MEASURING FATIGUE LOADS OF BOLTS IN RING FLANGE CONNECTIONS

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ABSTRACT: This paper presents experimental and numerical investigations of ring flange connections in steel towers of wind turbines. The experimental program covers laboratory tests as well as tests in operating wind turbines. An overview for both parts of the experiments and an explanation of the chosen instrumentation is given. The laboratory tests serve to verify a three-dimensional finite-element-model. For practical purposes, an overview of simplified calculations models that allow to omit FE-calculations is also given. Results from another FE-model of the total ring flange give insight into effects that are neglected when only one segment of the ring flange is investigated.

Keywords: Wind Turbines (HAWT)-Towers, Fatigue, Numerical methods

1 INTRODUCTION

Towers for wind turbines are usually tubular steel towers, that are manufactured in two or three parts, depending on their total height. They are connected on the construction site with bolted ring flanges.

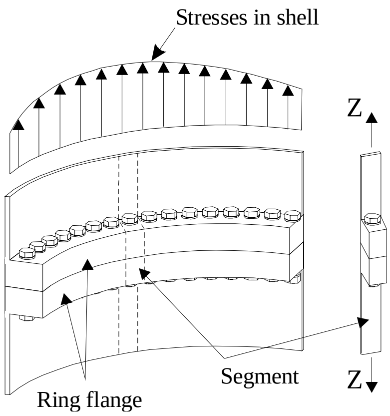

Fig. 1: Segment model

The calculation of stresses in the bolt for fatigue assessment and the assessment of ultimate strength are performed with one segment of the total flange. The segment is loaded with a tension force that sums up the stresses in the shell. This approach is called „segment model“ (Fig. 1).

The stresses in the bolt depend nonlinearly on the tension force as the connection has preloaded bolts. A typical graph showing the nonlinear correlation of external load and tension force in the bolt is shown in Fig. 2. The behaviour is similar for the bending moment in the bolt.

The complex nonlinear behaviour of this eccentrically loaded connection and high dynamic loads of wind turbines with more then 10^9 load cycles in 20 years demand for safe and economic design methods. Experimental investigations on flange segments in the laboratory and in operating wind turbines have been performed to calibrate the results of simplified calculation models against experimental values. Additionally, a 3D finite element model has been used to extend the range of investigated parameters.

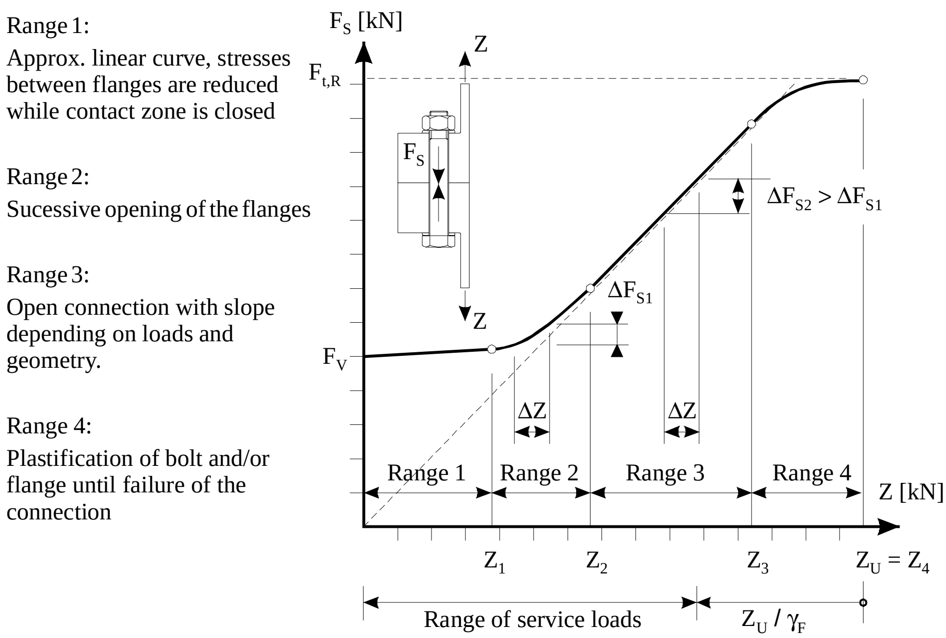

Fig. 2: Nonlinear curve of bolt force vs. external force

2 EXPERIMENTAL INVESTIGATIONS

The purpose of the experimental investigations was to obtain normal and bending stresses in the bolt in dependence of the external loads. The measurement equipment used is described below.

