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# COMPONENT FATIGUE TEST FACILITIES FOR FULL-SCALE LP STEAM TURBINE END STAGE BLADES

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## ABSTRACT

In connection with the energy transition, the demand for large steam turbines for power plant applications and their efficiency has significantly increased over the last years. Due to an increased injection of renewable energy sources, operational flexibility of power plants is getting more and more important. Robust low-pressure (LP) end stage blades are one of the key components and a crucial success factor to meet current and future market requirements and to master challenges associated.

In operation, LP end stage blades are exposed to high and complex mechanical loads. Against the background of increasing operational flexibility of power plants associated with a higher number of load cycles, reliable and verified design methods are essential for designing LP end stage blades and their structural integrity assessment. Supporting this purpose, several fatigue test facilities for full-scale LP end stage blades were established at Siemens recently. Besides the determination of component fatigue strength and the validation of the design procedure, the tests serve as part of up-front validation, minimizing risk for first time implementation of newly developed as well as next generation blades, and demonstrating operational robustness of the existing fleet.

This paper describes the development and setup of fatigue test facilities for LP steam turbine end stage blades at Siemens and the successful execution of component tests with focus on High-Cycle Fatigue (HCF) regime. Results for blades of different sizes, surface conditions and materials have been evaluated. In addition, crack growth and threshold behaviour of blades has been investigated in detail. Based on the test results, validation of the corresponding design methods has been performed.

## INTRODUCTION

The need for large steam turbines for fossil power plant applications significantly increased over the last years and will increase further in the future. In the past, fossil-powered plants have usually been operated as base load power plants (full load over a long period). Enhancements were mainly driven by power and efficiency increase under full load, reliability, and a growing number of operating hours.

Connected to the energy transition, associated with increased and fluctuating injection of renewable energy, operational flexibility of power plants is becoming more and more important. Additional challenges arise from the increasingly flexible operation of fossil power plants. The main challenges are high efficiency under part load, higher number of load cycles, higher load gradients, and shorter start-up times. Therefore, reliable and robust turbines have to be designed. As one of the key components, LP steam turbine end stage blades are the crucial success factor to meet current and future market as well as customer requirements, and to master challenges associated to this.

The design of turbine blades is complex. In operation, end stage blades of LP turbines are often exposed to high and complex mechanical load regimes. These loads lead to high stresses, often resulting in fatigue lifetime consumption. Manufacturers of large turbines for power plant applications usually cannot test their turbines and corresponding components in test facilities in advance. In addition, design faults could lead to failure of the components in operation and to substantial commercial damages. Because of these reasons, appropriate, reliable, and verified design methods and guidelines are essential for the development and design of LP turbine end stage blades. Their lifetime prediction and structural integrity assessment, enabling reliable operation of turbine blades over the entire life cycle of the power plant, is attached to these design methods and guidelines. In particular, this applies for describing precisely fatigue phenomena, i.e. Low-Cycle Fatigue (LCF) and HCF, and component (including the connection between blade root and rotor groove) behaviour under operating loads.

For large turbine blades, especially for LP steam turbine end stage blades, lengths up to 1800 mm and mass up to 330 kg result in huge centrifugal forces up to 15 MN per blade. Efficiency increase and power plant optimization yield to larger turbine outlet areas associated with larger LP turbine end stage blades. In addition, high mass flow and pressure yield to high steam bending forces.

Cyclic stresses mainly originating from variable centrifugal forces during start-up and shutdown have to be assessed against LCF criteria. The criteria for airfoil vibration induced by changing steam-driven bending forces are HCF/ endurance limit criteria.

Figure 1 shows the typical loading conditions of an LP end stage blade in real operation schematically.

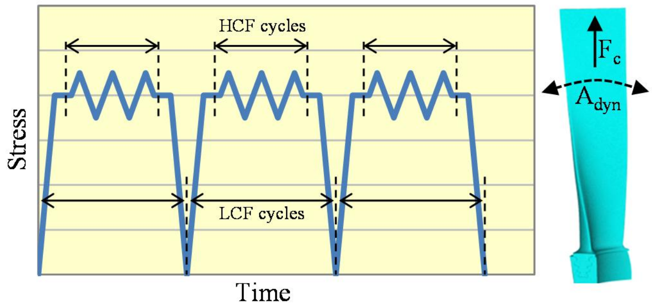


**Figure 1: Typical loading conditions of LP blades**

In order to develop and set up testing environments suitable for LP end stage blades, the following existing test facilities have been analysed.

In the past, efforts have been made within the framework of FVV (German Research Association for Combustion Engines) to investigate the fatigue behaviour using small-scale T-shaped specimens [1]. The T-specimen, see Figure 2a, represents the notch radius of a blade root. Under axial and bending loads, a similar local stress gradient as in a real blade root is ensured. However, the blade-to-rotor connection cannot be examined with this setup (Figure 2b).

