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Weight Reduction in Lightweight Structures of Dynamically Loaded Systems by New Energy Dissipative Elements in Bolted Joints

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ABSTRACT

In order to reduce vibration amplitudes, joint damping is being investigated at the MFPA Weimar and Fraunhofer IWM. It is intended to replace damping, often done by a frequency shift of naturals frequencies via added masses, and thus contribute to lightweight construction. To characterise the energy dissipation ability of joints, fretting wear tests with various parameter settings have been performed.

In fretting wear tests, two material samples are set in relative motion with a constant normal force. Friction in the joint creates a friction-force-hysteresis, the area of which reflects the energy dissipation. The larger the hysteresis area, the greater the energy dissipation. Based on the experimental observations, a new material model is formulated to capture energy dissipation starting form micro slipping up to macro-slip situations in joints.

Input parameters for the constitutive law are material pairing, the contact force, the frequency spectrum and the surface roughness. The constitutive law is defined in a finite element method (FEM) in intermediate elements between two friction bodies, where energy dissipation can be simulated for complex geometries. The numerical calculations are compared with validation experiments.

Bolted joints are investigated as an application. The pressure distribution in the connection depends on the distance of the considered point to the bolt. According to distance, the constitutive law is variously implemented in the joint. Bolted joints exhibit both micro-slip (near the bolt shank) and macro-slip as relative motions, resulting in different friction states in the joint. Despite the displacement, the function must be maintained, which is why materials with low fretting wear are used. Figure 1 illustrates the relationship.

***key words* - Bolted Joint, Damping, Finite Element Method, Constitutive Model, Fretting Wear, Energy Dissipation, Dynamically Loaded Systems**

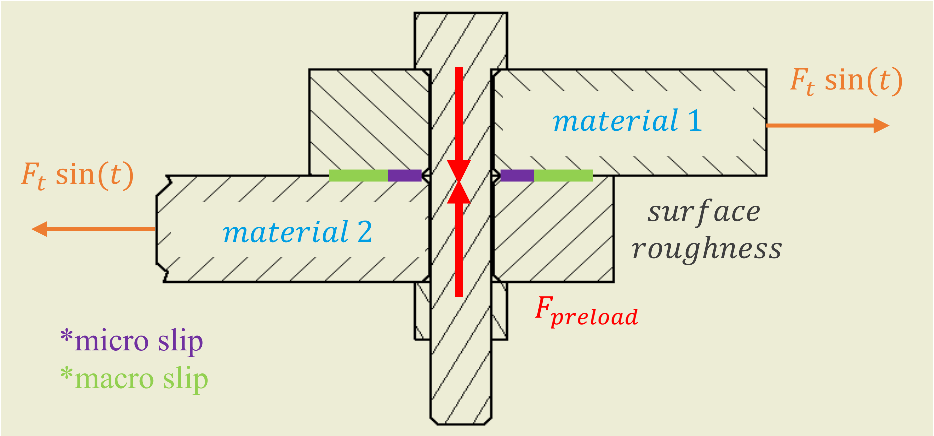


fig. 1: use case bolted joint and her dependencies for damping

1. INTRODUCTION

Lightweight structures often show large vibration amplitudes under dynamic loads due to unfavorable excitation close to resonance frequencies situations. The resulting large vibration amplitudes lead to negative effects on functionality, operational safety, and fatigue strength or might result in undesirable acoustic emissions of the components. A system's vibration response fundamentally depends on the mass, stiffness, and damping of the system itself [1]. With a reduction in weight, the susceptibility to vibration is therefore often increased, and in addition, a reduction in stiffness occurs together with the weight reduction [2]. The effect of stiffness is well-researched today, but damping as a consideration for reducing the vibration response is often simplified in engineering models, e.g., by simplified viscous damping models with constant parameters.

In the research project, the reduction of the mass and the stiffness of the system is counteracted by increasing the damping. Among all damping mechanisms, joint damping has been to be the type of damping that maximizes energy dissipation compared to other external damping sources. [3].

