Development and feasibility study of segment blade test methodology

Kwangtae Ha[1], Moritz Bätge[1], David Melcher[1] and Steffen Czichon[1]

[1]Fraunhofer Institute for Wind Energy Systems, Department Rotor Blades, Bremerhaven, 27572, Germany

Correspondence to: Kwangtae Ha (kwangtae.ha@iwes.fraunhofer.de)

Abstract. This paper outlines a novel segment test methodology for wind turbine rotor blades. The segment test mainly aims at improving the efficiency of the fatigue test as a future test method at Fraunhofer IWES. While resulting in reduced testing times, target fatigue bending moments over the intended test area have to be matched within an acceptable range of overload. The numerical simulation reveals that the proposed segment testing has a significant time saving up to 43% and 53% for 60m and 90m blades. When compared to the experimental data of 60m full-length blade fatigue test, the proposed methodology also shows better test quality over the intended area and better certifiable regions over the outboard area.

1 Introduction

Wind turbine rotor blades are designed to sustain the designed 20 ~ 25 years lifetime without structural failure. Reliability of the blade is essential for keeping maintenance and operations costs low and maintaining the designed power performance. Mechanical full-scale tests are the main process available for validating the structural integrity of wind turbine rotor blades (Spera, 2009). This is also required as part of the blade certification process according to IEC 61400-23 (IEC, 2014). A typical full-scale blade test consists of following test programs:

메모 포함[하1]: Response on minor comment #1 (2012 → 2014)

- Determining blade properties such as mass, center of gravity, and natural frequencies.
- Static tests
- Fatigue load tests
- Post fatigue static tests

메모 포함[하2]: Response on minor comment #2 (Based on IEC 61400-23, 2014, followed the written paragraph in test program in page 16, chapter 7.)

Among all structural tests, the fatigue load test is the most time-consuming process, and therefore this step accounts for most of the test cost involved. It is executed either in the flap or lead-lag direction independently, or simultaneously in both directions. Due to the large mass and low stiffness of the blades, test operating frequencies are very low, especially for flap fatigue tests. Therefore, fatigue tests take up to several months to accomplish the required cycle count of 1 to 5 million cycles, depending on the blade characteristics (Wingerde et al., 2015; Post, 2016). As blades are getting longer and bigger, both test time and costs increase significantly - especially for future offshore blade measuring more than 100m in length. Also, testing facilities for 100m+ blades are very limited at this moment. Hence, a reduction in test time and utilizing available test halls are important to accelerate the development cycle of future offshore turbines with 100m+ blades.

In this paper, a novel segment test methodology for wind turbine rotor blades is proposed and its benefits are investigated with a numerical simulation. The proposed test methodology decouples a blade root segment and a tip segment to improve test quality and minimize test time by performing both segment tests independently in parallel while meeting the original target bending moment within specific overload limit (5% for flap direction and 10% for lead-lad direction). Two representative blade models, a 60m onshore blade and a 90m offshore blade was used for numerical simulation to compare the fatigue test time and the test quality of segment blades with full-scale blades in ANSYS APDL and ANSYS Workbench 18.1 (ANSYS, 2018).

메모 포함[하3]: Response on major question #1-1
Clarified sentence by eliminating previous misleading sentence. And modified and added sentence in the Introduction chapter.

메모 포함[하4]: Response on major comment #1 -2

2 Segment blade test methodology

Since the tip portion of the blade is generally not very critical in terms of structural damage, the blade tip is sometimes removed during fatigue testing in order to reduce energy consumption and test time. This can also be done if space in the testing facility is limited. (Spera, 2009; Al-Khudairi et al., 2017; White, 2004). The segment blade test takes this approach a step further and divides the Device under Testing (DUT) into a root and a tip segment as shown in Fig. 1, which can then be tested in parallel.

2.1 Differences between full-length and segment testing

The test procedure remains essentially unchanged compared to the full-length blade test. However, there are several important differences in the test preparation and execution that have to be considered.

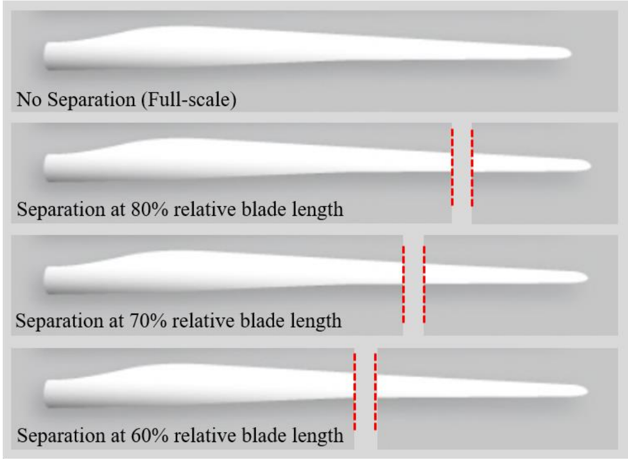
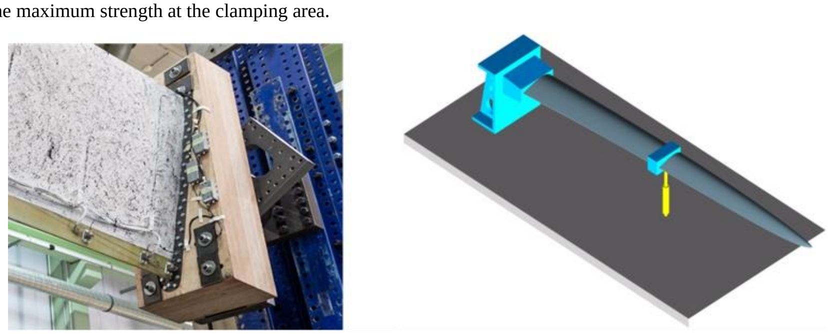


Figure 1. Schematic representation of a blade with different separation points

It is assumed that design-critical areas are not located near the separation points. If the areas of the separation point are to be verified in the test, a significantly greater manufacturing outlay arises, as overlapping segments have to be produced. In this work, the assumption applies that the separation point does not lie in one of the critical areas (Brondsted et. al, 2013). Special care has to be taken when cutting the blade to produce reliable segment blades without any defect. However, this aspect is not considered in this study (Skelton, 2017).

The expense of equipping the rotor blade with test-specific measurement sensors does not change significantly as a result of the segmentation. However, since the blade tip test time is much shorter than the blade root test due to the higher test frequencies, the preparation work for the tip segment can be postponed. In other words, after the blade root test is prepared and started, preparation work with the blade tip segment can be executed. In this way, additional time can be saved in the overall process of the test.

In order to improve transportability, some modern onshore blades are already produced in a modular design, where two halves are produced that are joined on the wind farm site. For these blades, the tip already has a connection to mount the tip segment to the test stand. If the blade is only separated for test purposes, the tip segment, unlike the root segment, has no prefabricated connection for mounting to the test stand. In this case, the mounting test stand must be fabricated for the tip segment. There are several possible solutions. One solution is that the segment can clamped by two fixed load frames arranged one behind the other. However, this leads to a reduction of the test area. Fraunhofer IWES has developed and validated an alternative fixture concept. The structure to be tested is glued firmly into a wooden frame, whereby the immediate connection point is reinforced by steel sheets (Rosemeier et. al, 2018). Fig. 2 (a) shows this connection technology used in the application of a trailing edge subcomponent test, and Fig. 2 (b) shows the connection design of the tip segment to the test bench as part of the entire test setup without additional masses. Depending on the length of the tip segment, the bonding depth to the load frame may vary to sustain the maximum strength at the clamping area.