Another biaxial test facility is reported in [2]. Here, combined-cycle-fatigue (CCF) behaviour of gas turbine blades in high temperature environment has been analysed using specifically designed specimens with a transition radius representing the critical location for crack initiation of a gas turbine blade. Excitation for HCF load was achieved using a shaker. With this test setup, the connection between blade root and rotor groove cannot be considered either.

The main challenge of setting up suitable test facilities is the appropriate application of huge centrifugal forces in combination with bending loads on full-scale components to simulate real operating conditions.

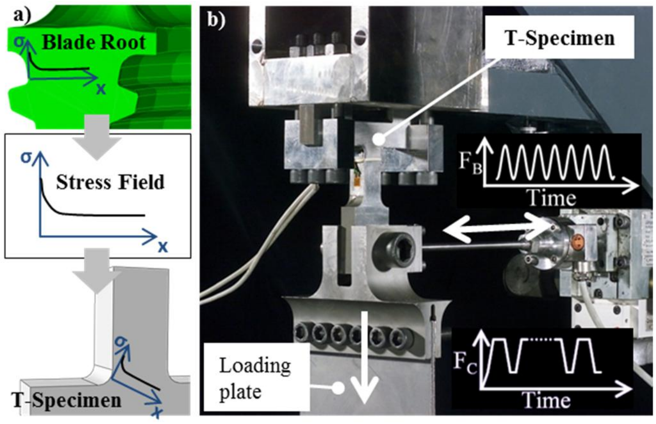


**Figure 2: a) Testing principle b) Testing facility for small-scale T-specimens [1]**

This paper deals with the development and setup of several component fatigue test facilities at Siemens and the successful execution of component tests with full-scale LP steam turbine end stage blades with main focus on High Cycle Fatigue (HCF) regime. Results have been evaluated and validation of the corresponding design methods has been performed.

## COMPONENT TEST FACILITIES

Siemens has developed and established several test facilities for full-scale LP end stage blades. Focus is on HCF and LCF strength under operational loading as well as on blade-to-rotor connection.

First HCF test results are reported in [3].

### HCF component test facility

The initial purpose of the HCF component test facility was to determine the endurance limit of full-scale freestanding LP end stage blades under real operation conditions. Thereby, the requirements for the test facility were considered omitting centrifugal load. In order to ensure similar conditions compared to those in real operation, the correct dynamic stress distribution and amplitude level in the blade root have to be met. This can be achieved by the excitation of blade eigenmodes at their eigenfrequencies combined with an even more important proper clamping of the blade root. Clamping of the root is achieved by applying a constant pressure on the fir-tree root.

An extension of the test rig comprises an automated clamping pressure variation, allowing simulating the effect of start-up and shutdown cycling on the upper bearing flank of the blade root.

#### *Development and setup of the HCF test facility*

The most crucial part of the component test facility is the clamping device. The clamping device consists of a seismic block with a prismatic pocket where the two-piece groove block is assembled in. The blade is clamped between the rotor groove blocks. A hydraulic cylinder captures the pressing force, and the cylinder force is distributed via a thrust plate. Therefore, the groove blocks are lifted into the seismic block and, caused by the bevelled bearing surfaces of the blocks, shifted laterally inwards. Figure 3 depicts the test setup principle.

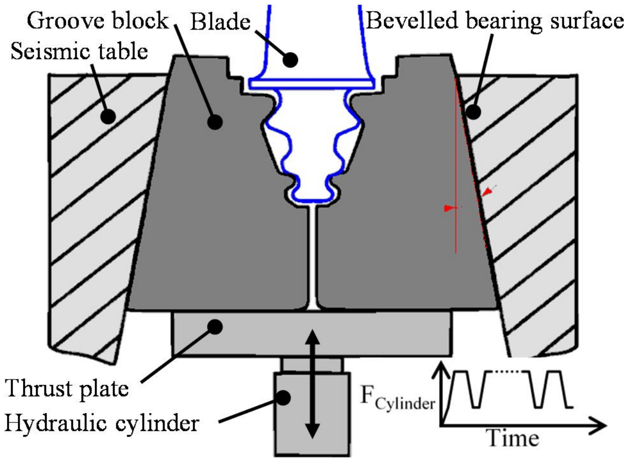


**Figure 3: Clamping device**

The interchangeable groove blocks achieve testing of each root shape and size from Siemens' portfolio of stream turbine blades.

The latest modification to the test facility is an extension regarding the clamping pressure. Now, automated loading and unloading cycles can be achieved within meaningful pressure limits. The load cycle characteristics consist of a loading ramp, holding time, a relief ramp, and another holding time at low-pressure load. The frequency of the load cycles can be adjusted to meet testing needs, e.g. to keep the entire test duration in acceptable limits.

