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**Summary (max 2000 characters):**

Full scale fatigue test is an important part of the development and design of wind turbine blades. Testing is also needed for the approval of the blades in order for them to be used on large wind turbines. Fatigue test of wind turbine blades was started in the beginning of the 1980s and has been further developed since then. Structures in composite materials are generally difficult and time consuming to test for fatigue resistance. Therefore, several methods for testing of blades have been developed and exist today. Those methods are presented in [1].

Current experimental test performed on full scale MW wind turbine blade are very time consuming and expensive. For the industry that means that the tests, both static and fatigue, are not a tool in or a part of the design process. In the academic community, full scale testing of modern and future wind turbine blades are even more challenging as requirements for experimental facilities are very demanding and furthermore the time for performing the experimental test campaign and the cost are not well suitable for most research projects.

This report deals with the advantages, disadvantages and open questions of using down-scaled testing on wind turbine blades.

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# Preface

This report is deliverable 1.2 of the project “Wind turbine rotor blade testing technology research and platform construction”. The project is supported by the Renewable Energy Development (RED) programme in which the Chinese and Danish governments are cooperating and aiming at institutional capacity building and technology innovation for renewable energy development.

This particular project is a partnership between the Chinese Baoding Diangu Renewable Energy Testing and Research Co., Ltd., a national wind and solar energy key laboratory for simulation and certification and from Denmark the Department of Wind Energy, Technical University of Denmark, a Danish wind energy research department that has provided a major part of the wind energy research in Denmark and is one of the leading wind energy research institutions in the world.

The project will focus on research for on-site, full-scale and down-scale structural testing of wind turbine rotor blades. An advanced blade on-site monitoring platform and full-scale testing platform will be constructed to strengthen the capacity of wind turbine blade testing and demonstrated in Baoding, city of Hebei Province in China.

The project will provide the manufacturers with the possibility to do comprehensive blade testing in order to achieve test data for fulfilling requirements of standards and in order to obtain better and more optimized blade design. Meanwhile advanced experiment tool and valid test data can also be provided for the research and certification institutions in order to develop better design methods and certification guidelines and standards.

The project has three main parts. The first part is research in full-scale and down-scale structural testing of wind turbine blades as well as condition monitoring for on-site testing of whole wind turbines. The next part is construction of platforms in China for full-scale fatigue testing of blades and on-site condition monitoring of wind turbines. Finally, the last part is to demonstrate the full-scale fatigue testing and the on-site condition monitoring.

Roskilde, Denmark
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# Content

# Summary

Full scale fatigue test is an important part of the development and design of wind turbine blades. Testing is also needed for the approval of the blades in order for them to be used on large wind turbines. Fatigue test of wind turbine blades was started in the beginning of the 1980s and has been further developed since then. Structures in composite materials are generally difficult and time consuming to test for fatigue resistance. Therefore, several methods for testing of blades have been developed and exist today. Those methods are presented in [1].

Current experimental test performed on full scale MW wind turbine blade are very time consuming and expensive. For the industry that means that the tests, both static and fatigue, are not a tool in or a part of the design process. In the academic community, full scale testing of modern and future wind turbine blades are even more challenging as requirements for experimental facilities are very demanding and furthermore the time for performing the experimental test campaign and the cost are not well suitable for most research projects.

This report deals with the advantages, disadvantages and open questions of using down-scaled testing on wind turbine blades.

# 1. Introduction

As wind turbine blades continue to grow in size the industry are facing more challenges in both designing and testing these very large structures. These very large wind turbines are located at more remote sites and the cost of downtime and repair is growing rapidly. Current experimental test performed on full scale MW wind turbine blade are very time consuming and expensive. For the industry that means that the tests, both static and fatigue, only will be performed after the design process. In other words the tests are not a tool in or a part of the design process, but are often only performed because of the requirements in the certification process.

In the academic community, full scale testing of modern and future wind turbine blades are even more challenging as requirements for experimental facilities are very demanding and furthermore the time for performing the experimental test campaign and the cost are not well suitable for most research projects.