In the tailgate application, an additional mass is introduced. This mass builds up a second vibration system, which counteracts the system response to be reduced [4]. Thus, this frequency shift measure leads to larger system masses and, therewith tends to make a weight-optimised structure heavier again. Another way of reducing amplitude is to use joint damping instead of an additional mass, which is being investigated in the research project. The following figure (fig.2) shows the two effects' impact on a system's vibration response. An additional mass splits a natural frequency into two frequency amplitudes. By splitting, the energy is divided, and the amplitudes are reduced. This effect only applies to one natural frequency. In contrast, damping does not lead to a frequency shift, and the dissipation behaviour reduces the amplitude [5].

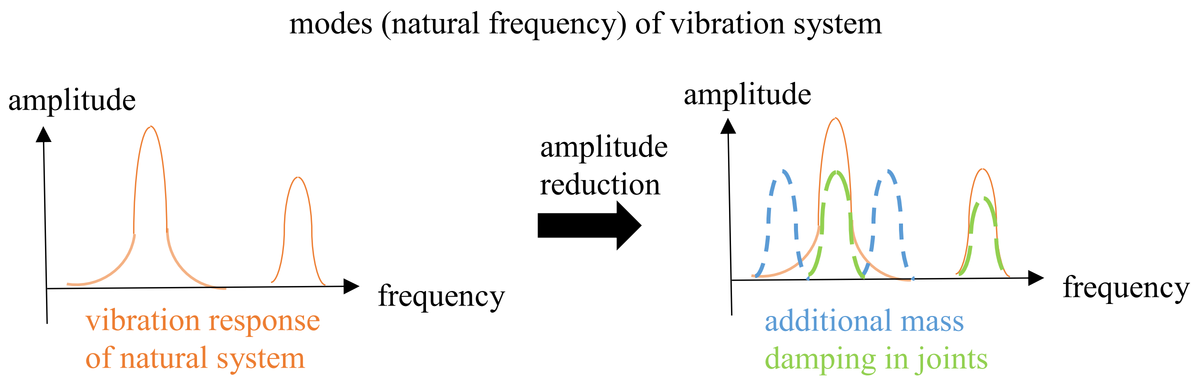


fig. 2: amplitude reduction in different ways

2. ROAD MAP

In the research project fretting tests are carried out by the Fraunhofer IWM. Energy dissipation in the form of hysteresis and wear over time are being considered. A material law for a FEM simulation is obtained from this data. The material law is used in thin layer elements (TLE). The FEM models are compared with validation experiments. As a practical application, a tailgate is considered in which the additional mass is replaced by new designs based on joint damping.

3. FRETTING TESTS

Fretting tests were performed with a ball on flat geometry in a fretting tester. Fretting is characterized by a small amplitude, oscillatory movement between two friction bodies [6]. At the beginning of the experiments the hertzian contact pressure corresponds to the contact pressure in a bolted joint. While one body is held, the other is moved by a shaker. The displacement of the moved body is recorded optically, while the frictional force is measured at the counter body by a piezoelectric sensor.

One friction partner is always a steel ball (100Cr6), and the second body is made of a nickel alloy (Inconel 718), a brass alloy (CuZn37Mn3Al2Si), or an aluminium alloy (EN AW-6056). The aluminium alloy is tested with and without a hard anodized coating with a thickness of 50 µm. The surface roughness was measured prior to the test with white-light-interferometry. Experiments were carried out with different frequencies and different normal forces. The test principle and some hysteresis are shown in figure 3.