(a) Load frame for blade subcomponent test (b) Connection design for blade tip segment

Figure 2. Solutions for mounting blade tip segment to the test stand

During the conventional fatigue test, the rotor blade is usually more stressed in the area near the root than in the area of the blade tip compared to the target loads. As an example, Fig. 3 shows an experimental overload distribution and an optimized overload distribution of a 60m blade in the lead-lag fatigue test. As a result of experimental fatigue test, the inboard areas of the rotor blade have already experienced the calculated loads from 20 years of life, but the test must continue to sufficiently load the under-stressed areas over 65% of blade length. Due to this “over-testing” or “over-stressing” of the inboard blade area, structural damage increasingly occurs towards the end of the test, which must be inspected and if necessarily, repaired (DNV-GL, 2015). This can result in delays of several weeks in the process. The numerical optimization of a full-length blade fatigue test setup resulted in a better and reduced overload distribution as shown in Fig. 3, but it still shows under-stressed areas after 75% of blade length. Most of all, the increased test time (reverse of test frequency) cannot be ignored as a future offshore blade is getting bigger. Details of an optimization process will be addressed in section 2.2.

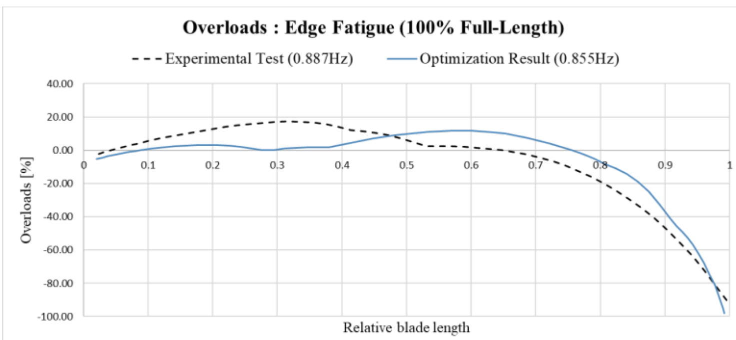


Figure 3. Overloads distribution from the full-scale lead-lag fatigue test of 60m blade

Segment test offers a major advantage regarding moment distribution over the blade length. By dividing a full-scale blade into blade root and blade tip segments, the inboard and outboard area of the rotor blade are decoupled and loaded independently, as shown in Fig. 4. From the Fig.4, the variables, M, F, and ω represent loadframe mass, force and frequency, respectively, and the subscript c represent cylinder actuator. The respective test can be stopped when the corresponding area has reached the required target loads. Also, should damage occur that necessitates repairs to the blade structure, only the respective segment test must be stopped for the inspection.

메모 포함[하5]: Response on major question #2-1
Optimization for a full-length blade fatigue test setup showed better overload compared to commercial (experimental) full-blade test. However, test speed was increased instead. Applying the optimization method to segment test concept will be beneficial to save test time while keeping overload to some extent.

메모 포함[하6]: Response on minor comment
M,F,w are variables, but not c.

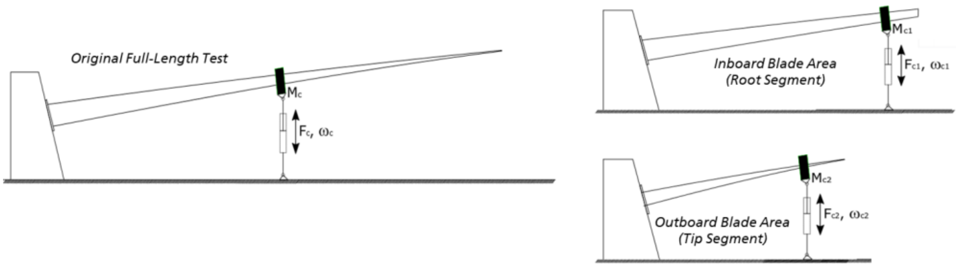


Figure 4. Comparison of blade fatigue test setup (full-length blade vs. segment blades)

A widely used method to achieve the introduction of shear forces and bending moment to approximate the bending moment distribution to the target loads is the attachment of additional masses on the blade. However, this practice leads to a drop in the test frequency (Spera, 2009; Gasch et. al, 2012). Alternatively, the bending moment distribution can be modified through artificial stiffness elements, as shown in Fig. 5 by introducing opposing forces and providing additional degrees of freedom for test quality improvement (Gere et. al, 2013). The stiffness elements can be implemented passively by mechanical or hydraulic springs or actively by hydraulic actuators (cylinders). In this model, a spring element with a maximum stiffness of 300 kN/m was implemented. In addition, the force entered by the spring into the blade was limited to 100 kN or less. Additional stiffness elements can also help to increase the systems natural frequency and reduce test time.

메모 포함[하7]: Response on minor comments
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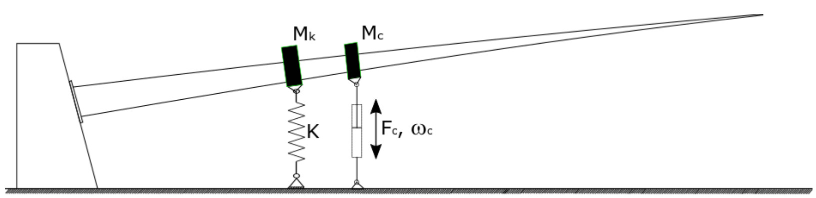


Figure 5. Spring element application to blade fatigue test setup

Naturally, the segment test must achieve the same bending moment distribution as the full-length test. However, it is intuitively obvious that the free end of the segment will experience a zero-bending moment. In order to overcome this, a blade dummy, representing mass and moment of inertia of the tip segment can be fixed to the root section as shown in Fig. 6, which is similar to the fixation of the blade tip segment to the test bench described above.

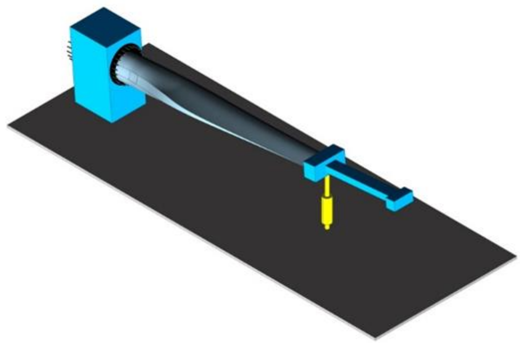


Figure 6. Cantilever structure for root segment test

2.2 Numerical model for optimization of segment test setup

Purpose of this study is to quantify the advantages of segment blade testing by comparing test setups for two different test cases. For 60m and 90m blade, an optimized test configuration is chosen using dynamic analysis of both blade and test setup.

Rotor diameters of wind turbines installed in 2017 ranged from 48 to 180 meters. The maximum rotor diameter was 142 meters for onshore wind turbine and 180 meters for offshore (Fraunhofer IEE, 2017). In this study, two representative blade models were selected to represent current onshore and offshore wind turbine rotor blades, shown as blue dots on the scaled trend in Fig. 7. Blades that have been tested at Fraunhofer IWES are also shown in red dots in Fig. 7. Table 1 lists the frequency information of two representative blade models.

