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Experimental investigation on ultimate strength and failure response of composite box beams used in wind turbine blades

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ABSTRACT

This study focuses on the ultimate strength and failure response of composite box beams under three-point bending. The box beams consist of spar caps and shear webs and they are typically used in wind turbine blades as load-carrying members. Different spar cap configurations and loading directions are examined experimentally to investigate structural behavior associated with multiple nonlinearities leading to structural collapse. Global displacements, local strains and video images are recorded throughout the loading history to capture failure initiation, propagation and the strain state contributing to post-collapse characteristics. The failure mechanisms of the box beams involving geometric, material and contact nonlinearities are discussed in detail. The study shows that compressive crushing failure, driven by local buckling of shear webs, determines the ultimate strength of the box beams under flapwise loading, and adhesive joint debonding, initiated by local adhesive cracking and spar cap buckling, is the critical failure mode of the box beams under edgewise loading. The Brazier effect and shear nonlinearity contribute to the initial failure depending on the loading directions. Debonding rather than delamination characterizes post-collapse behavior of all box beams examined in this study.

1. Introduction

A wind turbine blade is a hollow composite structure with outer aerodynamic shells and an internal loading-carrying member. Typically, the loading-carrying member is designed with a box-shaped cross section and usually consists of spar caps and shear webs adhesively bonded together. Experimental determination of ultimate strength of rotor blades is usually conducted through full-scale structural collapse tests, which provide invaluable information on failure mechanisms enabling further optimization of structural design [1–6]. Nevertheless, there are limitations of structural collapse tests of full-scale blades. First of all, technical, safety, and cost risks of these tests have increased dramatically with the growth of blade sizes in recent years, it is physically and economically challenging to load a very large full-scale blade to complete collapse as addressed by Chen [6]. Second, it should be noted that different structural designs with different blade geometries, material properties, load combinations, etc., lead to significant difference in structural behavior. The failure mechanism derived from one particular blade may not be necessarily applicable to other blades. One solution to deal with these limitations is through multi-scale testing, see Fig. 1(a), in which a test pyramid consisting of coupon testing, component testing and full-scale structural testing is used to evaluate structural performance of wind turbine blades at different scales as proposed by the DNV GL standard [7].

Typical failure modes of composite blades were studied in the full-scale collapse tests [1–6,8–12], including geometric nonlinearity mainly characterized as local buckling and cross-sectional ovalization, i.e., the Brazier effect, and material failures such as fiber breakage, matrix damage, debonding and delamination. These failure modes and failure behavior have also been investigated in more general thin-walled composite structures [13–15]. Nevertheless, the failure response has not been adequately studied in load-carrying box beam components, despite their critical role in determining structural strength and failure of wind turbine blades. So far, a few studies have considered the composite box beams used in wind turbine blades. Cole et al. [16] and Yu et al. [17] studied composite box beams to emulate structural characteristics of a rotor blade under flapwise loading in three-point and four-point bending tests. Their work focused on the failure modes and ultimate strength of the box beams and concluded that the adhesive layer had an appreciable impact on the load-carrying capability.

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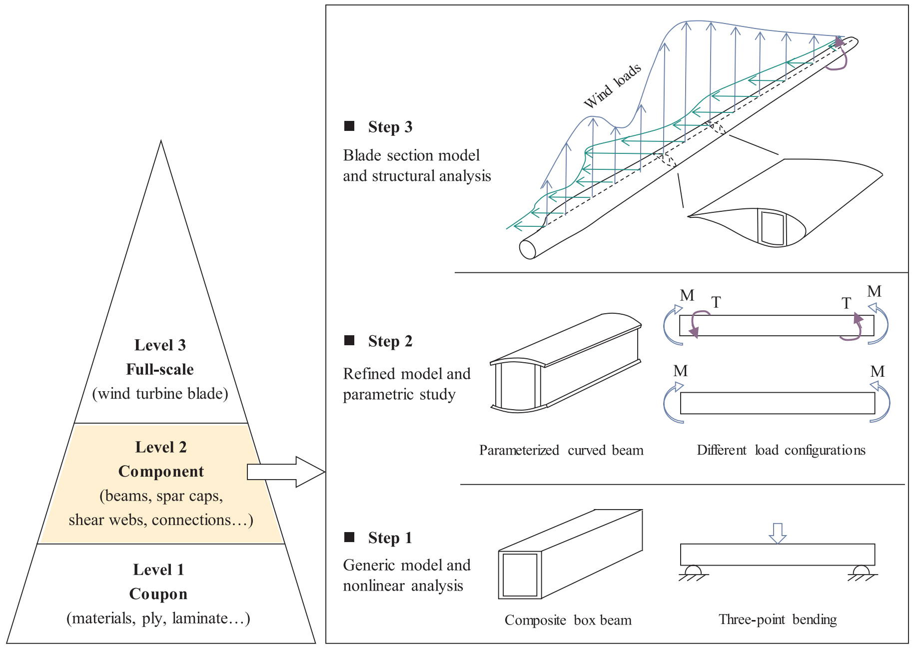