Since the setup, consisting of several individual parts, bears difficulties regarding a proper blade assembly, highest manufacturing accuracies have to be kept. The manufacturing procedure, along with the quality assurance measures, are described in [3] in closer detail.

A lateral shaker is used to oscillate the blade at its eigenfrequency. The shaker is connected to the blade airfoil via a thrust rod and a clamping frame enclosing the airfoil. A LASER sensing device, monitoring the airfoil motion, is used for vibration amplitude controlling. During one test, the amplitude level is kept constant. If the shaker power increases during testing, a change of the eigenfrequency of the blade is likely, indicating a crack. The entire setup is depicted in Figure 4.

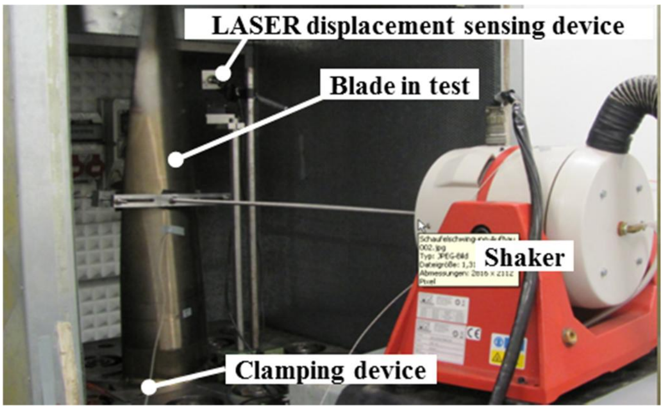


**Figure 4: HCF component test facility**

*Calibration and instrumentation*

As presented in [3], proper clamping of the blade root is indicated by a uniform contact pattern on the bearing flanks, verified by the copper foil imprint technique. An additional 3D measurement is used to prove a proper test setup. A further indication of proper clamping is the coincidence of the blade eigenfrequency in the test facility with the real, freestanding, blade eigenfrequency. The eigenfrequency is measured for various cylinder pressures to acquire a saturation curve and to confirm the appropriate static loading.

For pure HCF testing, strain gauges were applied in the upper notch above the contact surface. At the predicted crack location, a strain gauge chain was used. Here, the highest stress gradient can be found. The location of strain gauges is depicted in [3]. Data acquisition is conducted dynamically, i.e. only the alternating load (peak-to-peak) is recorded.

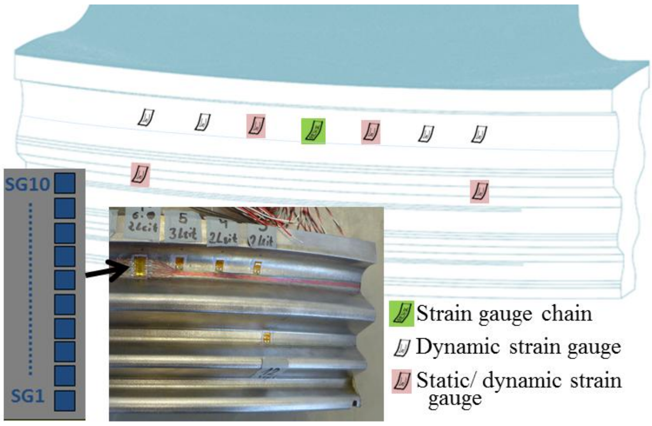


**Figure 5: Location of strain gauges at suction side**

For combined LCF pre-damage and subsequent HCF testing, the static strain level has to be determined as well. Therefore, the connection of several of the strain gauges of the HCF instrumentation was changed into a 3-wire connection, and additional strain gauges for static strain acquisition were applied between the upper and middle fir-tree root teeth. The extended instrumentation is depicted in Figure 5. The purpose of pre-damage testing is to investigate its influence on the HCF strength.

In order to verify operational capability of the test rig, the blade airfoil is excited and the foil vibration and strain amplitudes are recorded. This data is compared to the calculated figures. This calibration step is performed for every single blade. It can generally be stated that there is a good agreement of measured data and finite element (FE) results, proving a proper test setup.

The clamping pressure applied during pre-damage testing series is captured by static strain gauge measurements. During commissioning, it was observed that the static strain in the blade root was introduced properly while increasing the pressure (start-up simulation). However, during the relief phase, the strain in the root did not drop down as assumed. This behaviour could be addressed to the contact surfaces of the groove blocks and the seismic table. Here, despite of lubricating the contact faces, frictional forces led to a sticking effect, resulting in a persisting residual load. To eliminate this effect, the lubricant in the contact areas of the groove blocks and the seismic table was taken out and a PTFE interlayer was applied instead. The efficacy of this method is depicted in Figure 6, below. It can clearly be seen that during relief phases (upper part, dashed lines), the strain drops to a constant level around -10 % for the PTFE-separated test rig parts (solid red line) while there is a significant residual strain in the lubricant-separated case (starting at approximately -55 % and increasing to -90 %, solid black line). Note that the lubricant was applied to test rig parts only, i.e. not at the interface of the root to the clamping device at all.

