specimens represented a single insert of a blade root into the hub joint. The primary focus of the study was manufacturing, but a significant amount of static and fatigue strength data were generated by performing pull-out tests. Mandell et al. [3] conducted a study with the focus on skin-stiffener intersections and sandwich panel closeout. Their goal was to predict skin-stiffener fracture loads and evaluate performance at locations where the sandwich panel transitions into the normal laminate.

A few studies investigated the performance of adhesive joints and bond lines of a wind turbine blade using subcomponent testing. The idea was to test the static and fatigue properties of the shear web to spar cap bond under stress states that are representative of those seen during field service of a wind turbine blade. Sayer et al. [4] proposed an asymmetric three-point bending test where they used a custom beam configuration which has come to be called a Henkel beam. It was meant to give a comparable combination of bending moment and shear forces as a three-point bending test while reducing the stress concentrations at the clamped end. The specimen was used for a parametric study, investigating the influence of the design and manufacturing variables

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on shear web to spar cap adhesive joints [5]. Zarouchas et al. [6] performed a static four-point bending test on two symmetric I-beams. The tested I-beams represented the spar cap and shear web structure inside a wind turbine blade.

Although subcomponent testing is usually categorized as laboratory-scale test rigs, there are a few mid-level blade test approaches that fall into the subcomponent category. Jensen [7] conducted a study of the structural static strength of a box girder of a 34-m wind turbine blade, loaded in flap-wise direction. A combination of experimental and numerical work was used to address the critical failure mechanisms of the box girder of wind turbine blade. White et al. [8] developed a dual-axis test setup on a truncated 37-m wind turbine blade which combined resonance excitation with forced hydraulic loading to reduce the total test time required for evaluation. Subcomponents in this category are known as "Designed Subcomponents". Such subcomponents provide an accurate evaluation of the structural performance of the blade and can be used to characterize the dominant failure modes. However, such tests are involved, expensive and hard to implement on a laboratory scale.

The designed subcomponent (referred to as the "model") regardless of the size and complexity needs to be correlated with the full-scale component (referred to as the "prototype", see Fig. 1). The connection between the scaled model and the prototype must be based on the structural parameters that predict the behavior of the system under consideration. Similitude theory can extract scaling laws from the governing equations of the system to connect the response of the scaled-down model to the prototype. To take advantage of the scaling laws, a properly scaled model should be designed to work well with the derived scaling law. In other words, the designed scaled model should be able to predict the response the prototype accurately by using the derived scaling laws. Otherwise, the experimental data of the scaled model cannot be correlated with the prototype, and therefore, the designed model cannot be representative of its corresponding prototype. As the model is not always an exact scaled-down replica of the prototype, a logical methodology should be implemented to design scaled models that can be used with scaling laws to predict the response of the prototype.

Similitude theory is an analytical tool for determining the necessary and sufficient conditions of similarity between two systems. These similarity conditions may be derived directly from the governing equations of the system which lead to more specific similarity conditions than dimensional analysis. Simitses and Rezaeepazhand [9] established a technique that could be applied directly to the governing equation of a system to derive the scaling laws. The derived scaling laws are then used to predict or estimate the response of a prototype by the response of its associated model. The buckling response of an orthotropic and symmetric cross-ply laminated plate was investigated as a benchmark in that study. In later studies, they analyzed the vibration of scaled laminated rectangular plates [10]. Additionally, they studied the effect of axial and shear load on stability of scaled laminated rectangular plates [11,12]. According to their results, the scaling laws that are obtained directly from the governing equations can be used with perfect accuracy for cross-ply laminates, while for the angle-ply laminates the scaling laws did not show good accuracy. Later, this method was extensively used in their works regarding the vibration response of laminated shells [13,14].

The design of scaled models for a structure made of composite materials is more challenging than the same structural shape made of isotropic materials. Laminated structures cannot be scaled down to any arbitrary size because of the practical difficulties in scaling the thickness of the plies of a laminate. Design of scaled-down composite models with the same layup as the prototype will be limited by manufacturing constraints because only fabrics with specific thicknesses are available in industry. Therefore, making scaled-down composite models with a completely similar lamination scheme as the prototype is hard to implement. Therefore, use of partially similar scaled models can be considered as an alternative. Although ply-level scaling [9] within the scope of complete similarity has been implemented successfully, the design of partially similar models is still lacking a systematic methodology.

Within this study, which is an extension of Authors' previous work on design of scaled composite models [15–17], similitude theory is applied to the governing equations of motion for vibration of a thin-walled composite I-beam [18] to design scaled-down composite I-beams which are representations of the spar caps and shear web of a utility scale wind turbine blade [19] and satisfy the conditions of static and dynamic similarities for the beam geometry [20,21]. This paper presents the first work to design partially similar laminated models with totally different layups than their prototype using a systematic approach to predict the vibration response of the prototype. The main strength of the proposed approach compared to the numerical assessments is that a representative scaled model can be used for validation of

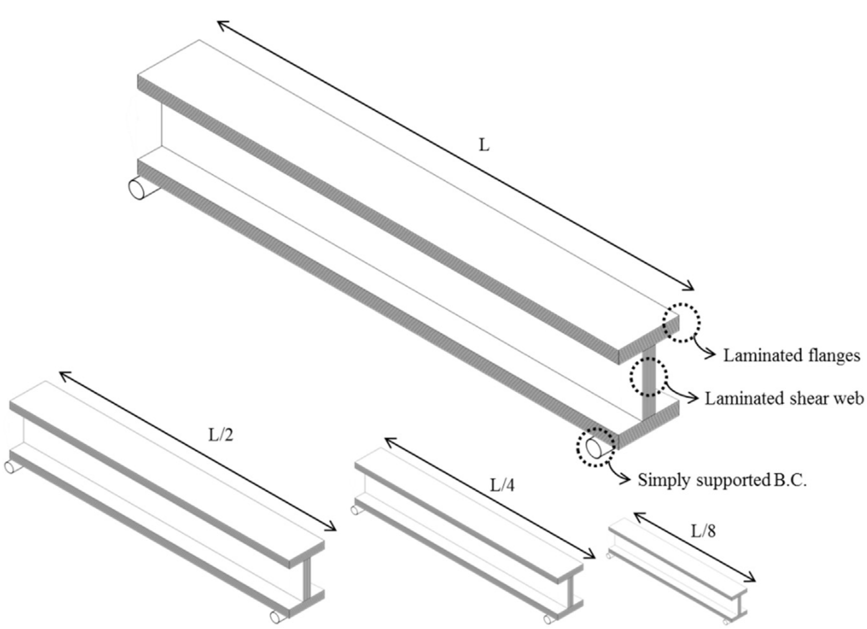

Fig. 1. Prototype (top) and Models with different scales and layups (bottom) showing the associated displacement boundary conditions.