(a) Pyramid test scheme (b) An analysis approach used in this study for load-carrying components

Fig. 1. Multi-scale structural testing of wind turbine blades.

Although the failure modes were presented and discussed, the root cause and interactive nonlinear behavior can be further explored in order to better understand the underlying failure mechanisms.

The composite box beam, as a backbone of the rotor blade, can be considered as a generic model for accessing structural strength and failure both experimentally and numerically at the component level. The entire planned work, as shown in Fig. 1(b), cannot be performed in a single study, and this paper is only the first step toward understanding how multiple local nonlinearities affect the global structural response including the final collapse. The scope of the current work is limited to experimental investigation of strength and failure of load-carrying box beams with rectangular cross sections. A particular focus is placed on interactive nonlinear structural behavior leading to the final structural collapse.

A simple three-point bending test setup is used in this study. Both flapwise and edgewise loading, which are required for certifying a new type of rotor blades in full-scale [18], are applied to the box beams. In the flapwise loading, pre-delamination is introduced in the spar caps as delamination is reported as a critical failure mode directly responsible for the loss of the load-carrying capacity of the blade and determining the ultimate load-carrying capacity [6]. With these tests, this study tries to achieve specific purposes as follows:

- o understand failure mechanisms associated with failure initiation, propagation and the strain state of composite box beams used in wind turbine blades;
- o examine different failure modes, ultimate strength and failure response between the flapwise loading and the edgewise loading;
- o analyze the influence of pre-delamination on the load-carrying capacity and post-collapse characteristics.

The following section introduces design and manufacturing of the box beam components and the test method; Section 3 analyzes the pre-peak structural response; Section 4 provides a detailed description of the failure response considering multiple nonlinear phenomena; and finally, Section 5 addresses the plausible failure mechanism of the box beams.

2. Box beam components and test method

2.1. Component design

The composite box beams are designed with reference to typical materials used in a generic load-carrying member in wind turbine blades. A region of blade length ranging from 30% to 45%, which is critical to structural integrity under extreme wind conditions [19–21], is considered for designing cross sections of the box beams. A schematic description of the box beams is shown in Fig. 2.

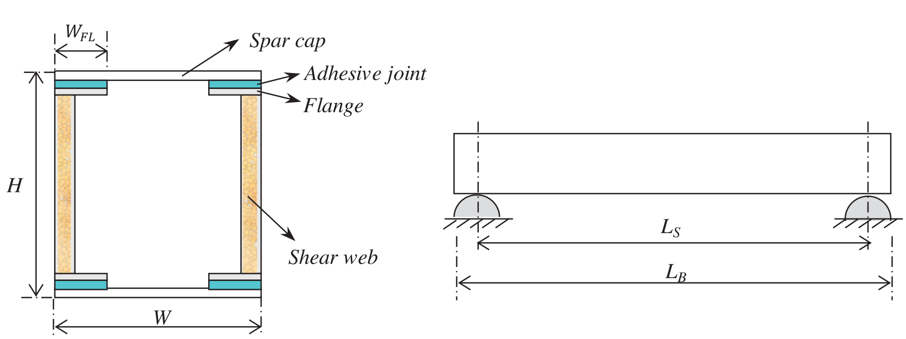

Fig. 2. Geometry of box beams.