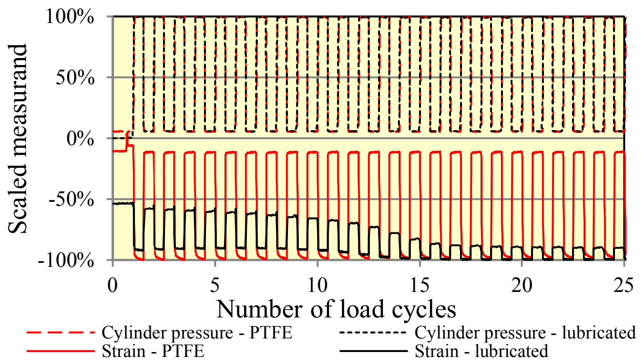


**Figure 6: Influence of lubrication on the relief behaviour**

## LCF test facility for full-scale blades

To determine the LCF strength of full-scale LP end stage blades, Siemens developed another test facility. Here, the blade root can be charged with a load similar to centrifugal forces under operation. One greater challenge was the proper clamping of the blades. Enabling the transmission of LCF forces up to 5 MN, the airfoil geometry was modified. A solid clamping device attached to the blade airfoil and a massive groove part enveloping the blade root were used to introduce the force. All parts were manufactured highly accurate to meet the quality requirements needed for proper clamping. The testing setup is shown in Figure 7.

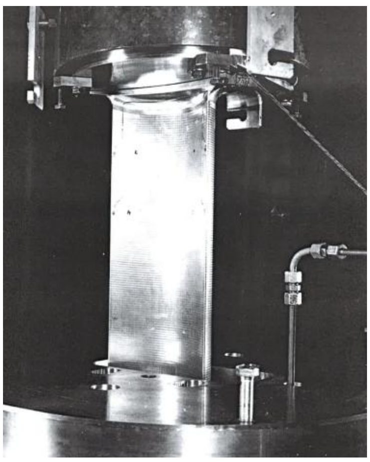

**Figure 7: LCF component test facility**

To acquire crack initiation and crack growth, strain gauges were applied in the upper root notch both at pressure and at suction side of the root. Providing an additional control mechanism, further strain gauges were installed on the blade airfoil. To calibrate the test rig, the strain amplitudes were recorded and compared to the calculated data. A near-perfect fit was achieved for the locations of stress maxima and strain levels at the location of the strain gauges.

## Test facility for blade-to-rotor connections

In order to extent testing to the interface of the root, including the groove, a third test rig was established. Again, at the regions of interest, similar loading conditions as under operation had to be kept.

For this testing program, a uniaxial testing concept was chosen. The Materials Testing Institute of the University of Stuttgart (MPA Stuttgart) was selected as outside partner.

A 3D model of the blade part and groove block is depicted in Figure 8 along with a photograph of the test pieces in the LCF testing machine at MPA Stuttgart.

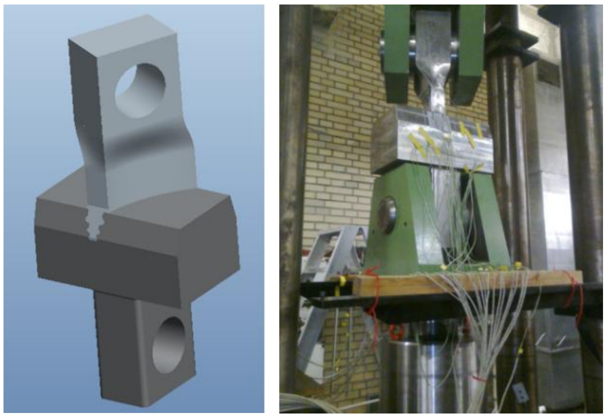

**Figure 8: 3D model and test facility for blade-to-rotor connection investigations**

The blade part was designed to ensure a proper load of the blade-to-rotor connection. Again, the manufacturing quality was essential to obtain reliable testing data.

Because of the high manufacturing accuracy and the thoughtful design, a similar strain distribution compared to real blades in operation was achieved for the tested blade roots and rotor grooves. One example is shown in Figure 9. Here, the very good agreement between operation and test facility is obvious for the lower notch of rotor groove at pressure side.