Measured values in the laboratory included strains in the bolt, deformation of the flange segment with a displacement transducer, strains in the flange and output data of the testing machine. In the operating wind turbines, strains in the bolt and in the tower shell and output values from the wind turbine (wind speed, rated power, rotating frequency and yaw angle) were recorded.

2.1 Measuring method to obtain stresses in the bolt

The tests were performed with bolt fittings according to DIN 6914. Strain gauges were applied on the bolt shank in order to obtain the axial force and the bending moment in the bolt. The shank diameter was reduced by 3mm to avoid contact between the strain gauges and the flange. The cables were run through a sloped hole, extending from the reduced area to the bolt head. Alternative paths e.g. through a notch in the flanges, was not possible because of the installation procedure of the tower. The influence of the reduced stiffness is relatively small. It can be directly considered when performing comparative calculations for the laboratory tests. In the flange in the operating wind turbine, the stresses in the bolt are proportional to the axial and bending flexibilities of machined and unmachined bolts.

Fig. 3: Bolt M30 with strain gauges

The configuration of the strain gauges was chosen to match these criteria:

1. Unequivocal determination of the bolt’s stress state was required. Thus three test points were arranged around the circumference of the bolt to describe the complete stress plane.
2. The measurement should not be influenced by temperature effects. Thus full bridge strain gauges were used.
3. Full bridge strain gauges have the additional advantage that measurement of axial components resulting from tension force and bending moment and shear components resulting from the torsional moment do not influence each other.

The measurement of the torsional moment allows the calculation of the friction coefficient of the bolt thread. This is useful for checking the plausibility of the measured preloads.

A complete measuring bolt is shown in Fig. 3. The copper rings were used to center the bolt in the hole.

The chosen instrumentation of the bolt is very expensive, because of high cost of the application of the eight strain gauges and their cost of approximately 150 Euro. These costs are justified because of the meaningful information that is obtained.

2.2 Laboratory tests

The test setup in the laboratory is shown in Fig. 5. The flange segment is loaded with up to 530 kN tensile force in ultimate load tests by the structural actuator. The data provided by the test system (proof load and piston stroke) and the strain-gauge signals are recorded with a Spider-8 universal digital multichannel system.

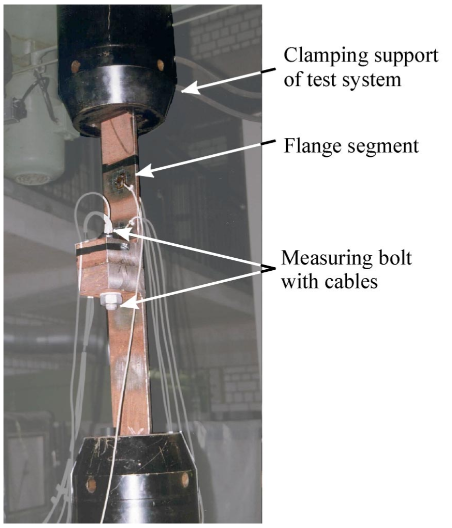

Fig. 5: Test with flange segment in the laboratory

A total of four flange segments with different dimensions were tested in the laboratory (Fig. 4). Two flanges were machined out of original flanges used in large wind turbines, the other two flanges were machined from the first ones by reducing the thickness. The thin flanges 3 and 4 were used to cover a wide range of parameters. The original flanges 1 and 2 were „thick“ flanges, flanges 3 and 4 were rather thin.

The analysis of test data was performed with a special software that calculates axial force, bending moment and direction of the bending moment. The software has been developed at the Institute for Steel Construction.