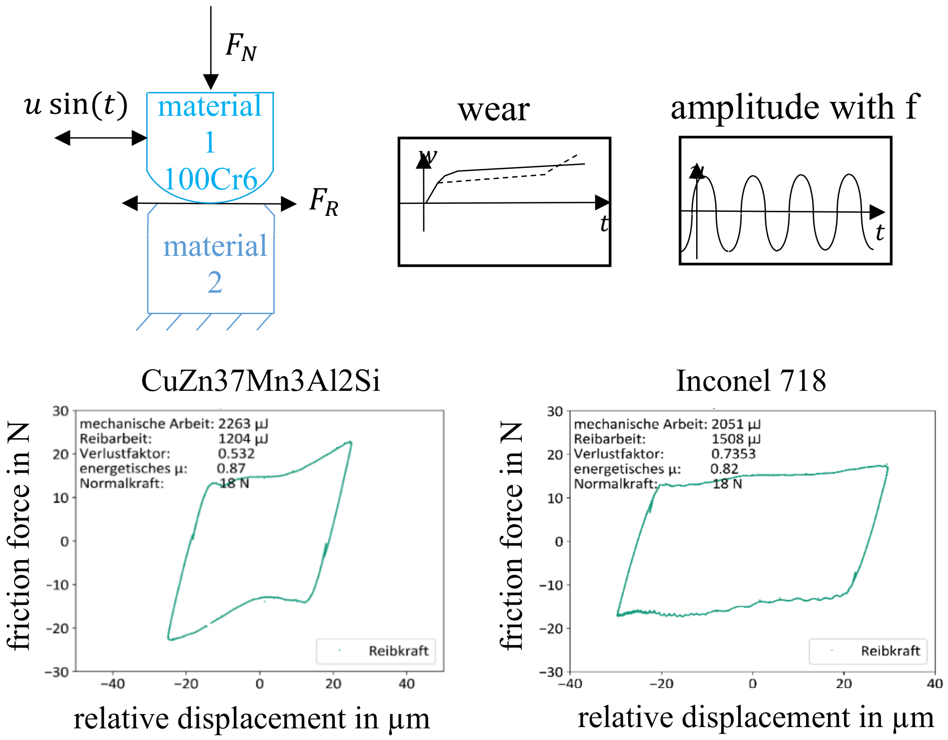


fig. 3: test principle and test examples

A hysteresis is obtained if the friction force is plotted against the relative displacement. In the microslip-regime, this corresponds to an ellipse. If the relative displacements is increased or the normal force decreases, the shape changes to a rectangle, and we enter the macroslip-regime. Since the area of the hysteresis is a measure of energy dissipation, the dissipation is more significant in the macroslip [7]. The wear volume of both samples is determined using white light interferometry. The function of the dissipative elements must be ensured over a product life cycle, such as that of a car and, the wear, therefore, should be as small as possible.

Furthermore, a bolted joint in a dynamically loaded system has a behaviour that must be considered over time. First, as with any other friction defect, friction causes wear. With the wear and the additional relaxation of the bolt, a settling behaviour of the connection results in a decreasing normal force. This means that the shape of the hysteresis is depends not only on the distance between the surface under consideration and the screw but can also change over time, as the following figure 4 shows.

The experiments showed that for a frequency of 30 Hz, a normal force of 20 N (corresponding to 320 MPa hertzian pressure at the start of the experiments) and an amplitude of 30 µm the mean dissipated energy for the different materials varies. The mean value for brass varied between 1200 and 1400 µJ per cycle. For Inconel and the not anodized aluminium the range was between 1500 and 1600 µJ per cycle. The experiments with the anodized had a higher scatter with a variation between 1300 and 1900 µJ per cycle. The experiments were all carried out in the macroslip-regime.

