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Experimental investigation on structural collapse of a large composite wind turbine blade under combined bending and torsion

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ABSTRACT

This study presents a comprehensive investigation on structural collapse of a 47 m composite blade under combined bending and torsion in a full-scale static load test. The primary focus is placed on root causes and failure mechanism of the blade collapse. The investigation consists of three parts. First, video records of the blade collapse are examined on a frame-by-frame basis. Direct evidence is presented on how the blade collapses in progressive chain events. Second, the detailed post-collapse investigation is conducted both in-situ and in laboratory. The critical failure modes and the associated stress/strain state once experienced by the blade are indentified. Third, strain measurements are analyzed to provide quantitative evidence of the process leading to the blade collapse and consequently confirm the findings of this study. It is found that longitudinal compressive crushing failure and the following delamination of the spar cap, which are driven by local buckling, are the root causes of the blade collapse. The constraint of the loading saddle and local reinforcement of the blade section also contributes to the blade collapse. Torsion loads, although exhibiting no significant effect on the blade strength, are found to affect post-collapse characteristics of the blade.

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1. Introduction

Wind turbines and their rotor blades continuously increase in size in order to harvest more wind power in higher atmosphere altitude. Structural performance of the blades, which is usually of less concern when the blades are small, becomes more important and it draws considerable attention in recent years [1–7]. As one of the most important structural performance, ultimate strength determines the load-carrying capacity of large blades and it has to be carefully studied. Before a type of rotor blade can be manufactured for mass production, static load tests need to be conducted both before and after fatigue tests according to international test standard IEC 64100-23 [8] to ensure that the ultimate strength of the prototype blade is not reached at a specific load level which represents extreme load conditions. The prototype blade can be certified if no major structural failure occurs when the applied loads reach the load level. These certification tests do not require the blades to be loaded to collapse and they provide not much information on structural response of the blades at their ultimate state, although the information is very valuable and essential for the possible improvement of structural design and/or weight reduction of large composite blades.

Due to the high cost and the potential safety concern associated with the collapse test especially when it is conducted on large blades, there are only a few studies managed to conduct and report their experimental work on the collapse response of composite blades [9–15]. Major attention of these studies has been paid to geometric nonlinearity due to cross-sectional ovalization, or the Brazier effect [9,16], delamination and buckling [10–12] and adhesive joint debonding [13,14]. These studies contributed valuable knowledge to structural response of composite blades. Nevertheless, common agreement has not been fully reached on the root causes because different blades are expected to have different failure mechanisms. Specifically, Jensen et al. [9] concluded that the Brazier effect induced crushing pressure on the blade cross section was the cause of the blade collapse. Overgaard et al. [10] concluded that the blade collapse was caused by geometric nonlinearity in the form of local buckling and delamination instead of the Brazier effect. Chen et al. [11,12] had a similar opinion to Overgaard et al. [10] but emphasized the contribution of the three-dimensional stress to the blade collapse. To make this issue more complex, Yang et al. [13] and Lee and Park [14] concluded that adhesive joint debonding of blade shells was the primary cause responsible for the blade collapse. The studies on full-scale structural collapse tests of large composite wind turbine blades are summarized in Table 1.

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Nomenclature

SC	spar cap	PS	pressure side
SW	shear web	LS	loading saddle
LP	leading edge panel	SG	strain gauge
AP	aft panel	UD	unidirectional
LE	leading edge		
TE	trailing edge		
SS	suction side		

Table 1
Summary of studies on full-scale structural collapse tests of large composite blades.

Authors	Blade length (m)	Loading condition	Technical approach used	Root causes of failure/failure mechanisms
Jensen et al. [9]	34	Flap-wise bending	Local displacement measurement	Cross-sectional ovalization due to the Brazier effect
Overgaard et al. [10]	25	Flap-wise bending	Strain and local displacement measurement	Local buckling and delamination rather than Brazier effect
Yang et al. [13]	40	Flap-wise bending	Strain measurement	Adhesive joint debonding followed by buckling rather than Brazier effect
Chen et al. [11,12]	52.3	Flap-wise bending	Strain measurement and detailed post-collapse inspection	Local buckling and 3D stress-driven delamination rather than Brazier effect
Lee and Park [14]	48.3	Flap-wise bending	Detailed post-collapse inspection	Adhesive joint debonding followed by torsional failure of the blade section

It can be seen that all blades used in the existing studies were subject to the flap-wise bending, which is the primary loading state of the blades in service. Torsion loads are neglected in the tests because they are usually small compared to the dominant bending loads. Nevertheless, the blades would have lower torsional eigenfrequency as the increase of their size. As a result, the torsional mode may couple with some of the lower bending modes, leading to the concern of structural failure due to combined bending and torsion. According to the author's literature survey, there is by far no experimental work being reported focusing on the ultimate strength and the collapse of large blades under the combined loading state. Although the pioneering work by Berring et al. [17] investigated torsional performance of a 23-m blade under combined bending and torsion, it only focused on the deformation of the blade. In order to find out the potential effect of combined bending and torsion on the blade strength, there is an urgent need of experimental study to be carried out on the full-scale large blades.

Also worth noting is the technical approaches used in the existing studies. Some researchers [9,10,13] primarily worked on quantitative strain and/or local displacement measurements while the others [14] worked on qualitative failure observation from the detailed post-collapse inspection. In the author's opinion, these two approaches have their own advantages in proving useful information on the blade collapse. On the one hand, quantitative measurements provide accurate and precise information on structural response in the entire loading history of the blades. Based on these information it is possible to understand how the blade responses to the applied loads and how different phenomena interact during the loading. On the other hand, the detailed inspection on the post-collapse scene provides direct evidence on failure characteristics of the blades, helping researchers identify the most critical failure modes and indicate the strain/stress state once experienced by the blades. In this regard, it is suggested that two approaches are used together as complements in order to obtain in-depth understanding of the blade collapse.

In view of the aforementioned discussion, this study, aiming to provide new insights into the collapse of large composite blades, conducts a collapse test on a 47-m composite blade under combined bending and torsion. The work is by far, to the author's best knowledge, the first public study reporting the ultimate structural response of the full-scale blades in the combined load state, which represents a more realistic extreme load condition of the blades when their size becomes large. Attempt is made to: (1) find out the potential effect of the combined bending and torsion on the ultimate strength and the collapse response of the blade, (2) identify the critical failure modes responsible for the blade collapse, and (3) clarify the failure mechanism associated with interactive nonlinear phenomena such as local buckling, the Brazier effect, delamination and adhesive joint debonding, which eventually lead to the blade collapse.

To facilitate this endeavor, comprehensive methods are used in this study by integrating information from both qualitative investigation and quantitative measurements. Specifically, video records which capture the drastic collapse process of the blade are analyzed on a frame-by-frame basis. A series of progressive chain events occurred at the collapse instance provide direct phenomenological evidence on how the blade collapses at its ultimate state. The detailed post-collapse investigation is conducted in-situ to identify the critical failure modes associated with the blade collapse. Spar cap (SC) samples at the failure region are cut from the blade and they are further examined in laboratory to find out more evidence which helps reflect the stress/strain state the blade has experienced. Strain measurements in the failure region are analyzed to understand the development of local buckling and the Brazier effect during the loading history and consequently confirm the findings of the study. Based on all the evidence presented in this study, the most likely failure scenario of the blade is reconstructed, and the plausible failure mechanism is also deduced accordingly at the end of this paper.

2. Blade specimen and test method

2.1. General information of the blade

The test article is a 47-meter long composite rotor blade of 2 MW wind turbines. It is made of glass fabrics and vacuum

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