It has been suggested that some of the challenges of full-scale tests described above can be mitigated by performing these tests on geometrically down-scaled blades. Below are listed some of the advantages and some of the disadvantages / open questions related to down-scaled testing.

Advantages:

- The costs for down-scaled blades are much lower. Therefore a larger number of tests can be performed yielding statistically significant results. Moreover, the tests can be performed at an earlier stage of the design process.
- As the natural frequencies of the down-scaled blade are higher, more load cycles could be reached in a given time.
- Many theoretical tools and methods within experimental testing and numerical investigations used in academia seem more suitable to perform on down-scaled test specimens.
- Geometrically down-scaled blades will have similar elastic responses as full scale blades, which means that failures caused by instability, such as buckling can be investigated in down-scaled tests.
- More advanced load configurations, both static and fatigue, can be tested and thereby provide additional insight into the blade design.

Disadvantages / open questions:

- How well will a geometrically down-scaled blade represent the real blade?
- What limitations are there in down-scaling the composite layup?
- Will manufacturing defects in the down-scaled blades be representative of the manufacturing defects in the real blade?
- New molds have to be manufactured for the down-scaled blades.
- How well will a geometrically down-scaled blade capture the fatigue properties of the real blade?
- Can a test campaign on down-scaled blades in the future affect the certifications process and maybe resulting in reduced partial safety factors?

- Where are down-scaled tests used today and what are the possibilities and limitations of these tests?
- What is the additional cost for performing a down-scaled test campaign?

The list of disadvantages and open questions above indicates that much research is required before down-scaled tests can become a tool used by the industry and in the academic community. Furthermore an improved understanding of scaling-effects in large composite structures needs to be further investigated. Especially fatigue and fracture mechanic of down-scaled composite structures needs to be further researched to clarify the limitations and possibilities. This deliverable will aim at investigating these questions and generate the initial steps setting up a platform for performing geometrically down-scaled tests on wind turbine blades.

# 2. Natural frequencies and bending moments

One of the benefits of down-scaling blades is that the tests loads are much lower than full-scale loads. Another benefit is that natural frequencies of the down-scaled blade are higher, so more load cycles can be reached in a given time. In the following this is studied based on known data for blades from commercial 1.5MW and 2.3MW wind turbines as well as the DTU 10MW reference wind turbine [2]. The scaling rules are based on Chaviaropoulos [3].

First the known data is scaled to correspond to 1-3MW wind turbines. The expected natural frequency and root bending moment amplitude for fatigue testing of blades for 1-3MW wind turbines are shown below in Figure 1. The length of the corresponding blades is 27 - 51m.