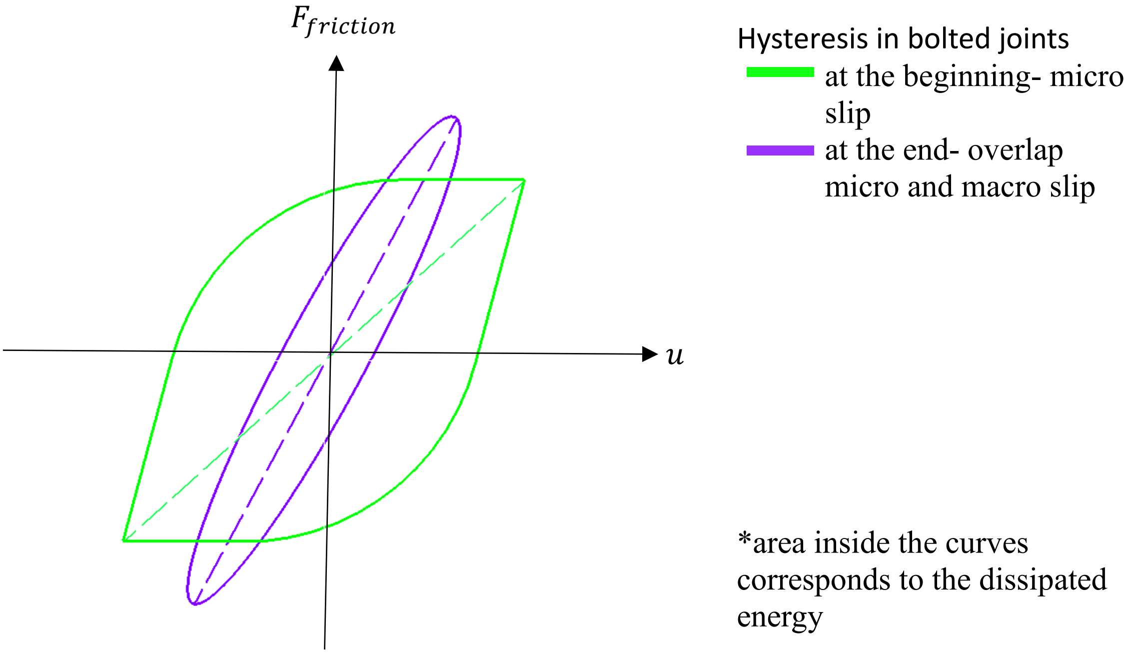


fig. 4: hysteresis in bolted joints at beginning and to the end

4. CONSTITUTIVE MODEL

The constitutive law is defined with the hysteresis data obtained by the previously described experiments. The constitutive law has a velocity-proportional damping, whereby the hysteresis no longer consists only of ideal stiffness in the form of linear ones, but an ellipse is formed. Another characteristic is that stiffness is switched on and off by activating elements via control of the occurring forces. This results in non-linear material behaviour. An ageing parameter differentiates between behaviour in micro- and macro-slip. In this way, a loss of stiffness of the joint over time due to friction and wear can be mapped in the simulation.