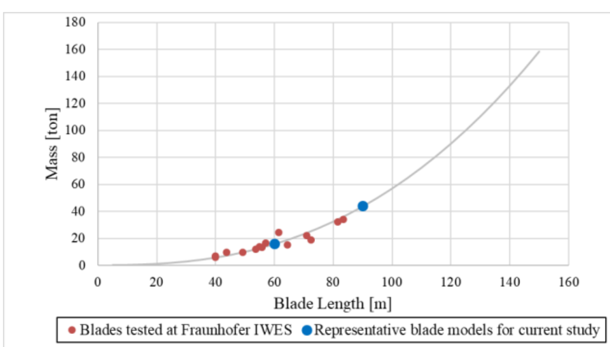
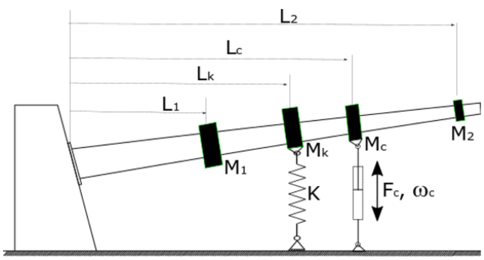


Figure 7. Scaled trend of blade mass and length

Table 1. Representative blade models

Blade length [m]	Test frequency in flap [Hz]	Test frequency in lead-lag [Hz]
60	0.71	0.86
90	0.49	0.82

FE beam models of the blades were used for numerical simulation in ANSYS Workbench 18.1 in order to find the optimal test configuration. Fig. 8 shows a schematic representation of the fatigue test model in flap direction and design variables for optimization analysis. Up to four load frames are included at varying positions along the blade. Each load frame has an associated mass that can be used to tune the frequency and dynamic bending moment distribution. One load frame also acts as the connecting point for a ground-based actuator. Frequency and force amplitude of the actuator can be changed as part of the test configuration. Furthermore, a spring element can be connected to one of the load frames to further modify the system stiffness and natural frequency.



L_1, L_2, L_k, L_c	Location of load frame (m)
M_1, M_2, M_k, M_c	Mass of load frame (kg)
K	Spring stiffness (N/m)
F_c	Sinusoidal force (N)
ω_c	Actuator frequency (Hz)

Figure 8. Schematic representation of the root segment fatigue test setup

The ranges and constraints of given parameters are listed in Table 2 and Table 3.

Table 2. Range of variable input parameters

Variable inputs	Lower bound	Upper bound
L_1	L_{cr} [m]	$(L_{100}+L_{cr})/2$ [m]
L_2	$(L_{100}+L_{cr})/2$ [m]	L_{100} [m]
L_k, L_c	L_{cr} [m]	L_{100} [m]
M_1, M_2	0 [kg]	7000 [kg]
M_k, M_c	500 [kg]	7000 [kg]
ω_c	$0.9\times\omega_1$	$1.1\times\omega_1$

K	0 [N/m]	300×10^3 [N/m]

∗ L_{cr} : Critical location, L_{100} : Location of blade tip, ω_1 : 1st eigenfrequency

Table 3. Range of constrained parameters

Contrained parameters	Upper bound
F_c	100 [kN]
F_k	100 [kN]
D_c	1.3 [m]

∗ F_c: Cylinder actuator force amplitude, ∗ F_k : Spring force, ∗ D_c : Cylinder actuator displacement amplitude

By varying all parameters mentioned above, the system response can be modified to find an optimal test setup. The target function for the optimization process was set to maximize the excitation frequency, while keeping the overload of the bending moment distribution between 0% and 5% for flap and between 0% and 10% for lead-lag test, respectively.

$$\text{Goal: Max}(\omega_c) \qquad \text{Eq. (1)}$$

$$\text{Constraints: } 0 \leq \text{Overload}\left\{{}^{(\mathrm{M}-\mathrm{M}_0^*)}/_{\mathrm{M}_0^*}\right\} \leq 0.05\ (\text{flap}), 0.1\ (\text{lead lag}) \qquad \text{Eq. (2)}$$

In Eq. (1) and Eq. (2), M is the bending moment calculated from the segment blade fatigue simulation, and M_0* is the target bending moment of the full-scale blade. It has to be noted that the constraints are only set for an area of interest, which is defined as ranging from 5% to 50% of the relative blade length for blade root segment, and from division point up to the relative blade length of 90% in case of blade tip segment.

In order to reduce the computational effort for the optimization, harmonic analysis is used to avoid calculations in the time domain. For the current study, the full harmonic method based on nodal coordinates is used to apply the prescribed displacements support to simulate the realistic test environments at a specific test frequency (ω_c) within the range listed in Table 2, and beta damping is used for damping model. As a result, optimization calculations with a large number of individual cases are feasible. Comparison with computations in the time domain (transient analysis) have shown that the error introduced by this approach is small. The sequence of this test optimization is shown in Fig. 9. The optimization problem is solved using internal optimization routines provided in ANSYS Workbench. Both gradient based methods and genetic algorithms have proven to give similar results. The optimization parameter used in MOGA (Multi-Objective Genetic Algorithm) is listed in Table 4.

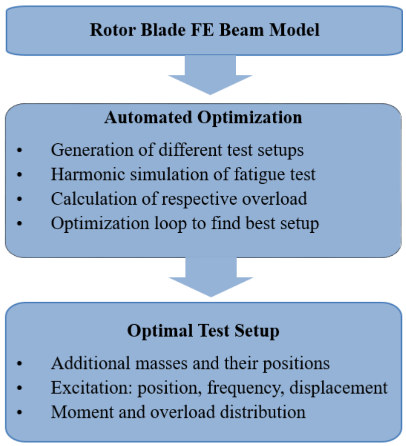


Figure 9. Simulation procedure for test optimization

Table 4. Optimization parameters in MOGA

Optimization parameter	Value
Number of initial samples	1000
Number of samples per iteration	50
Maximum number of iterations	20

Considering only the pure execution time, test duration can directly be calculated from the actuator frequency and the cycle time. For all considerations in this paper, the number of cycles of the fatigue test are assumed to be 3 million cycles for lead-lag fatigue test and 1 million cycles for flap fatigue test. The test quality is assessed based on the overloading of calculated bending moments over target bending moments. As addressed above, the overloading is restricted to below 5% for flap fatigue test and 10% for lead-lag fatigue test in the area of interest.

3 Feasibility assessment of segment blade fatigue test

Optimized test setups were calculated for the 60m and 90m reference blades using the target functions and optimization constraints above. Test duration and quality as estimated from the numerical simulation is used to evaluate the feasibility of segment blade fatigue tests.

3.1 Test time

The segment blade tests imply parallel testing of root and tip segments. Due to the limitation of root segment length and its lower test frequency than the tip segment, the root segment test is only considered as total fatigue test duration. In a first step, the optimization was conducted without incorporating spring elements. Fig. 10 shows the normalized fatigue test times for root segment tests at varying segment lengths (60%, 70%, 80%, and 100%) of the two blades (60m and 90m) obtained from optimization process stated in section 2.2. In comparison to the full-length test, the segment test can reduce the test time down up to 67% and 64% for the 60m and 90m blade, respectively. Test time reduction was found to be larger for the 90m blade. Blade separations at 60% of the blade length or shorter did not converge in the optimization, as the criterion for the overload was not matched. This can be explained by the fact that no dummy element as suggested in Fig. 6 was included in the simulations.

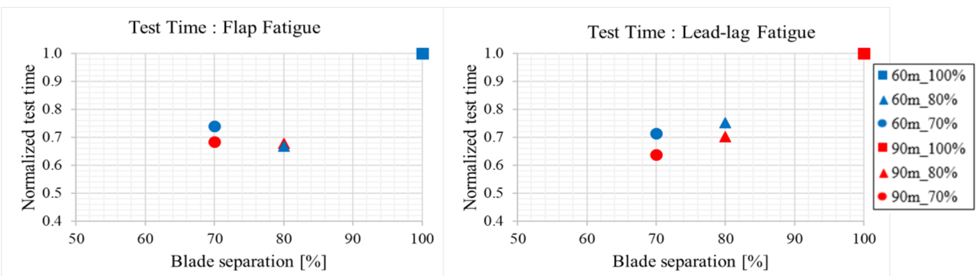


Figure 10. Normalized fatigue test time of blade root segments

For the flap fatigue, test time of the 70% root segment is higher than the 80% root segment test time. This is due to the heavy masses added at the outboard of the root segment to meet the target bending moment as explained above.