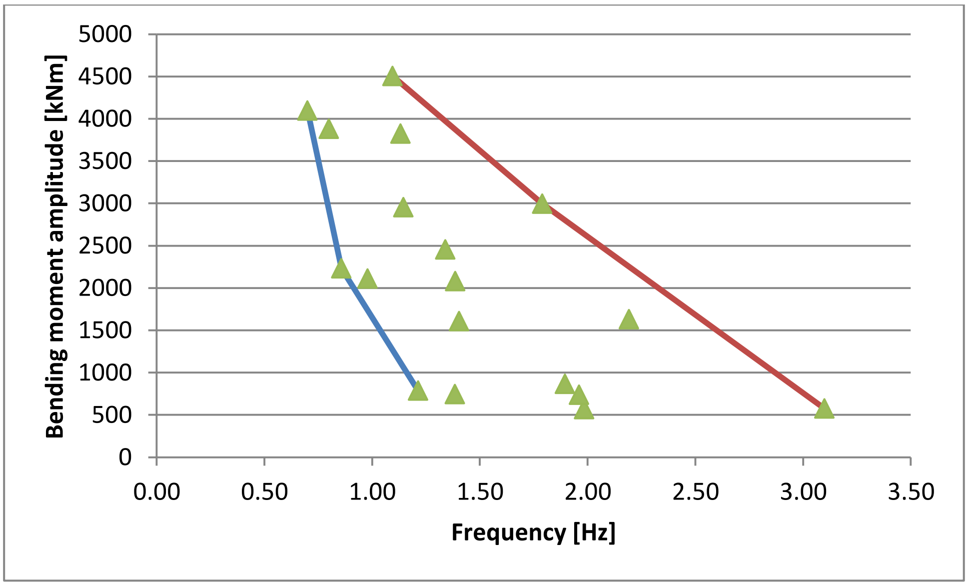


*Figure 1  Expected natural frequency and root bending moment amplitude for fatigue testing of blades for 1-3MW wind turbines.*

Then the known data is scaled to correspond to 100-300kW wind turbines. The expected natural frequency and root bending moment amplitude for fatigue testing of these blades are shown below in Figure 2. The length of the corresponding blades is 9 - 16m.

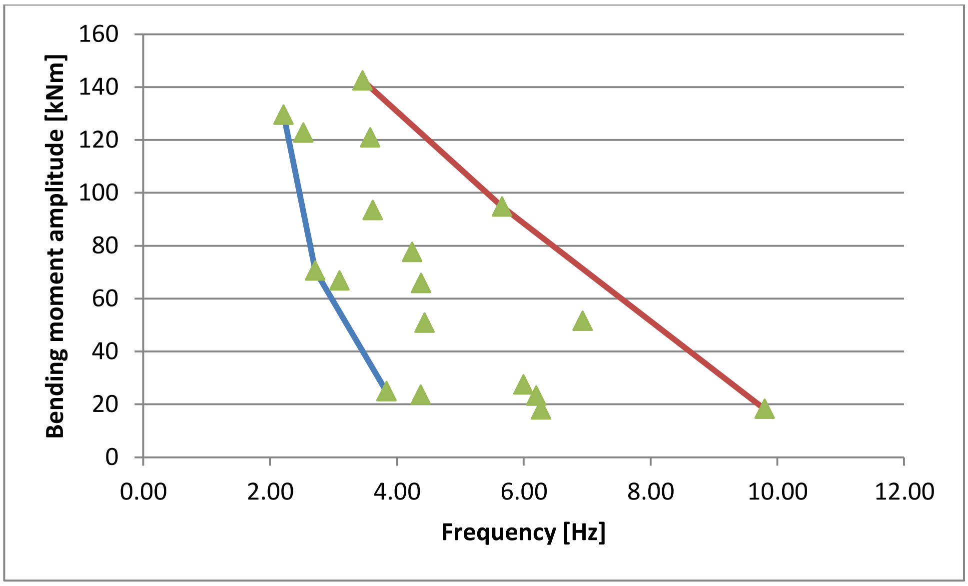


*Figure 2 Expected natural frequency and root bending moment amplitude for fatigue testing of blades for 100-300kW wind turbines.*

If the scaling factor is *S* and the length of the full-scale blade is *L*, while the length of the down-scale blade is *l*, then

$$l = L / S \qquad (1)$$

The root bending moment is $S^3$ times smaller for the down-scaled blade than for the full-scale blade and the natural frequency for the down-scaled blade is *S* times larger than for the full-scale blade. This means that it takes 1/*S* of the time of obtain the same number of cycles for the down-scaled blade than for the full-scale blade.

There is an issue with heating of the composite material at high frequency.
In a study by Apinis [4] it was concluded that the fatigue tests of most frequently used polymer composite materials can be accelerated considerably by increasing the loading frequency up to several hundreds of hertz, without a correction for the influence of loading rate on the fatigue properties of the materials. However, Apinis pointed out that a necessary condition for the performance of high-frequency tests is an intense cooling of specimens to prevent the matrix of specimen material from transition into a highly elastic state.