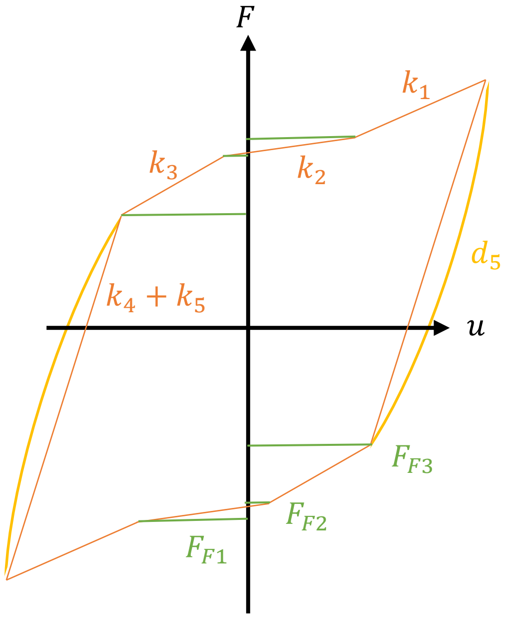


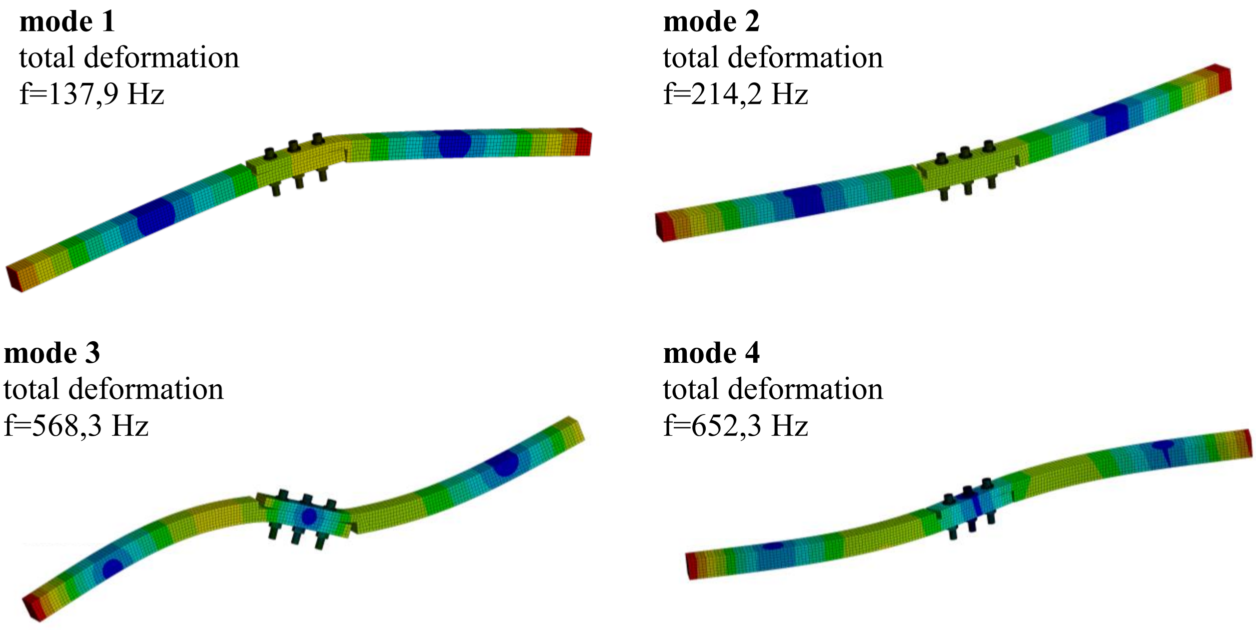
fig. 5: representation of parameters in hysteresis

5. FEM-MODELING

In the simulation, intermediate elements are introduced into the joint, which are implemented with the established constitutive law. Although no new material can be found there in reality, this allows calculating energy dissipations numerically. The intermediate elements are thin-layer elements. This means that they only have a small thickness. The ratio between length and width to thickness can be up to 1000:1 [8]. The TLE are hexahedral elements with an orthotropic constitutive law. In the normal direction, pure linear elastic material behaviour can be assumed. The normal stiffness is many times higher than in the tangential direction. The energy dissipation is mapped in the tangential direction. The TLE's are connected to the friction bodies trough contact conditions such as bonding. In the practical application of the bolted joint, it must be noted that over time the bolts exhibit settling behaviour when subjected to vibration. As it turns out, large relative movements are needed to maximise dissipation. Low preload forces are needed, or other constructive ways must be found to make this possible. The FEM allows finding places of large relative displacements before manufacturing the part and thus considering the energy dissipation early in the development process.

6. VALIDATION

Experiments validate the FEM-model. A transfer of the small-area contact from the fretting tests to a two-dimensional contact is created by Validation. In the first step, a beam system called the Brake-Reuss-Beam is considered. [9]. Two L-shaped beams are connected via bolts. The number of bolts and their pretensioning forces have an influence on the pressure distribution in the connection and, thus, on its damping behaviour. The beam investigates whether the damping is proportional to each natural frequency (see fig. 2) or whether the joint damping varies for each mode. The vibration modes are considered. In the first two modes, large vibration movements are found in the area of the joint. In contrast, vibration minima are found in the joint for modes three and four. Thus, the beam can be used to prove whether the damping is effective for each mode or not (fig. 6).



mode 1
total deformation
f=137,9 Hz

mode 2
total deformation
f=214,2 Hz

mode 3
total deformation
f=568,3 Hz

mode 4
total deformation
f=652,3 Hz

fig. 6: modal analysis of Brake-Reuss-Beam

Furthermore, the contact pressure distribution in the joint can be measured by pressure-measuring foils. Based on the number of bolts, the effect can be measured either by a bolted joint itself, or an overlap in the case of several bolts, to get a correlation between the pressure distribution and the damping.