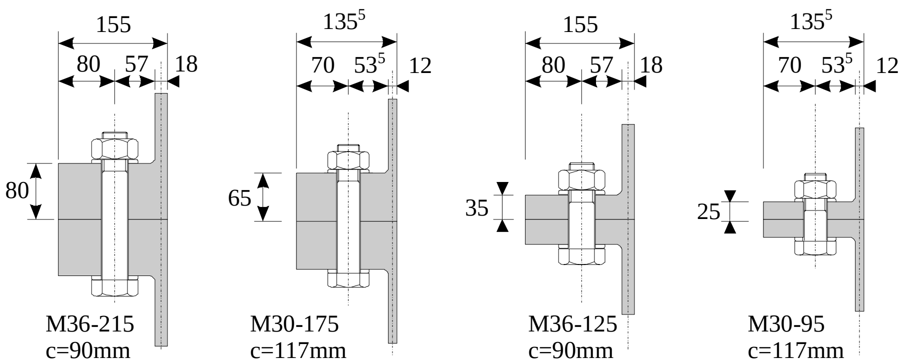

Fig. 4: Test flanges

2.3 Tests in operating wind turbines

Tests in operating wind turbines were performed as a comparison to the laboratory tests. To determine stresses in the tower, strain gauges were applied below the flange on the inner and outer side of the shell. Four test points were arranged around the circumference, so a check of the measured values was possible by comparison of opposite test points. In contrast to other investigations, e.g. load spectra measurements, online reduction of the data was not possible. Corresponding values of all channels were required, thus time series were recorded. An example is shown in Fig. 8. The chart shows the external tension force that was calculated from the strains in the shell and the corresponding bolt force. It is obvious that external force and bolt force correlate, but the variation of bolt force is much smaller than the variation of the external force due to the positive effect of the preloaded bolts.

To reduce the amount of recorded data, a special control of saving frequency was applied. The saving rate was dynamically adjusted from 1/60 to 10 Hz depending on the wind speed. Thus a good resolution was guaranteed in times of high loads without saving useless data in times of low loads. Nevertheless, around 10 GB of data were recorded within eight months.

Additionally the flatness of the flange was measured to gain an impression of the deviation from the target geometry. The thickness of the coating was measured to evaluate the influence on loss of preload because of settlement effects.

3 NUMERICAL INVESTIGATIONS

As the investigation of flange connections can not be exclusively performed by experiments, a 3D-FE-model was build to compare the numerical results with the experiments and to extend the range of parameters that are investigated. The tests serve to calibrate the model. A wide range of numerical calculations can then be used to evaluate simplified calculation methods.

3.1 FE-Modelling

Different 3D-models of a flange segment and of the total flange were used. A detailed description of the models can be found in [1]. A summary with focus on modelling of the bolt was published in [3].

Two FE models have been used: A 3D model of one segment (Fig. 6) and an refined model of the total flange. As the use of brick elements in the total model produces too many elements, so called super elements were implemented. With this calculation technique, a part of the model is condensed into the stiffness matrix before the main calculation. This matrix element is called a superelement. The superelement is part of the total model just like any other element. As it does only allow linear properties, it can not be used if non-linear effects, e.g. plasticity or geometric non-linearity, are present. When calculating fatigue loads, plasticity is not an issue and geometric non-linearity is negligible. The advantage is that a relatively fine mesh can be used with reasonable computing time.

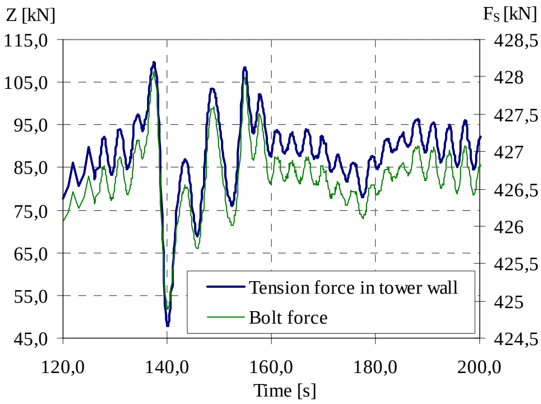

Fig. 8: Example for a time series of calculated load per flange segment (left ordinate) and bolt force (right ord.)

Fig. 7 shows the comparison of test result and FE-calculation for test flange 1 (dimension see Fig. 4). The agreement is good, similar results were obtained for the other test flanges.