# 3. Testing equipment

The equipment for applying loads on down-scaled wind turbine blades is in principle the same equipment that is needed for full-scale testing. The loads and amplitudes (strokes) are much smaller for down-scale testing compared to full-scale testing. However, the cyclic testing frequencies for fatigue tests are higher for down-scale testing compared to full-scale testing.

It makes good sense to develop advanced fatigue test methods such as dual-axis testing on down-scaled blades as the loads are much smaller. As the dimensions and loads are smaller the needed loading equipment is smaller, lighter and easier to handle. It is also cheaper and faster to change test setups when they are small in order to experience with different test methods.

The most common way to fatigue test blades is to use a mass resonant system. MTS has together with National Renewable Energy Laboratory (NREL) developed such a mass resonant system based on hydraulic actuators. They call the system IREX (Inertial Resonance Excitation) and is shown in Figure 3. Each IREX system integrates two double-ended, fatigue-rated hydraulic actuators, linear side bearings, a hose stand, and adjustable masses to accurately apply both flap-wise and edge-wise resonant-frequency cyclic loads (see [5]).

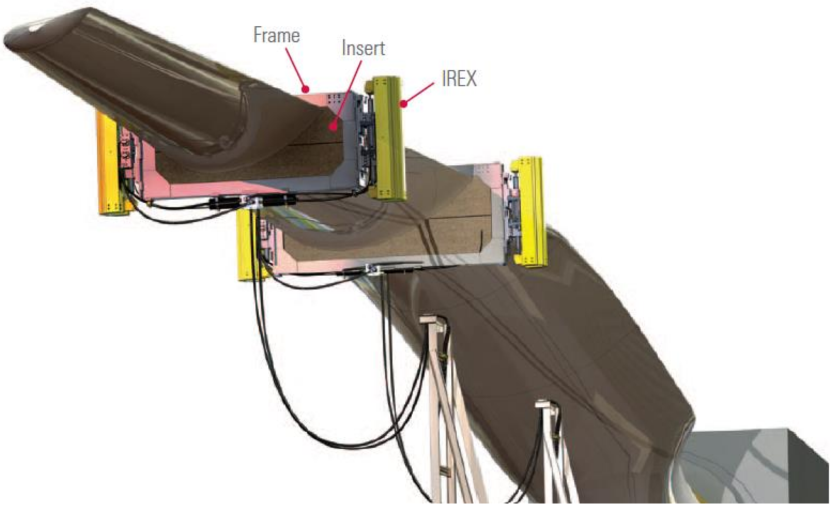


*Figure 3  The Inertial Resonance Excitation (IREX) system by MTS.*

Another mass resonant system developed by MTS is their Ground Resonance Excitation (GREX) system shown in Figure 4. This is a hydraulic actuated floor-coupled load application system features versatile base and swivel design to accommodate wide variety of loading fixtures and blade angles. The lower equipment mass added to the blade leads to faster testing as the natural frequency is not lowered as much (see [6]). According to MTS the GREX and IREX systems in combination is capable of dual-axis resonant blade testing.

