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# A review of full-scale structural testing of wind turbine blades

H.F. Zhou [a,*], H.Y. Dou [a], L.Z. Qin [a], Y. Chen [b], Y.Q. Ni [b], J.M. Ko [b]

[a] *College of Architecture and Civil Engineering, Wenzhou University, Chashan University Town, Wenzhou 325035, China*
[b] *Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong*

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ABSTRACT

The blades that play a key role to collect wind energy are the most critical components of a wind turbine system. Meanwhile, they are also the parts most susceptible to damage. Structural health monitoring (SHM) system has been proposed to continuously monitor the wind turbine. Nevertheless, no system has yet been developed to a stage compatible with the requirements of commercial wind turbines. Therefore, full-scale structural testing is the main means available so far for validating the comprehensive performance of wind turbine blades. It is now normally used as part of a blade certification process. It also allows an insight into the failure mechanisms of wind turbine blades, which are essential to the success of SHM. Furthermore, it provides a unique opportunity to exercise SHM and non-destructive testing (NDT) techniques. Recognizing these practical significances, this paper therefore aims to carry out an extensive review of full-scale structural testing of wind turbine blades, including static testing and fatigue testing. In particular, the current status in China is presented. One focus of this review is on the failure mechanisms of wind turbine blades, which are vital for optimizing the design of themselves as well as the design of their SHM system. Another focus is on the strengths and weaknesses of various SHM and NDT techniques, which are useful for evaluating their applicability on wind turbine blades. In addition, recent advances in photogrammetry and digital image correlation have allowed new opportunities for blade monitoring. These techniques are currently being explored on a few wind turbine blade applications and can provide a wealth of additional information that was previously unobtainable. These works are also summarized in this paper in order to discover the pros and cons of these techniques.



**Contents**



## 1. Introduction

Being a renewable and green source of energy, wind energy has become a pillar of the energy systems in many countries and is recognized as a reliable and affordable source of electricity.

* Corresponding author. Tel.: +86 577 8668 9575; fax: +86 577 8668 9611.
*E-mail address:* mailtofei@wzu.edu.cn (H.F. Zhou).

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It has seen an average growth of 30% in the past decade and the wind capacity doubles every third year. In the year 2012, 100 countries were identified where wind energy was used for electricity generation. In total, the worldwide wind capacity reached 282,275 MW. The contribution of wind energy to the energy supply has reached a substantial share even on the global level: all wind turbines installed around the globe by the end of 2011 contribute potentially 580 Terawatthours to the worldwide electricity supply, more than 3% of the global electricity demand. Furthermore, substantial growth is expected in the future, although the growth in 2012 went down to the lowest rate of 19.1% in the two decades. It is estimated that a global capacity of more than 500,000 MW by the year 2016, and around 1,000,000 MW by the year 2020 are possible [1].

The other side of the coin is that the development of wind energy cannot be smooth sailing all the way. The wind turbines, which convert wind power into mechanical energy and then generate electricity, often operate in harsh environments. Therefore, they may be damaged by many load and environmental factors like fatigue, lightning, fire, strong wind, moisture, and so on. Wind turbine accidents have been reported from time to time. An extensive documentation of wind turbine accidents is provided by Caithness Windfarm Information Forum (http://www.caithnesswindfarms.co.uk) [2]. Fig.1 shows the statistics of wind turbine accidents recorded since 1970s. By September 30 2013, a total of 1446 accidents have been reported worldwide. In trend, more accidents occur as more wind turbines are built. There are an average of 8 accidents per year from 1993 to 1997 inclusive; 33 accidents per year from 1998 to 2002 inclusive; 80 accidents per year from 2003 to 2007 inclusive; and 141 accidents per year from 2008 to 2012 inclusive. The most dangerous failure is a high wind failure, which occurs when the braking system fails, causing the rotor to hit the tower at a high speed. This resulted in considerable damage from parts of the blade to the entire nacelle (rotors attached) flying off the tower structure. Blades and other substantial parts have landed as far away as 500 m in typical cases. For example, the Hedingshan Wind Farm in China's east coastal city of Wenzhou suffered heavy damage after being swept by Typhoon Saomai with wind speeds up to 67 m/s in mid August 2006. Blades suffered the most serious damage. 15 Vestas 600 kW turbines and two Dewind 600 kW units were either fragmented or broken into three parts, while one Vestas 660 kW and two Windey 750 kW machines were toppled. Only eight of the 28 installed wind turbines barely survived.