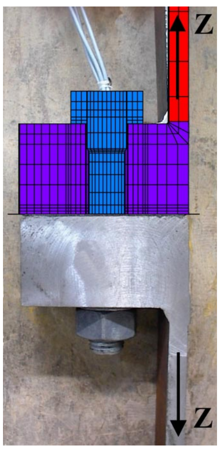

Fig. 6: Test flange 1 and FE-model

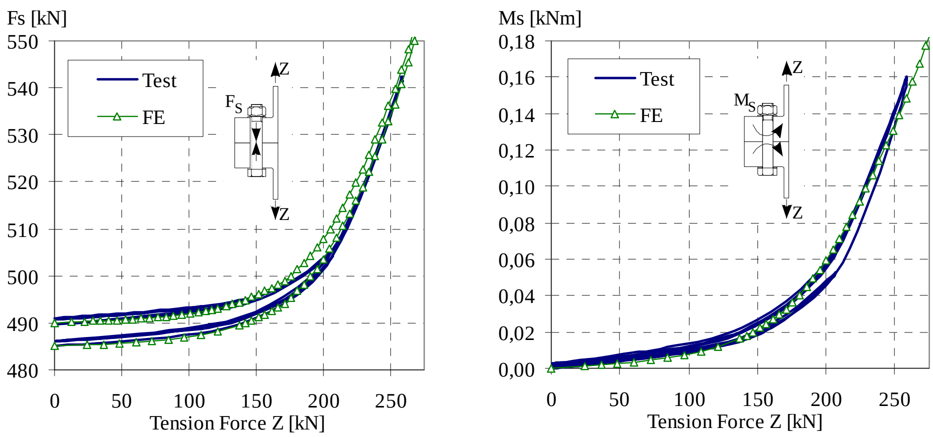

Fig. 7: Comparison of test result and FE-calculation for test flange 1

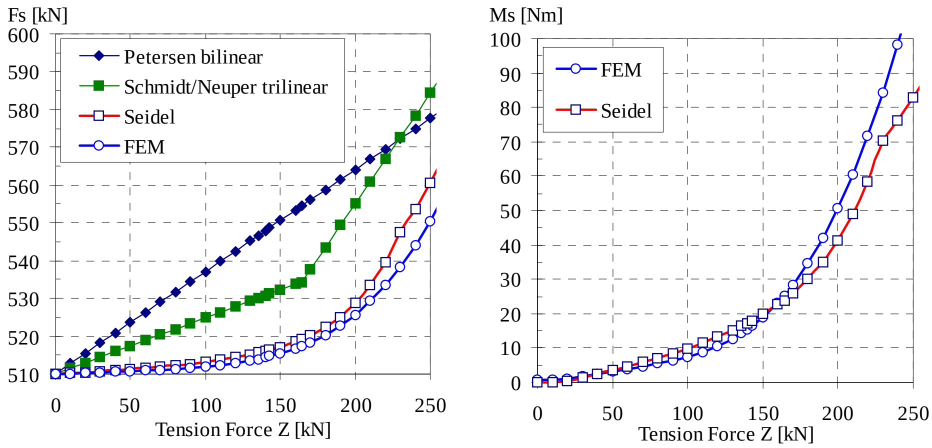

Fig. 9: Comparison of FE-results and simplified calculation methods

3.2 Simplified calculation models

Even though finite element calculations are not uncommon for the assessment of wind turbines, simplified methods are useful for predesign and comparative studies. In Germany, proposals from Petersen [2] and Schmidt/Neuper [4] have been used to assess flanges. A new proposal from Seidel [1] allows for a better approximation of the non-linear relationship between external loads and bolt force. Additionally, the bending moment in the bolt is obtained. Fig. 9 shows a comparison of the three calculation methods with the FE-results for test flange 1. The older models attain a safe approximation of bolt force and slope of the curve for low tension force, but for high tension forces the slope can be underestimated. This can be important for load cycles with a high mean value. The approach from Seidel [1] attains a safe approximation for both bolt force and slope of the curve for all tension forces. A slight underestimation of the bending moment occurs for high tension forces, but this is compensated by the overestimation for the axial force.

The amount of bending stresses that is superimposed to the axial stresses is considerable. In this case, the additional stresses $\Delta\sigma_N$ and $\Delta\sigma_M$ are in the same order of magnitude. Thus it is not justifiable to neglect the bending stresses for fatigue assessment. According to Eurocode 3-2 [5] the assessment can be performed using detail category 50* against the sum of axial and bending stresses.

3.3 Effects of the total system

An FE model of the total ring flange was used to evaluate the influence of effects that are neglected with the segment model. The following results were obtained:

1. The difference between the segment model and the total flange model is small for typical flanges of wind turbines within the range of service loads. The difference becomes greater for high loads that are close to the limit load.
2. The deformation of each segment is dominated by the total system. Thus a local change in stiffness, e.g. by a low preload of one bolt, does not influence the additional stresses.
3. A constant gap on the inner side of the flange is advantageous for the carrying behaviour and results in lower additional stresses in the bolt.

4 SUMMARY AND PERSPECTIVE

The stresses in bolts of eccentrically loaded, preloaded flanges depend nonlinearly on the external loads. Accurate knowledge of axial and bending stresses in the bolts is necessary for fatigue assessment. An expensive but useful experimental setup for laboratory and field tests has been presented for the investigation of the bolt’s stress state. A comparison of experimental and numerical values has shown that a good agreement can be achieved. As an addition to numerical methods, simplified methods have been investigated to show the accuracy of results. As axial and bending stresses occur in the same order of magnitude, only models that allow for the calculation of both should be used.

In the complete system, effects that are not covered by the segment model can also be important. A FE model of the total flange has shown that the calculation of stresses for fatigue assessment can be performed with the segment model because the differences are negligible for the investigated range of loads.

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