

Condition Monitoring of Multi-Bolted Joints with Combination of Preload Measurement and Extended Evaluation from FEA

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ABSTRACT

This paper shows an approach developed to cover in detail different behaviour of threaded fasteners with a robust test setup for multibolted joints and numerical simulations by means of finite element analysis (FEA). Resulting from this combination, it is possible to monitor the axial, torsion and bending stress in fasteners themselves. Importance is given to interpretation of the measurement signals of strain gauge bolts. Integrity of the complete structure can be better interpreted with this approach. This depends on the modelling of bolts for FEA and the quality of the measured signals from experiments. For FE modelling the general purpose non-linear solver Abaqus is used, for preload measurement strain gauges are integrated into metric bolts. Simulation and experimental results from this unique test setup with several bolts are shown. This test-setup allows investigation of not only the preload distribution but also the resulting behaviour of the structure with regards to external loading and bolt stressing in detail. Typical preload deviations from tightening procedure are considered. With this combination of preload measurement at several bolts and transfer of data obtained from FEA, a detailed monitoring of the structure's status is possible. Investigations are performed on previously unexplored influences on self-loosening for example from number of bolts and geometry of the clamped part.

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INTRODUCTION

Bolted joints in application always involve more than one bolt even though their analytical design is performed based on idealization and the bolt encountering the maximum load. In today's engineering world multi-bolted joints must be considered as a fastening system which has influences not just from the number of bolts in the system but also the complex structure in which the bolts are present and interact with each other through transmission of forces and vibration.

Innovative products need intensified reliability against functional failure of the complete structure and also to detect component faults if there is redundancy dimensioned for the system (to find the defect by a continuous operating system) e.g. one bolt has a lower preload. Typical failure modes of bolted joints include rotational loosening (self-loosening), non-rotational loosening (seating, load induced plasticity, thermal creep), corrosive failure, fatigue and rupture. However, the basic design of bolted joints does not cover all these nonlinear behaviors in detail. An improper design of the joint can not only lead to bolt failure but also component failure based on the loading and environment. Hence it is essential to extend the design process of joints to evaluations with FE simulation and experimental testing of the complete joint.

Self-Loosening of Multi-Bolted Joints

Rotational self-loosening of bolted joint is one of the predominant failure modes, especially for bolts under vibration loading. This phenomenon is critical especially for joints where the vibrations can

induce relative transverse movements in the clamped parts [1]. A test setup developed in late 1960's by Gerhard Junker is nowadays part of a German national standard - DIN 65151 [11]. Another standard DIN 25201-4 [13] describes test methods based on the test setup of DIN 65151 as a design guide for railway vehicles. The above tests with an eccentric cam drive producing a relative transverse displacement between clamped parts, to induce rotational self-loosening in bolts, are good only to visualize the phenomenon but not for giving suitable design guidelines to avoid or predict it. This is due to the limited possibilities for variation of the joint design parameters. Only one bolt can be assessed at a time with different clamp length and thread engagement lengths. Recent findings have shown a significant difference in the self-loosening behavior of single bolt joints and multi bolted joints [4, 7, 8, 10]. A comprehensive study on the effect of clamped part in a multi-bolted joint on self-loosening behavior can be found in [10].

Condition Monitoring of Multi-Bolted Joints

Structural Health Monitoring (SHM) is a modern technique to detect faults and failure of the monitored structure. Different types of sensors are often used for monitoring e.g. strain gauges, accelerometers, etc. These sensors are often fixed at different locations in the whole structure. From the perspective of multi-bolted joints, bolts integrated with strain gauges as sensors, are particularly interesting. With this an idea of the prevailing preload and additional axial forces could be monitored. As a consequence, it is important to know how the axial additional bolt load is distributed within the

unique test setup -MoHaS is developed. The abbreviation MoHaS stands for “**M**onitoring of **S**tructural **H**ealth and **S**elf-loosening”. It is built to encompass different functional failures with multi-bolted joints and to study their cause and effect scenarios. On one hand structural monitoring with different load types and bolt arrays is possible and on the other hand self-loosening tests on a two bolt multi-bolted joint is possible. In this paper the focus is set to introduce the testing stand MoHaS and to show an analytical model of the main bolt arrays. For a defined experimental load case results are compared with FEA.

Another part is the bending sensitivity of bolts with integrated strain gauges.