Figure 11 and Figure 12 show the numerical results from the fatigue test models of 60m and 90m segment blades with spring elements in comparison to those without spring elements. Depending on the separation point and test direction, the test duration can be reduced by up to 42% more than test cases without stiffness elements. The achievable effects in the lead-lag direction are particularly large.

메모 포함[하8]: Response on major question #2-2
Experimental test time was not plotted in Fig. 10.
Test time between experiment and optimization results was already mentioned in Fig. 3. The difference was about 4%. So for better visualization, it was not plotted.

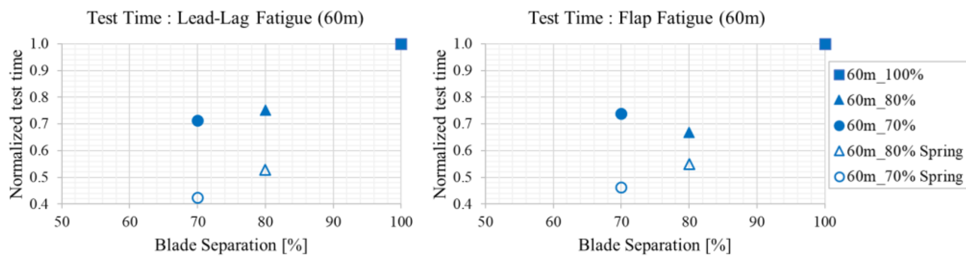


Figure 11. Effect of spring elements on fatigue test time of 60m blade root segment

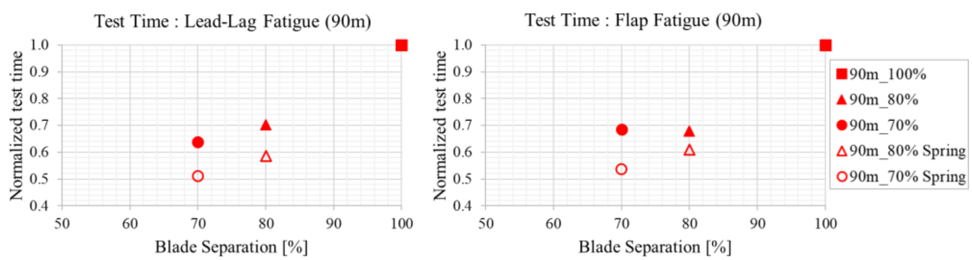


Figure 12. Effect of spring elements on fatigue test time of 90m blade root segment

3.2 Test quality

Figure 13 shows the overload comparison from the fatigue test in the lead-lag direction of the 60m full-scale blade with segment blades with 100%, 80% and 70% separation point, respectively. It shows that optimized segment blade fatigue tests apparently achieve better test quality compared to the traditionally performed full-scale blade case having about 20% overload. It should be remined that optimization of 70% segment test shows 30% reduced test time than a 100% full-length blade optimization though maximum overload values are quite similar to each other due to the overload constraints in optimization process.

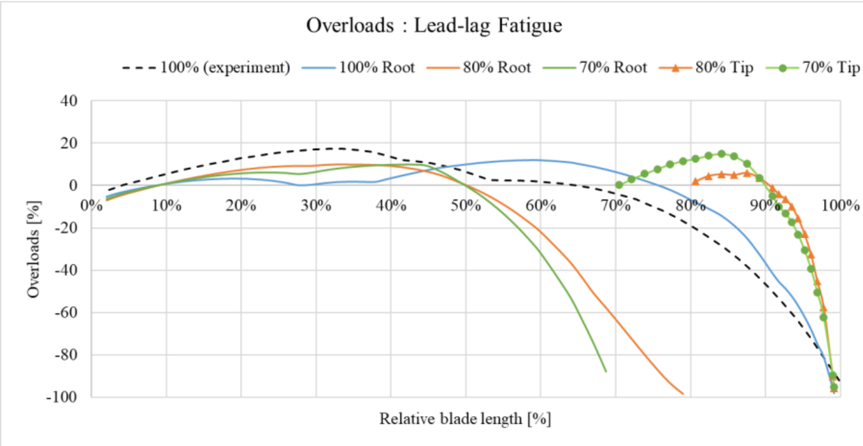


Figure 13. Overloads comparison in lead-lag fatigue of 60m blade (full-scale vs. segment)

In the experimental test of a full-length blade, where all areas are tested simultaneously and at the same frequency, the possibility of sufficiently examining the total blade area is pretty much limited to 65% of the blade length as shown in. The fatigue test of tip segment, however, covers the area from separation point to 90% of blade length sufficiently. If special interest between 50% and 70% are required, a significantly greater manufacturing outlay like overlapping segments needs to be performed at the separation point of root segment or a blade dummy representing mass and moment inertia of the tip segment could be fixed to the free end of root section as shown in Fig. 6.

Figure 14 shows the visual comparison of the lead-lag fatigue test setups and under-stressed areas from experimental full-length test with the optimized segment test setup obtained from simulation results. The under-stressed areas are not certifiable because the target moments were not achieved during fatigue testing. While it is not possible to conclude that the overall area of certifiable regions is significantly increased in the segment blade test, this methodology is able to target regions in a larger range of locations along the blade. Depending on the specific blade design and location of critical regions, this could pose a significant advantage in the certification process.

메모 포함[하9]: Response on major question #3
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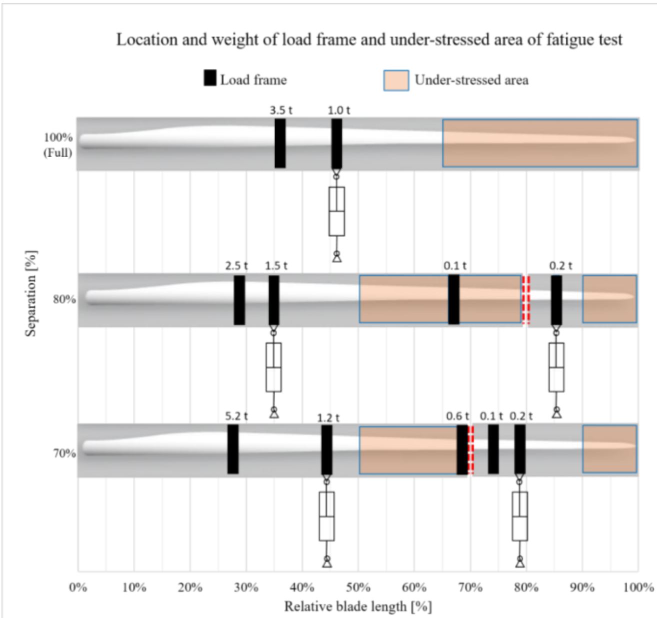

Figure 14. Comparison of test setups and under-stressed areas (60m blade, lead-lag fatigue test)

4 Conclusions

In this study, a blade division through the separation point at 60% of the blade length or further toward blade root was not feasible without additional structures such as cantilever structure or stiffness elements, since the test quality is poor due to its high overloads. However, he proposed segment test methodology showed the reduction of the total fatigue test time incorporating both flap and lead-lag test up to 72% and 65% for 60m blade and 90m blade, respectively, and further reduction to 43% and 52% with an additional stiffness element in case of 70% segment blade fatigue test compared to full-length fatigue test duration (100%).