In contrast to the beam, plates oscillate more due to a lower mass-stiffness ratio. Therefore, the possibility of achieving large relative movements is more significant. Therefore, in the second stage, a plate system is considered which consists of a base plate and the corners are connected to each other via connecting plates. This creates a new level in which relative movements are deliberately permitted. The following figure shows the validation level two and an oscillating form of it.

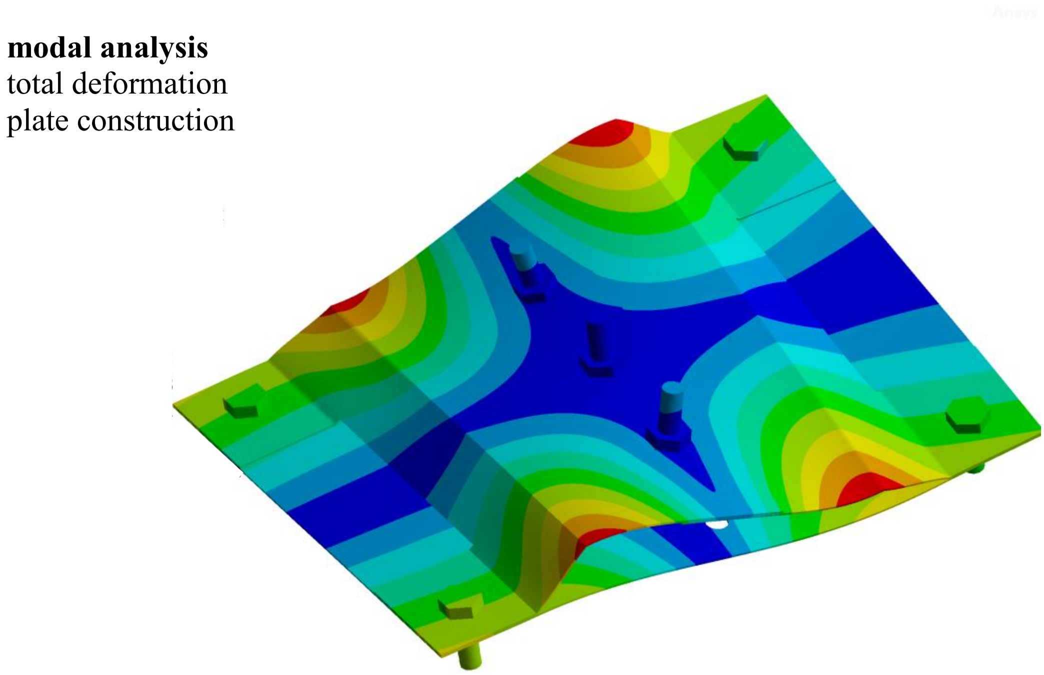


fig. 7: validation level two and a vibration form of it

Validation level two also allows different vibration shapes, the number of screws, and their preload (i.e., contact pressure) are to be investigated. In validation experiments, an impuls excites the system and its response is recorded during a swing-out test. For the hysteresis measurement, the measurement is made via a shaker whose force is recorded, and with the help of two measured vibration accelerations, the hysteresis can be formed.

7. CONCLUSION

At the end of the research project, the goal is to ensure that the additional friction elements do not increase the mass of the system of already existing structures and thus eliminate the need for components such as an additional mass.

With the help of joint damping, vibration amplitudes can be reduced due to energy dissipation through relative movements. Wear occurs due to friction. The wear stabilises after a running-in period, so joint damping can be used in practice. The greater the relative movements in the joint, the more energy can be dissipated. The combination of screw connection and relative movements has the risk of the screw loosening over time. This mechanism must be counteracted constructively. Approaches are being developed for this, which will be published at a later date.

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