MoHaS Test Stand

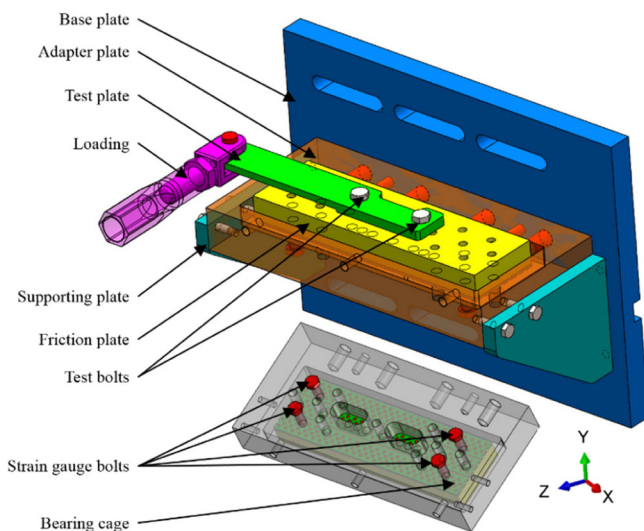


Figure 1. A view of the test-stand - MoHaS with a mirrored image of the adapter plate.

The test configuration developed at University of Siegen - MoHaS (Figure 1) combines different objectives. It enables us to investigate the transmission behavior and the self-loosening behavior of different multi-bolted-joint arrays. For this purpose, two interfaces in the XZ plane are envisaged. The top most plate (shown in green) provides the force introduction point. This plate can be used as a multi bolted joint with two M10 bolts with different load introduction possibilities and to study the self-loosening behavior as in [10]. The underlying plate (shown in yellow, hereafter called friction plate) is one part of the investigation in this paper and has M10 nut threads at different positions to allow studies to be performed from the top side and the bottom side. The perforations are such that the bolt positions can be varied for the study of self-loosening and condition monitoring. To minimize the influence of friction, flat bearing cages are used in the second interface. The influence of friction is minimized, to reduce the possible influences on the test configuration. The adapter plate (shown in orange) supports the flat cage and the friction plate. At the mirror imaged representation in the lower part of Figure 1 are the four red bolts which are monitored. The base plate (blue) is fixed to an angle plate of a hydraulic pulsator. The preload is measured by means of a quarter-bridge strain gauge in the shank of the bolt. Here, a strain gauge is glued into the range of homogeneous strain in the shank. It can detect the amount of preload by prior tensile calibration.

The four bolts shown in red are M10×50 with grade 10.9, selected in accordance with DIN EN ISO 4014 [12]. The bolt is tightened using preloadcontrol method with a load of 29.6 kN. The coefficient of friction is assumed as 0.12 for head and thread region. A utilization factor of 90% for strength grade 8.8 [14] is chosen. The discrepancy between strength grade 10.9 and preload for 8.8 was deliberately chosen as a safety measure owing to the diminished cross sectional area due to the integration of strain gauge in the shank.

CONDITION MONITORING WITH MOHAS

As a first step an analytical representation is made by using the method of equilibrium state (refer Fig. 2). The load F which is prefaced in the lever is divided into forces U_1 and U_2 . These forces are the loads for this bolt array and must be compensated by the bending stiffness of the bolts and friction at the interface. $F_{QS1/2}$ is the force component acting on the bolts 1 and 2 whereas $F_{QS3/4}$ is acting on the bolts 3 and 4. To account for preload variation from assembly influences, the transmitted friction forces in the interface are subtracted from the transverse force in each case. This was calculated for the bearing cage with $\mu_T = 0.01$ and the existing preload. Calculation is based on the simple friction law by Coulomb. By building the ratio of the forces $F_{QS1/2}$ and $F_{QS3/4}$ and using the intercept theorem it is possible to calculate the center of rotation in every case.

Simulation was performed with Abaqus 6.11, using the complete test-stand, paying attention to the bolt array as in Fig. 2. The load is a sinusoidal force with an amplitude of ± 3 kN in Z-direction. The bolts are preloaded to 28.9 kN using a pretension section. From the simulation, no displacement of the bolt heads could be observed even though modelling is performed with contact definition without tie constraints. As a first result, preload behavior under the defined load condition is compared in Fig. 3 for simulation and experiments. It is obvious that in the test with strain gauge screws, significantly higher values for F_{SA} (additional bolt force) were determined as against the simulation. The ordinate shows only the segment 25-31 kN. Since the displacement values of simulation match with those of the experiments, some questions arise as to measurement errors or unrecognized factors influencing the accuracy of the strain gauge integrated bolts. Among other things, the bending of the bolt (S-deformation), position of the strain gauge in the bore, influence of reduced cross-section of the bolt could be the contributing factors. Conversely, errors could have appeared from the numerically determined values. In preliminary studies it could be observed that quarter-bridge strain gauge screws are sensitive to bending stress and high bolt load [9].

The diagram Figure 4 shows the developing of the axial additional bolt load dependent on the angle of rotation of the bolt. This is interesting to know if you have bolts with transverse load and bending of the screw (not only tensile load). For this experiment, vibration test stand adapted from Junker [11] is used. Displacement amplitude of ± 0.5 mm was set as load for this test. The load itself is in sine form due to the rotating cam drive of vibration test stand. Speed of the testing stand was set to 50 revolutions per minute. A bolt with integrated strain gauge was used that was calibrated to a maximum of 30 kN.