The study also showed lower overloads in the areas of interest, compared to the full-length test. Furthermore, it was demonstrated that sufficient loading of the tip section can be achieved. It has to be noted that the optimization goal was to minimize execution time. Using the same numerical models, it is also possible to optimize the setup with respect to minimizing the overload. While this may lead to an increase in test time, it is likely that a larger certifiable region or lower overloads are obtainable.

In conclusion, the study is indicating that segment testing is an effective approach to reduce the duration and increase the test quality of full-scale blade tests – increasingly so for larger turbine blades.

Author contributions. KH compiled the literature review, performed numerical simulations, post-processed the data, and wrote the bulk of the paper. MB helped formulate the ideas in the regular discussions. DM perfomend numeric simulations and supported the optimization analysis. SC participated in structuring and review of the paper.

Data availability. The data that supports the finding of this research are not publicly available due to confidentiality constraints.

Competing interests. The authors declare that they have no conflict of interest.

5 Acknowledgements

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메모 포함[하1]: Correction

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- Fatigue load tests
- Post fatigue static tests

Among all structural tests, the fatigue load test is the most time-consuming process, and therefore this step accounts for most of the test cost involved. It is executed either in the flap or lead-lag direction independently, or simultaneously in both directions. Due to the large mass and low stiffness of the blades, test operating frequencies are very low, especially for flap fatigue tests. Therefore, fatigue tests take up to several months to accomplish the required cycle count of 1 to 5 million cycles, depending on the blade characteristics (Wingerde et al., 2015; Post, 2016). As blades are getting longer and bigger, both test time and costs increase significantly - especially for future offshore blade measuring more than 100m in length. Also, testing facilities for 100m+ blades are very limited at this moment. Hence, a reduction in test time and utilizing available test halls are important to accelerate the development cycle of future offshore turbines with 100m+ blades.

In this paper, a novel segment test methodology for wind turbine rotor blades is proposed and its benefits are investigated with a numerical simulation. The proposed test methodology decouples a blade root segment and a tip segment to improve test quality and minimize test time by performing both segment tests independently in parallel while meeting the original target bending moment within specific overload limit (5% for flap direction and 10% for lead-lad direction). Two representative blade models, a 60m onshore blade and a 90m offshore blade was used for numerical simulation to compare the fatigue test time and the test quality of segment blades with full-scale blades in ANSYS APDL and ANSYS Workbench 18.1 (ANSYS, 2018).

2 Segment blade test methodology

Since the tip portion of the blade is generally not very critical in terms of structural damage, the blade tip is sometimes removed during fatigue testing in order to reduce energy consumption and test time. This can also be done if space in the testing facility is limited. (Spera, 2009; Al-Khudairi et al., 2017; White, 2004). The segment blade test takes this approach a step further and divides the Device under Testing (DUT) into a root and a tip segment as shown in Fig. 1, which can then be tested in parallel.

2.1 Differences between full-length and segment testing

The segment testing procedure remains essentially unchanged compared to the full-length blade test. However, there are several important differences in the test preparation and execution that have to be considered.

메모 포함[하2]: Better correction. Thanks.

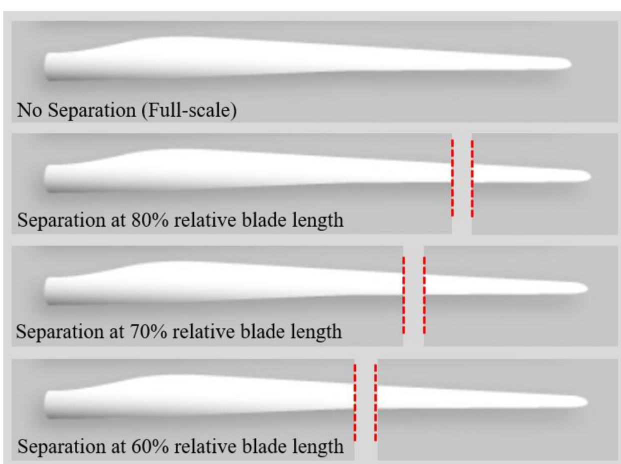


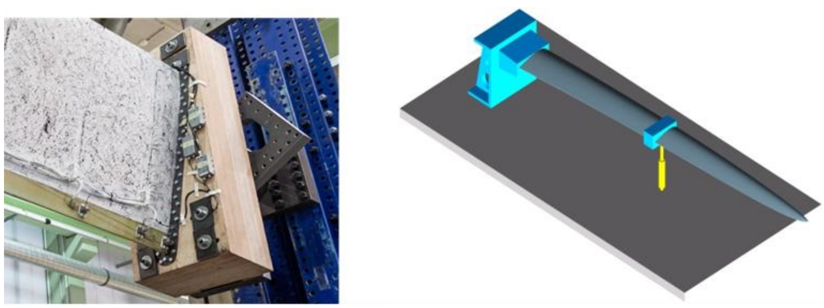
Figure 1. Schematic representation of a blade with different separation points

It is assumed that design-critical areas are not located near the separation points. If the areas of the separation point are to be verified in the test, a significantly greater manufacturing outlay arises, as overlapping segments have to be produced. In this work, the assumption applies that the separation point does not lie in one of the critical areas (Brondsted et. al, 2013). Special care has to be taken when cutting the blade to produce reliable segment blades without any defect. However, this aspect is not considered in this study (Skelton, 2017).

The expense of equipping the rotor blade with test-specific measurement sensors does not change significantly as a result of the segmentation. However, since the blade tip test time is much shorter than the blade root test due to the higher test frequencies, the preparation work for the tip segment can be postponed. In other words, after the blade root test is prepared and started, preparation work with the blade tip segment can be executed. In this way, additional time can be saved in the overall process of the test.

In order to improve transportability, some modern onshore blades are already produced in a modular design, where two halves are produced that are joined on the wind farm site. For these blades, the tip already has a connection to mount the tip segment to the test stand. If the blade is only separated for test purposes, the tip segment, unlike the root segment, has no prefabricated connection for mounting to the test stand. In this case, the mounting test stand must be fabricated for the tip segment. There are several possible solutions. One solution is that the segment can be clamped by two fixed load frames arranged one behind the other. However, this leads to a reduction of the test area. Fraunhofer IWES has developed and validated an alternative fixture concept. The structure to be tested is glued firmly into a wooden frame, whereby the immediate connection point is reinforced by steel sheets (Rosemeier et. al, 2018). Fig. 2 (a) shows this connection technology used in the application of a trailing edge subcomponent test, and Fig. 2 (b) shows the connection design of the tip segment to the test bench as part of the entire test setup without additional masses. Depending on the length of the tip segment, the bonding depth to the load frame may vary to sustain the maximum strength at the clamping area.

메모 포함[하3]: Correction



(a) Load frame for blade subcomponent test (b) Connection design for blade tip segment

Figure 2. Solutions for mounting blade tip segment to the test stand

During the conventional fatigue test, the rotor blade is usually more stressed in the area near the root than in the area of the blade tip compared to the target loads. As an example, Fig. 3 shows an experimental overload distribution and an optimized overload distribution of a 60m blade in the lead-lag fatigue test. As a result of experimental fatigue test, the inboard areas of the rotor blade have already experienced the calculated loads from 20 years of life, but the test must continue to sufficiently load the under-stressed areas over 65% of blade length. Due to this "over-testing" or "over-stressing" of the inboard blade area, structural damage increasingly occurs towards the end of the test, which must be inspected and if necessarily, repaired (DNV-GL, 2015). This can result in delays of several weeks in the process. The numerical optimization of a full-length blade fatigue test setup resulted in a better and reduced overload distribution as shown in Fig. 3, but it still shows under-stressed areas after 75% of blade length. Most of all, the increased test time (reverse of test frequency) cannot be ignored as a future offshore blade is getting bigger. Details of an optimization process will be addressed in section 2.2.