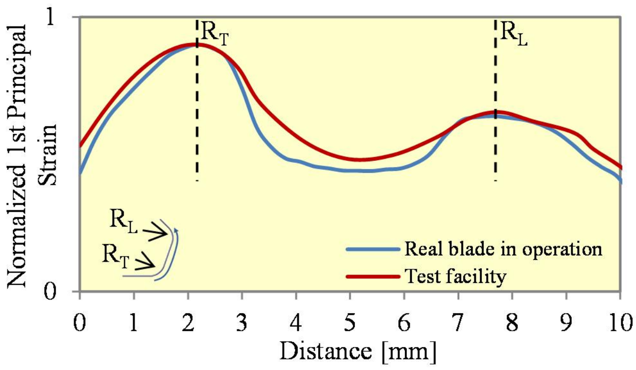


**Figure 9: Strain distribution in the test facility compared to real operation**

Strain data was acquired using strain gauges in the notches of the groove and the blade part as well as on the mounting shanks. The data was used for calibration purposes and for operating the test rig.

## COMPONENT TEST RESULTS

### HCF Testing Results

The HCF component tests were carried out at the first eigenfrequency (mode 1) of the tested blades at specified deflection amplitudes up to $10^8$ cycles or to cycles of crack initiation. Reliable indicators for crack initiation were a change of the blade eigenfrequency along with an increase of shaker power [3]. Furthermore, the occurrence of a crack can be detected by changes of the acquired strain levels.

At the end of each test, the cracked blades were examined regarding the crack initiation locations and the crack depths.

The observed crack locations correlated very good with the predicted position, see Figure 10. Hence, the general design calculation methods could be positively confirmed.

In the following sections, investigation results from different blade types of Siemens' portfolio of LP end stage blades are exemplary shown. Its root and airfoil shapes as well as size characterize a blade type.

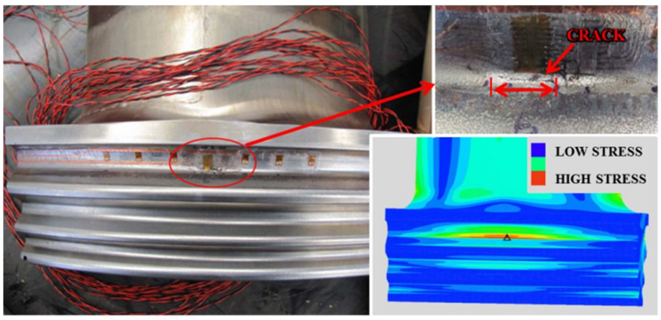


**Figure 10: Crack initiation location of tested blade compared to prediction**

The investigation of the influence of different blade materials on the component endurance limits was conducted with blades of type I with the same surface treatment (shot-peened).

The results depicted in Figure 11 clearly show an increased endurance limit for material II with the higher strength properties. The determined increase matches with the expected endurance limit change derived from material properties (shown as stress-cycle- (S-N-) curves). Exceeding the results shown in [3], the testing scope for material I was extended to higher amplitude levels, i.e. to the low cycle fatigue regime. It also applies for these amplitudes that the correlation with the S-N-curve is very good.

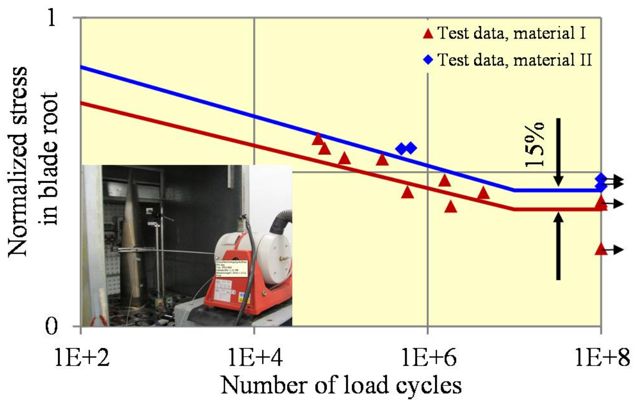


**Figure 11: Influence of the material on the endurance limits**

With blade type II, the influence of the surface treatment on the endurance limit was examined. In [3], it could clearly be shown that shot-peening increases the endurance limit in comparison to milled-only surfaces. Here, the influence of spinning of shot-peened blade roots on the HCF strength is investigated closer. Based on the testing results, there is no significant difference between non-spun and spun blades, see Figure 12. The endurance limits and fatigue strengths are in the same scatter band. Hence, spinning of blades, which is an inherent part of the manufacturing process, does not influence the blade root itself.

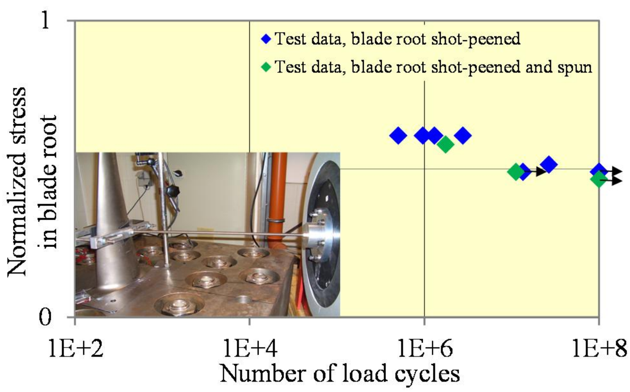


**Figure 12: Influence of spinning of shot-peened blades on the fatigue behavior**

Another testing aspect was fracture mechanics. After identifying crack initiation, threshold and crack propagation were investigated. As stated before, strain gauge data and shaker power were analyzed to notice crack initiation. Non-destructive testing (NDT) utilizing the phased array ultrasonic testing method (PA-UT) was applied to prove crack initiation and to monitor crack propagation without disassembling the blade. However, at certain intervals, the blade was removed for standard dye penetrant testing (PT) to verify crack initiation or crack propagation indicated by the PA-UT technique.