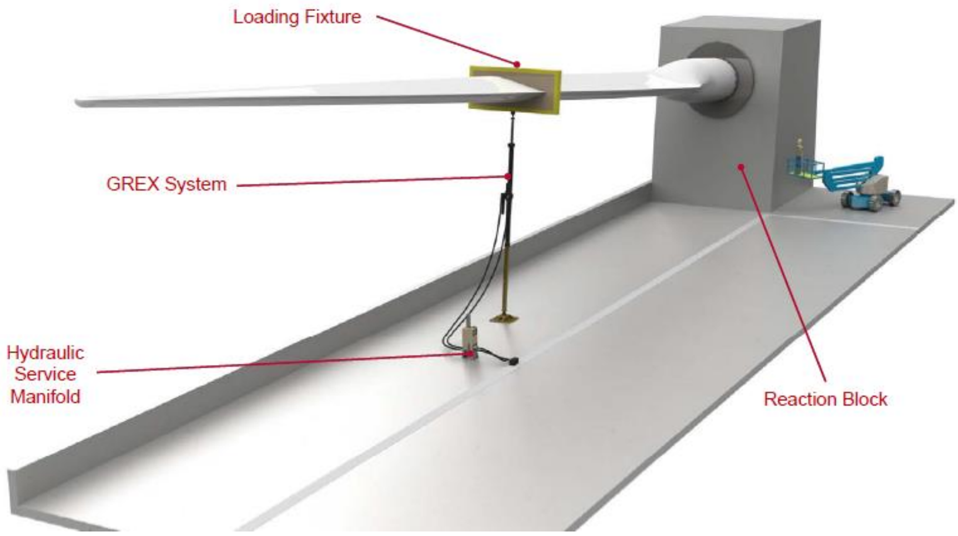


*Figure 4  The Ground Resonance Excitation (GREX) System by MTS.*

Different methods for dual-axis fatigue test methods are described in [1]. Here mass resonant methods and forced displacement methods are discussed together with hybrid systems where different methods are combined.

# 4. Composite layup and failures

Down-scaling the composite materials provides special challenges as the thickness of the fibers and the cell size in the foamed core materials in general cannot be scaled down. This raises some questions. What limitations are there in down-scaling the composite layup? How well will a geometrically down-scaled blade capture the fatigue properties of the real blade?

If the number of composite layers in the down-scaled blade should be the same as for the full-scale blade then the fiber areal weight should be scaled down. However, it is difficult to obtain the same fiber volume fraction with low fiber areal weight layers as it is with high fiber areal weight layers (1200-1600 g/m$^2$) that are typically used in wind turbine blades. There exist commercial available fabrics with much lower fiber areal weights than those normally used for wind turbine blade. It will probably be most realistic for down-scaled blades to reduce the number of layers in order to still obtain a desired fiber volume fraction.

The foamed plastic core materials also provide a special challenge as cell size in the foamed plastic is not scaled down. For low density foams the cell size is usually quite big and a down-scaled low density sandwich core may only have a few cells through the thickness. When the core is bonded to the faces of the sandwich the cut cells at the surface of the core is filled with adhesive. Therefore, the down-scaled sandwich core will in general be relatively more filled with adhesive than the full-scale sandwich core. This means that the down-scaled sandwich core is relatively more heavy and stiff.

The adhesive bonding of the different parts in a wind turbine blade also provides a special challenge as it is difficult to scale down the thickness of the bondline. Bondlines in full-scale wind turbine blades are typically 5-10mm thick and with a scaling factor of 5 it is a challenge to realistically make bondlines of 1-2mm thickness for the down-scaled blade. The effect of bondline thickness is discussed by Wetzel [7] and Canales [8]. Using an adhesive with less viscosity may help solve the challenge.

Down-scaling the manufacturing defects also provide special challenges and raise some questions. Will manufacturing defects in the down-scaled blades be representative of the manufacturing defects in the real full-scale blade? Can a test campaign on down-scaled blades in the future affect the certifications process and maybe resulting in reduced partial safety factors?

The manufacturing defects can be dry spots and dry areas between fibers, voids in the resin, misalignment of fibers, fiber waviness and wrinkles. Other defects are delaminations between composite layers and debonded areas in the adhesive bonds. There might also be geometrical imperfections such as surface dimples and misalignment of structural parts.

The geometrical imperfections should scale correctly and their effect can therefore be studied by down-scaled tests. Also buckling and other stability phenomena can be studied by down-scaled tests as they are scaling correctly.

The scaling of the other manufacturing defects listed above is more challenging and much research is needed in that area. With down-scaled tests it is realistic to build artificial and well defined defects into these smaller and much less expensive blades. The effect of defect can then be tested in a more controlled way using down-scaled testing. Much research is however needed to study similarities and differences between artificial defects and real manufacturing defects.

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We have more than 240 staff members of which approximately 60 are PhD students. Research is conducted within nine research programmes organized into three main topics: Wind energy systems, Wind turbine technology and Basics for wind energy.

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