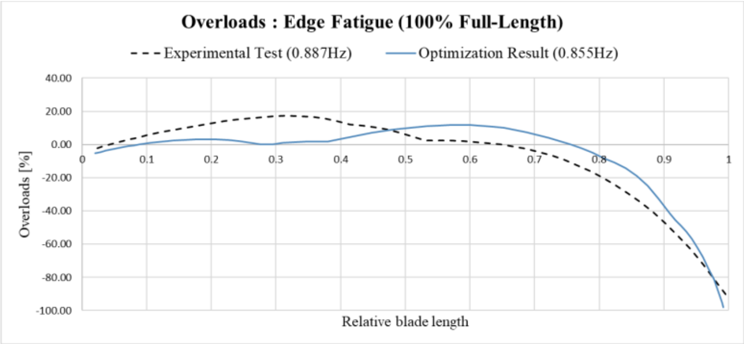


Figure 3. Overloads distribution from the full-scale lead-lag fatigue test of 60m blade

Segment test offers a major advantage regarding moment distribution over the blade length. By dividing a full-scale blade into blade root and blade tip segments, the inboard and outboard area of the rotor blade are decoupled and loaded independently, as shown in Fig. 4. From the Fig.4, the variables, M, F, and ω represent loadframe mass, force and frequency, respectively, and the subscript c represent cylinder actuator. The respective test can be stopped when the corresponding area has reached the required target loads. Also, should damage occur that necessitates repairs to the blade structure, only the respective segment test must be stopped for the inspection.

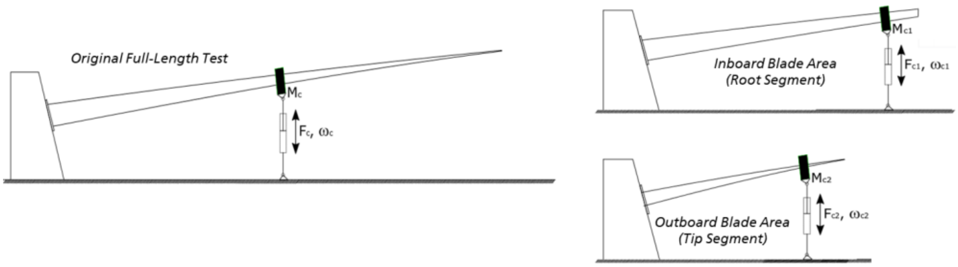


Figure 4. Comparison of blade fatigue test setup (full-length blade vs. segment blades)

A widely used method to achieve the introduction of shear forces and bending moment to approximate the bending moment distribution to the target loads is the attachment of additional masses on the blade. However, this practice leads to a drop in the test frequency (Spera, 2009; Gasch et. al, 2012). Alternatively, the bending moment distribution can be modified through artificial stiffness elements, as shown in Fig. 5 by introducing opposing forces and providing additional degrees of freedom for test quality improvement (Gere et. al, 2013). The stiffness elements can be implemented passively by mechanical or hydraulic springs or actively by hydraulic actuators (cylinders). In this model, a spring element with a maximum stiffness of 300 kN/m was implemented. In addition, the force entered by the spring into the blade was limited to 100 kN or less. Additional stiffness elements can also help to increase the systems natural frequency and reduce test time.

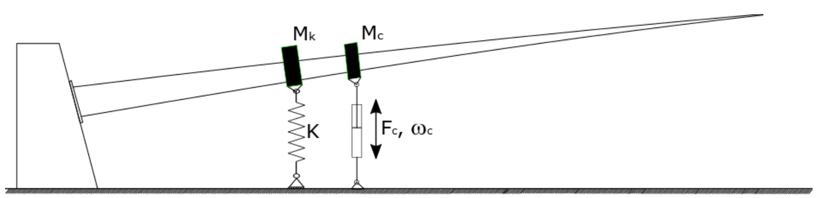


Figure 5. Spring element application to blade fatigue test setup

Naturally, the segment test must achieve the same bending moment distribution as the full-length test. However, it is intuitively obvious that the free end of the segment will experience a zero-bending moment. In order to overcome this, a blade dummy, representing mass and moment of inertia of the tip segment can be fixed to the root section as shown in Fig. 6, which is similar to the fixation of the blade tip segment to the test bench described above.

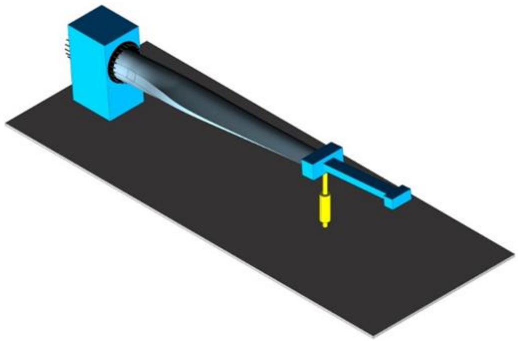


Figure 6. Cantilever structure for root segment test

2.2 Numerical model for optimization of segment test setup

Purpose of this study is to quantify the advantages of segment blade testing by comparing test setups for two different test cases. For 60m and 90m blade, an optimized test configuration is chosen using dynamic analysis of both blade and test setup.

Rotor diameters of wind turbines installed in 2017 ranged from 48 to 180 meters. The maximum rotor diameter was 142 meters for onshore wind turbine and 180 meters for offshore (Fraunhofer IEE, 2017). In this study, two representative blade models were selected to represent current onshore and offshore wind turbine rotor blades, shown as blue dots on the scaled trend in Fig. 7. Blades that have been tested at Fraunhofer IWES are also shown in red dots in Fig. 7. Table 1 lists the frequency information of two representative blade models.

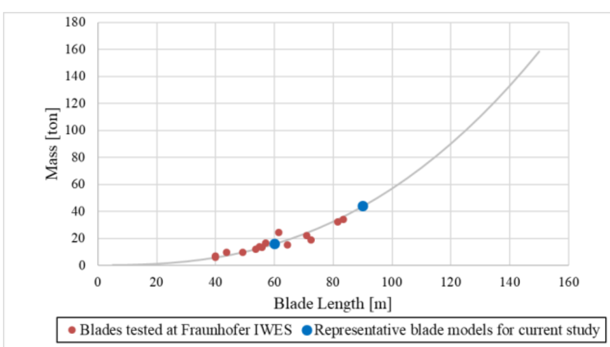
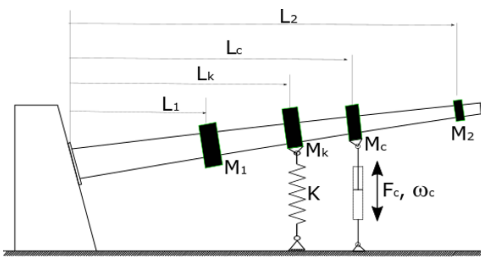


Figure 7. Scaled trend of blade mass and length

Table 1. Representative blade models

Blade length [m]	Test frequency in flap [Hz]	Test frequency in lead-lag [Hz]
60	0.71	0.86
90	0.49	0.82

FE beam models of the blades were used for numerical simulation in ANSYS Workbench 18.1 in order to find the optimal test configuration. Fig. 8 shows a schematic representation of the fatigue test model in flap direction and design variables for optimization analysis. Up to four load frames are included at varying positions along the blade. Each load frame has an associated mass that can be used to tune the frequency and dynamic bending moment distribution. One load frame also acts as the connecting point for a ground-based actuator. Frequency and force amplitude of the actuator can be changed as part of the test configuration. Furthermore, a spring element can be connected to one of the load frames to further modify the system stiffness and natural frequency.