The heat-tinting method was used to colorize the crack surface. This method enables the determination of crack size and shape and the investigations regarding crack initiation, threshold and crack propagation.

Finally, the blade root was cut from the entire blade and broken up along the crack surface for an exact determination of crack size and shape. Figure 13 shows one example for this examination.

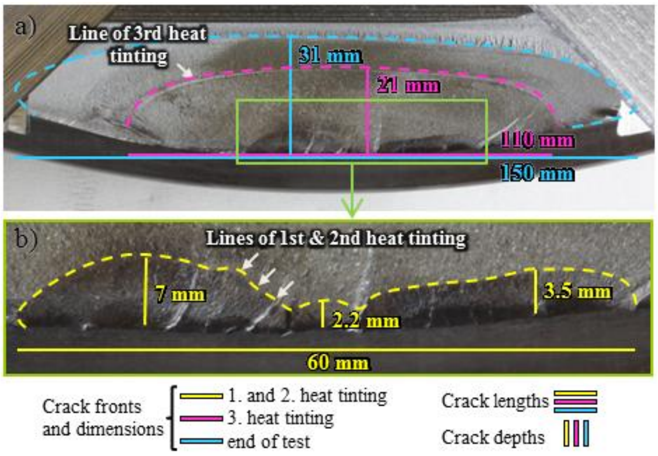


**Figure 13: Crack surface analyses a) Fracture surface b) Crack initiation area**

The last stage of crack propagation can clearly be seen in Figure 13a. Maximum crack depth is approximately 31 mm, and the crack length is approximately 150 mm as it was determined by PT testing.

Details of the fracture surface relating to crack initiation are shown in Figure 13b. Maximum crack depth for the threshold test is 2.2 mm and 7 mm and the total length of the initiated crack is approximately 60 mm.

The crack sizes have been predicted by fracture mechanical analysis. The measured and predicted crack propagation in crack depth direction are in good agreement, see Figure 14.

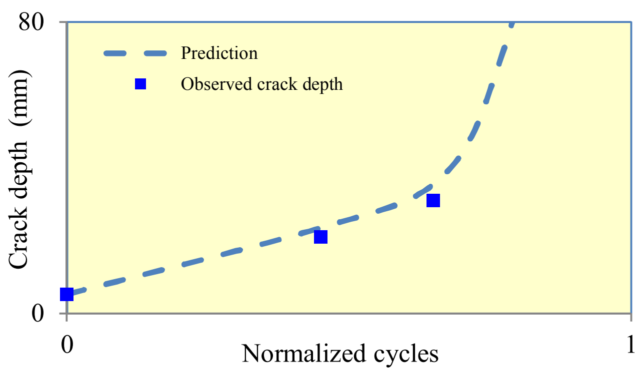


**Figure 14: Comparison of measured and predicted crack depths**

## LCF Component Test Results

The LCF tests for full-scale LP end stage blades were carried out with a constant loading rate of three cycles per minute. Crack initiation was predicted by means of measured strain changes and the potential drop method. At the end of each test, the cracked blade was examined regarding the crack initiation location and crack size.

As shown in Figure 15, the crack initiation locations correlate well with the prediction by means of FE calculations. The primary crack was initiated in the upper notch at suction side (note that the crack in the second notch was initiated later during other tests).

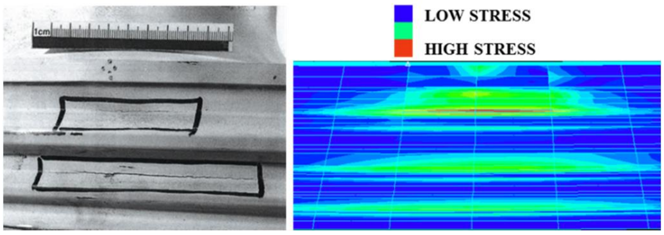


**Figure 15: Crack initiation location of a tested blade compared to prediction**

All tests were performed for one blade type with three different surface conditions to determine the LCF strength and to investigate the influence of surface treatment in the range of LCF numbers relevant for blade design. As shown in Figure 16, shot peening and rolling significantly improves the LCF life, and the determined LCF lifetime lies above the LCF curve of standard smooth specimens. The definition of LCF lifetime relates to crack initiation detected by strain change correlating very well with typical crack initiation definitions.