Although damage can occur to any component or part of the wind turbine, blade failures are a prominent structural failure and are the most common type of damage that occurs in a wind turbine system. According to the accident statistics provided by Caithness Windfarm Information Forum [2], by far the biggest

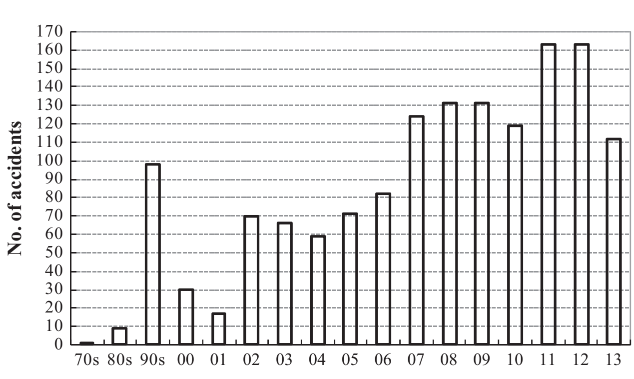


**Fig. 1.** Statistics of wind turbine accidents recorded since 1970s.

number of incidents found was due to blade failure: a total of 265 separate incidents were found. It has also been shown that the blade damage is the most expensive type of damage to repair and requires considerable repair time. Furthermore, rotating mass unbalance due to minor blade damage can cause serious secondary damage to the whole wind turbine system if prompt repair action is not taken and this can result in the collapse of the whole tower. A failed blade might damage other blades, the tower, the wind turbine itself, and possibly other turbines in the wind farm. Last but not least, the blades are generally regarded as the most critical component of the wind turbine system. The cost of the blades can account for 15–20% of the total wind turbine system [3]. Therefore, utmost care should be given to the wind turbine blades.

To keep wind turbines in continuous operation, structural health monitoring (SHM) of wind turbines is more becoming daily practice. An extensive review of SHM for a wind turbine system has been presented by Ciang et al. [4]. To date, the most successful application of SHM technology has been for condition monitoring (CM) of rotating machinery [5]. Now the CM system has become an integral part of a wind turbine system. The gearbox, bearings, etc. are online controlled with methods derived from CM. Monitoring of these parts is mostly done with accelerometers. Since a lot experience exist in CM, many companies and research institutes worldwide offer their services for monitoring machine parts. The reader is referred to [6,7] for comprehensive reviews of CM of wind turbines. The blade is another most monitored component in a wind turbine system. However, the SHM of wind turbine blades is still in development [8].

So far, full-scale structural testing is the main means available for validating the comprehensive performance of wind turbine blades. It is now normally used as part of a blade certification process. It also allows an insight into the failure mechanisms of wind turbine blades, which are essential to the success of SHM. In addition, it provides a unique opportunity to exercise SHM and non-destructive testing (NDT) techniques in a laboratory environment. The applicability of a big palette of SHM and NDT techniques on wind turbine blades can be tested in the full-scale structural testing. Recognizing these significances, full-scale structural testing of wind turbine blades has been carried out worldwide. A variety of testing procedures, methods, and techniques has been proposed, which usually led to the diversity of testing results. It therefore necessitates a review of these works to help the reader obtain a comprehensive understanding of the full-scale structural testing of wind turbine blades. To the best of the authors' knowledge, reviews in this regard have not been reported yet. This paper therefore aims to carry out an extensive review of full-scale structural testing of wind turbine blades. The review makes a reference database for different testing procedures, methods, techniques, and results, which is beneficial to the reader to enhance their understanding of full-scale structural testing of wind turbine blades. Specifically, a collection of failure mechanisms of wind turbine blades can be used to optimize the design of large-scale wind turbine blades and guide the design of SHM system for them. An assortment of strengths and weaknesses of various SHM and NDT techniques can be employed to evaluate their applicability on wind turbine blades. A collective report of new measurement technologies can help discover their pros and cons as well as indentify promising in-service wind turbine SHM techniques.

The paper is organized as follows. In Section 2, a review of full-scale structural testing of wind turbine blades, including static testing and fatigue testing, is presented. In particular, the current status in China is reported. The failure mechanisms of wind turbine blades are emphasized in this review. Meanwhile, promising SHM and NDT techniques exercised in the full-scale structural