L_1, L_2, L_k, L_c	Location of load frame (m)
M_1, M_2, M_k, M_c	Mass of load frame (kg)
K	Spring stiffness (N/m)
F_c	Sinusoidal force (N)
ω_c	Actuator frequency (Hz)

Figure 8. Schematic representation of the root segment fatigue test setup

The ranges and constraints of given parameters are listed in Table 2 and Table 3.

Table 2. Range of variable input parameters

Variable inputs	Lower bound	Upper bound
L_1	L_{cr} [m]	$(L_{100}+L_{cr})/2$ [m]
L_2	$(L_{100}+L_{cr})/2$ [m]	L_{100} [m]
L_k, L_c	L_{cr} [m]	L_{100} [m]
M_1, M_2	0 [kg]	7000 [kg]
M_k, M_c	500 [kg]	7000 [kg]
ω_c	$0.9\times\omega_1$	$1.1\times\omega_1$

K	0 [N/m]	300×10^3 [N/m]

∗ L_{cr} : Critical location, L_{100} : Location of blade tip, ω_1 : 1st eigenfrequency

Table 3. Range of constrained parameters

Contrained parameters	Upper bound
F_c	100 [kN]
F_k	100 [kN]
D_c	1.3 [m]

∗ F_c: Cylinder actuator force amplitude, ∗ F_k : Spring force, ∗ D_c : Cylinder actuator displacement amplitude

By varying all parameters mentioned above, the system response can be modified to find an optimal test setup. The target function for the optimization process was set to maximize the excitation frequency, while keeping the overload of the bending moment distribution between 0% and 5% for flap and between 0% and 10% for lead-lag test, respectively.

$$\text{Goal: Max}(\omega_c) \qquad \text{Eq. (1)}$$

$$\text{Constraints: } 0 \leq \text{Overload}\left\{{}^{(\mathrm{M}-\mathrm{M}_0^*)}/_{\mathrm{M}_0^*}\right\} \leq 0.05\ \text{(flap)}, 0.1\ \text{(lead lag)} \qquad \text{Eq. (2)}$$

In Eq. (1) and Eq. (2), M is the bending moment calculated from the segment blade fatigue simulation, and M_0* is the target bending moment of the full-scale blade. It has to be noted that the constraints are only set for an area of interest, which is defined as ranging from 5% to 50% of the relative blade length for blade root segment, and from division point up to the relative blade length of 90% in case of blade tip segment.

In order to reduce the computational effort for the optimization, harmonic analysis is used to avoid calculations in the time domain. For the current study, the full harmonic method based on nodal coordinates is used to apply the prescribed displacements support to simulate the realistic test environments at a specific test frequency (ω_c) within the range listed in Table 2, and beta damping is used for damping model. As a result, optimization calculations with a large number of individual cases are feasible. Comparison with computations in the time domain (transient analysis) have shown that the error introduced by this approach is small. The sequence of this test optimization is shown in Fig. 9. The optimization problem is solved using internal optimization routines provided in ANSYS Workbench. Both gradient based methods and genetic algorithms have proven to give similar results. The optimization parameter used in MOGA (Multi-Objective Genetic Algorithm) is listed in Table 4.

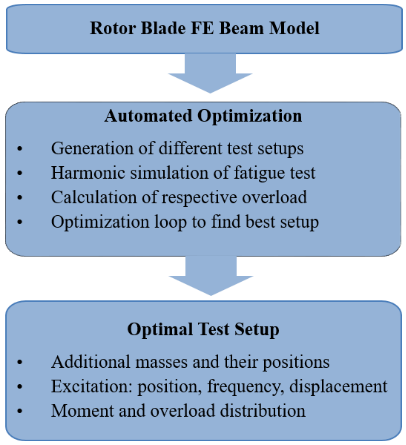


Figure 9. Simulation procedure for test optimization

Table 4. Optimization parameters in MOGA

Optimization parameter	Value
Number of initial samples	1000
Number of samples per iteration	50
Maximum number of iterations	20

Considering only the pure execution time, test duration can directly be calculated from the actuator frequency and the cycle time. For all considerations in this paper, the number of cycles of the fatigue test are assumed to be 3 million cycles for lead-lag fatigue test and 1 million cycles for flap fatigue test. The test quality is assessed based on the overloading of calculated bending moments over target bending moments. As addressed above, the overloading is restricted to below 5% for flap fatigue test and 10% for lead-lag fatigue test in the area of interest.

3 Feasibility assessment of segment blade fatigue test

Optimized test setups were calculated for the 60m and 90m reference blades using the target functions and optimization constraints above. Test duration and quality as estimated from the numerical simulation is used to evaluate the feasibility of segment blade fatigue tests.

3.1 Test time

The segment blade tests imply parallel testing of root and tip segments. Due to the limitation of root segment length and its lower test frequency than the tip segment, the root segment test is only considered as total fatigue test duration. In a first step, the optimization was conducted without incorporating spring elements. Fig. 10 shows the normalized fatigue test times for root segment tests at varying segment lengths (60%, 70%, 80%, and 100%) of the two blades (60m and 90m) obtained from optimization process stated in section 2.2. In comparison to the full-length test, the segment test can reduce the test time down up to 67% and 64% for the 60m and 90m blade, respectively. Test time reduction was found to be larger for the 90m blade. Blade separations at 60% of the blade length or shorter did not converge in the optimization, as the criterion for the overload was not matched. This can be explained by the fact that no dummy element as suggested in Fig. 6 was included in the simulations.

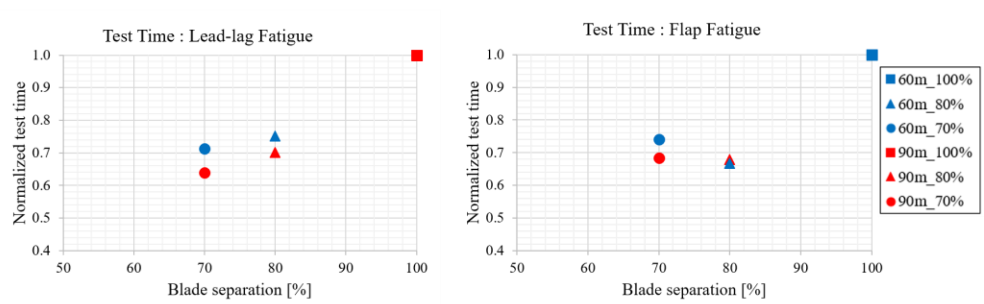


Figure 10. Normalized fatigue test time of blade root segments

For the flap fatigue, test time of the 70% root segment is higher than the 80% root segment test time. This is due to the heavy masses added at the outboard of the root segment to meet the target bending moment as explained above. For the lead-lag fatigue, test time of the 70% root segment is lower than 80% root segment time because root segment is stiffer over the whole blade length in lead-lag direction than in flap direction, which require less masses at the outboard of the root segment to generate target curvature at the outboard of the root segment.

Figure 11 and Figure 12 show the numerical results from the fatigue test models of 60m and 90m segment blades with spring elements in comparison to those without spring elements. Depending on the separation point and test direction, the test duration can be reduced up to 43% for a 60m blade and 52% for a 90m blade more than full-length test case without stiffness elements. The achievable effects in the lead-lag direction are particularly large.