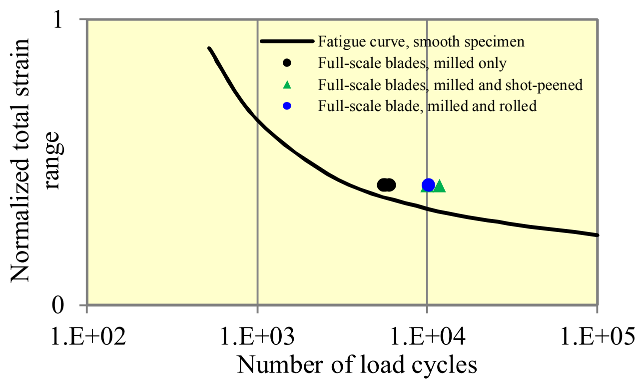


**Figure 16: Comparison of LCF numbers**

## Blade-to-rotor Connection Test Results

A modern lifetime prediction method of blade roots and rotor grooves requires improved understanding of blade-to-rotor-connections under real operational conditions. Siemens has conducted a series of full-scale blade-to-rotor connection tests. These tests were performed with the same loading rate as for the full-scale blades, i.e. three cycles per minute.

Testing revealed a significant drop of strains in the lower notch of the grooves at the very beginning of the test. This behaviour can be addressed to friction effects correlating with increase of friction coefficient. At a certain number of cycles a constant strain level and ultimate value of friction respectively is reached. The phenomenon observed correlates very well with published literature, e.g. reported in [4].

The investigation was conducted on a full-scale end stage blade-to-rotor connection with different surface conditions of the blade vs. the groove, i.e. milled vs. milled and shot-peened vs. milled. The testing results are exemplarily shown in Figure 17 and Figure 18.

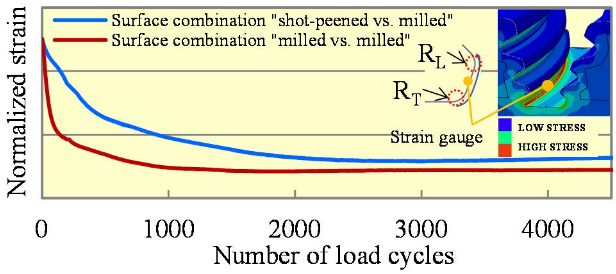


**Figure 17: Measured strains under LCF loading**

The strains gained from the surface condition combination milled vs. milled decreases faster compared to the combination shot-peened vs. milled, Figure 17. However, at a higher number of cycles, the measured strains converge achieving finally a steady state value.

Based on the measured strains and FE-modelling, friction coefficients were derived for the tested full-scale blade-to-rotor connections. As shown in Figure 18, the friction coefficients of both surface combinations increased at the beginning and reached a similar ultimate value of friction in the steady state after approximately 1,700 cycles. At the beginning, the friction coefficient of the surface combination milled vs. milled was higher compared to the surface combination shot-peened vs. milled.

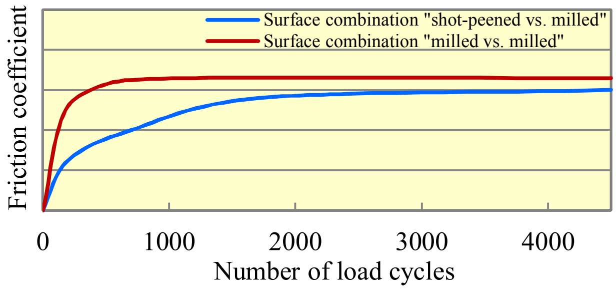


**Figure 18: Friction coefficients under LCF loading**

## VALIDATION OF THE HCF CALCULATION METHOD

The HCF blade tests have also been utilized to validate the HCF calculation method. The procedure of this validation is exemplary described for blade type I with material I in [3].

Here, the good match between the calculation and the testing results of blade type II prove the design method further.

The test rig was modelled using the FE analysis software Abaqus 6.11.2. The FE model of the test setup was prepared with contact between the blade root and the groove. The sidewalls of the groove blocks are slidable on their mating surface in the seismic table. A static load corresponding to the cylinder pressure acting from below was applied to hold and load the blade statically. Then, a modal analysis was performed as a linear perturbation step. 1st-mode results are used for the evaluation.

The measured strains and blade deflection were compared with the FE results. The measured strains along the gauge chain and blade deflection were used for the evaluation.

An example of the good match between measured strains and the strains predicted by an FE analysis is depicted below (Figure 19) for several blades. Here, strains are scaled to the same amplitude level. The green dots represent the FE-calculated strains while the lines show the measured strains along the strain gauge chain.