메모 포함[하4]: Reply to comment #6
Swich the figures like Fig. 11 and Fig. 12

메모 포함[하5]: Reply to comment #3

메모 포함[하6]: Reply to comment # 4 and # 5
% relative to full-length case both for 60m and 90m

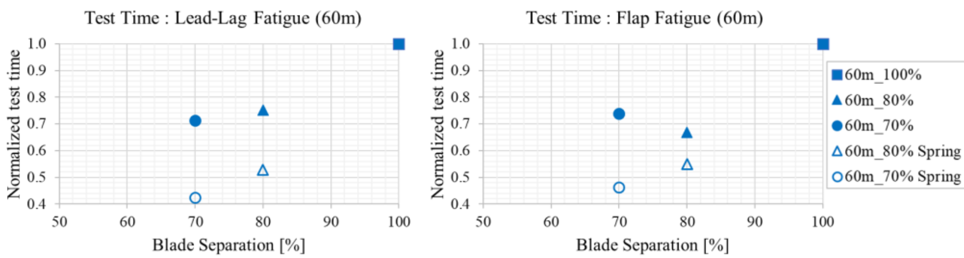


Figure 11. Effect of spring elements on fatigue test time of 60m blade root segment

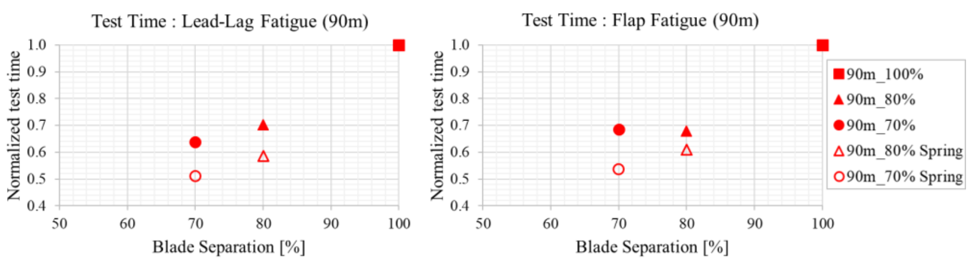


Figure 12. Effect of spring elements on fatigue test time of 90m blade root segment

3.2 Test quality

Figure 13 shows the overload comparison from the fatigue test in the lead-lag direction of the 60m full-scale blade with segment blades with 100%, 80% and 70% separation point, respectively. It shows that optimized segment blade fatigue tests apparently achieve better test quality compared to the traditionally performed full-scale blade case having about 20% overload. It should be remined that optimization of 70% segment test shows 30% reduced test time than a 100% full-length blade optimization though maximum overload values are quite similar to each other due to the overload constraints in optimization process.

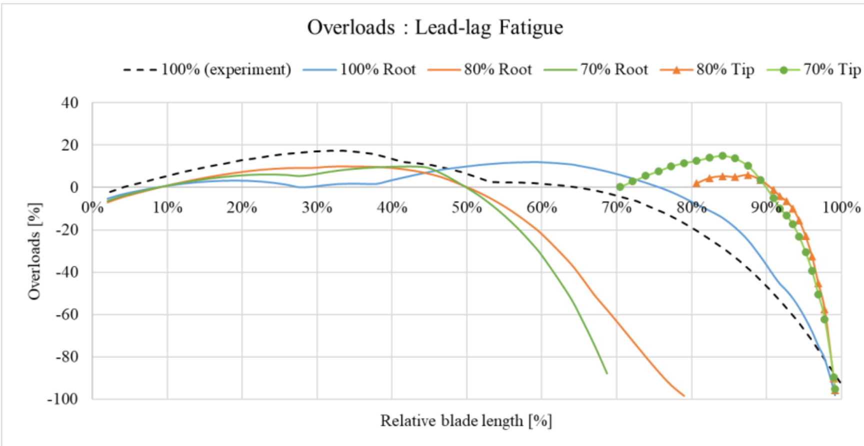


Figure 13. Overloads comparison in lead-lag fatigue of 60m blade (full-scale vs. segment)

In the experimental test of a full-length blade, where all areas are tested simultaneously and at the same frequency, the possibility of sufficiently examining the total blade area is pretty much limited to 65% of the blade length as shown in. The fatigue test of tip segment, however, covers the area from separation point to 90% of blade length sufficiently. If special interest between 50% and 70% are required, a significantly greater manufacturing outlay like overlapping segments needs to be performed at the separation point of root segment or a blade dummy representing mass and moment inertia of the tip segment could be fixed to the free end of root section as shown in Fig. 6.

Figure 14 shows the visual comparison of the lead-lag fatigue test setups and under-stressed areas from experimental full-length test with the optimized segment test setup obtained from simulation results. The under-stressed areas are not certifiable because the target moments were not achieved during fatigue testing. While it is not possible to conclude that the overall area of certifiable regions is significantly increased in the segment blade test, this methodology is able to target regions in a larger range of locations along the blade. Depending on the specific blade design and location of critical regions, this could pose a significant advantage in the certification process.

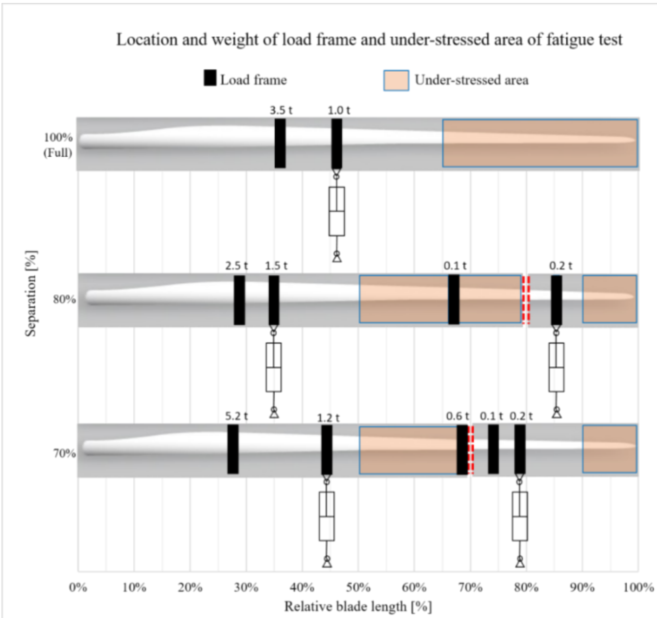


Figure 14. Comparison of test setups and under-stressed areas (60m blade, lead-lag fatigue test)

4 Conclusions

This paper proposed a novel segment test methodology for wind turbine rotor blades which mainly aims at improving the efficiency of the fatigue test as a future test method at Fraunhofer IWES. From this study, a blade division through the separation point at 60% of the blade length or further toward blade root was not feasible without additional structures such as cantilever structure or stiffness elements, since the test quality is poor due to its high overloads. However, the proposed segment test methodology showed the reduction of the total fatigue test time incorporating both flap and lead-lag test up to 72% and 65% for 60m blade and 90m blade, respectively, and further reduction to 43% and 52% with an additional stiffness element in case of 70% segment blade fatigue test compared to full-length fatigue test duration (100%).

The study also showed lower overloads in the areas of interest, compared to the full-length test. Furthermore, it was demonstrated that sufficient loading of the tip section can be achieved. It has to be noted that the optimization goal was to minimize execution time. Using the same numerical models, it is also possible to optimize the setup with respect to minimizing the overload. While this may lead to an increase in test time, it is likely that a larger certifiable region or lower overloads are obtainable.

메모 포함[하7]: Reply to comment #7
Added a short paragraph explaining the purpose of the study

메모 포함[하8]: Correction

In conclusion, the study is indicating that segment testing is an effective approach to reduce the duration and increase the test quality of full-scale blade tests – increasingly so for larger turbine blades.

Author contributions. KH compiled the literature review, performed numerical simulations, post-processed the data, and wrote the bulk of the paper. MB helped formulate the ideas in the regular discussions. DM performed numeric simulations and supported the optimization analysis. SC participated in structuring and review of the paper.

Data availability. The data that supports the finding of this research are not publicly available due to confidentiality constraints.

Competing interests. The authors declare that they have no conflict of interest.

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