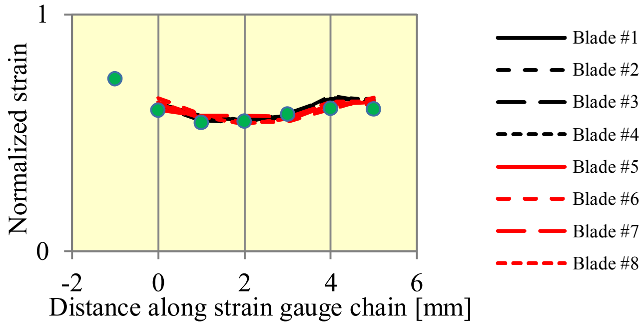


**Figure 19: Comparison of measurement and FE results along the strain gauge chain**

Based on the good match between calculation and measurement, the maximum strains, at locations that cannot directly be captured by strain gauges, could be estimated. The strains were then transformed into stresses using the FE analysis result.

The resulting dynamic notch stresses of each individual blade are plotted into a component Wöhler diagram (normalized airfoil amplitude vs. load cycles). Here, the results for blade type I and for blade type II are coincidently shown (see Figure 20).

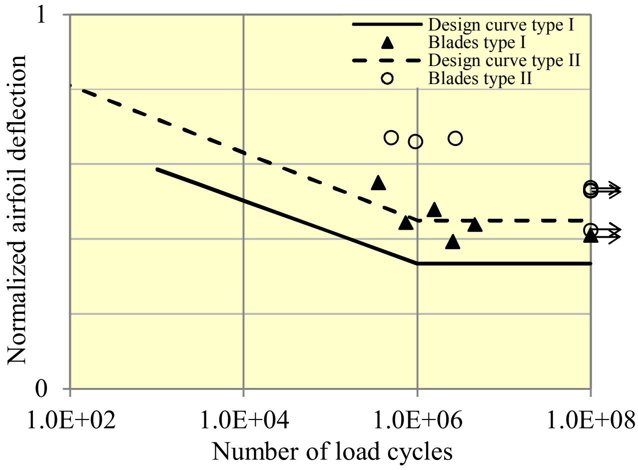


**Figure 20: Validation of design Wöhler curves**

For both blade type I and blade type II, it can be seen that the fatigue strengths lie above their corresponding design limit curves. This proves the design method and displays that there is sufficient safety margin against HCF failures.

## OUTLOOK

The testing facilities and methods presented in this paper get along with idealizations. Hence, the next consequent step is to extend the testing method as appropriate.

A research project within the framework of AG-Turbo, partly funded by German government, has been initiated in cooperation with MPA Stuttgart in 2013 [5]. Current focus of the project is HCF for blades under consideration of centrifugal load.

## SUMMARY AND CONCLUSION

LP end stage blades are exposed to complex mechanical load, resulting in stresses mainly due to blade vibration and high centrifugal forces. For lifetime and endurance predictions, it is necessary to understand the component behaviour under real operation loading including blade-to-rotor connection. Especially in cases where experimental life time prediction is technically not possible or economically not justifiable, appropriate, reliable and verified design methods and guide lines are essential for development and design of LP turbine end stage blades. This belongs to their lifetime prediction and structural integrity assessment as well enabling reliable operation of turbine blades over the entire lifetime of the power plant. Design faults could lead to failure of the components in operation and to substantial commercial damages. Although much effort has been made to test specimens, real component behaviour cannot be investigated sufficiently. Tests on full-scale blades are becoming more and more important.

To investigate full-scale LP end stage blades including blade to rotor connection under real operating conditions, several test facilities have been developed, setup and established at Siemens. Significant calibration effort has been performed to verify their operational capability. HCF and LCF strength (fatigue and endurance limits) as well as threshold and fatigue crack propagation under real operating loads have been successfully determined for different LP end stage blade types. The impact of different materials and surface treatments on fatigue and endurance limit has been investigated. The positive effect of compressive residual stresses on LCF and HCF strength has been proven. Based on the results, all calculation methods applied have been successfully validated.

In order to extend the investigations on full-scale LP end stage blades, a test facility allowing for combined HCF loading, centrifugal force and LCF loading is under development.

## NOMENCLATURE/ ABBREVIATION

| | |
|---|---|
| $A_{dyn}$ | Dynamical deflection of airfoil |
| CCF | Combined-cycle fatigue |
| $F_B$ | Bending force |
| $F_C$ | Centrifugal force |
| FE | Finite-Element |
| HCF | High-cycle fatigue |
| LCF | Low-cycle fatigue |
| LP | Low-pressure |
| NDT | Non-destructive test |
| PA-UT | Phased array ultrasonic testing, NDT |
| PT | Penetrant testing, NDT |
| PTFE | Polytetrafluoroethylene |
| SG | Strain gauge |
| S-N | Stress-cycle |

## PERMISSION FOR USE



## REFERENCES

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