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DESIGN OF A SENSOR FOR MEASUREMENT OF BOLT PRETENSION

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Abstract
The article discusses the issue of strain gauges sensors for measuring bolt pretension. The aim of the research is to determine negative effect of both low rigidity of joint contact surface and uneven layout of contact force on the accuracy of measurements. In the conclusion, design alterations of the sensor and a new principle of measurement for elimination of these negative effects are proposed.

Key words: *strain gauges; bolt pretension; sensor; screw.*

INTRODUCTION

Bolt connections are arguably the most commonly used type of mechanical connection. However, in some fields of technical practice these connections must meet particularly high technical requirements. These are the so called critical connections *(Zhu, et al., 2017)*, where these connections are subject to great pressure and temperature load, or alternating temperature in the operation exerted by external forces *(Začal, 2016)*. Furthermore, the specific tightness given by standard *(ČSN EN 1591-1, 2015)* must be met. In addition, these connections might pose a threat to both lives and the environment. In order to satisfy all these requirements, a number of experimental measurements needs to be conducted, so as to determine the actual magnitudes of bolt pretensions. This needs to be done at various combinations of tightening torque, lubricant, types of screw washers, material of the bolts, technology of manufacturing of the thread etc. When a suitable method is applied, the friction factor under the screw and in the thread, can be found from the bolt pretension as well. A tensometric sensor was developer for this purpose. After calibration of the first design, the sensor appeared to be fully operational, despite the low credibility of the measured data when compared to the practice.

In the article, the design and operation of the sensor are described, as well as the analysis of the measurements, identification of the error and its eliminations. The results are supported by graphs and figures.

MATERIALS AND METHODS

Firstly, a sensor of a simple cylindrical geometry was proposed. On the outer side of the cylinder, four foil resistance strain gauges for measuring of stress-strain were attached, which were subsequently plugged into a measuring bridge according to Wheatston *(Hoffmann, 1989)*. The calibration was conducted on a tear machine, where ten levels of compression force in the interval of 40 to 400 (kN) were exerted on the sensor. The maximum measurement deviation *(Bernard, 1999)* was 8.7 (%) and corresponded to the lowest level of compression (Fig. 3, A). In greater strain, the magnitude of the measurement devitation can be considered tolerable, given the anticipated strain in the practice, where the expected magnitude of measured pretension in a bolt is greater than 100 (kN). The proposed sensor, therefore, satisfied all the requirements. However, the sensor was designed only as a part of a testing device (stand). In reality, the sensor was placed between two steel plates, that were then drawn to each other using bolts. After a series of measurements of the magnitudes of pretension in bolts, the resulting values appeared to be lower than expected. Thus, it was apparent, that the stand significantly influences the results. This was concluded on the assumption that as a result of uneven contact areas of the sensor and in the connected parts, a change of strain flow can be observed (Fig. 1). In the left-hand and right-hand side of the picture, there is an example of symmetric strain and of the strain on uneven contact area respectively.

Subsequently, the sensor was again calibrated, this time together with the testing device. The error of the sensor's measurement was as high as 16.7 (%) (Fig. 3, B), and it did not fall below 10 (%) (Fig. 3, B) in any of the levels of compression. The effect on the results was also due to a slight rotation of the sensor (Fig. 3, C). Therefore, a control of the sensor's geometry was conducted using three-dimensional measuring mechanism, in which values of planarity, perpendicularity and parallelism were ensured. Nevertheless, the functional areas of the sensor did not show any malfunction. After a further analysis of the tightening, a slight rotation of the contact area was exhibited, as a result of incorrect construction of the testing device. Furthermore, a significant and uneven compression damage was of contact areas of the steel plates occurring, as they had been manufactured from a steel of low rigidity. The impact of the rotation of the parts of the testing device can at least partially be eliminated by a suitable modification the shape of the sensor. By means of symmetrical narrowing of the casing, such point is created in which tension, arising as a result of added bending from uneven contact of the contacting areas.

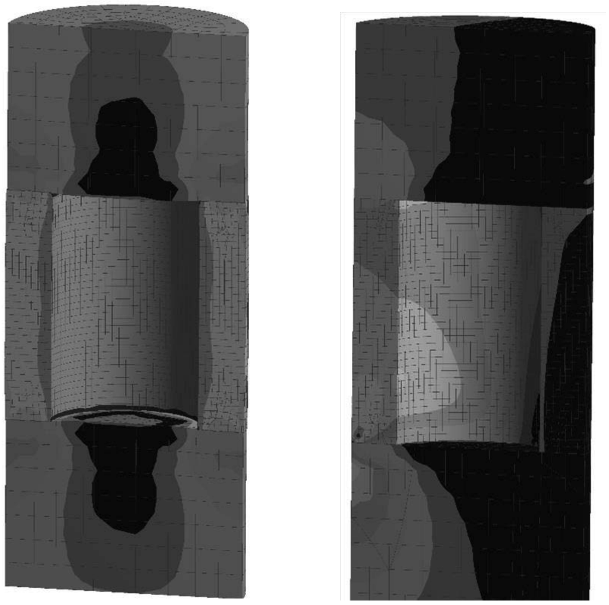

Fig. 1 *The change in the strain flow on the sensor of a cylindrical shape.*

Using the FEM calculation (in ANSYS Workbench R18.0 Academic), several different geometries of the sensor were tried. It was shown that symmetrical reduction of the casing from outer and inner side is the the optimal modification of the shape (Fig. 2).

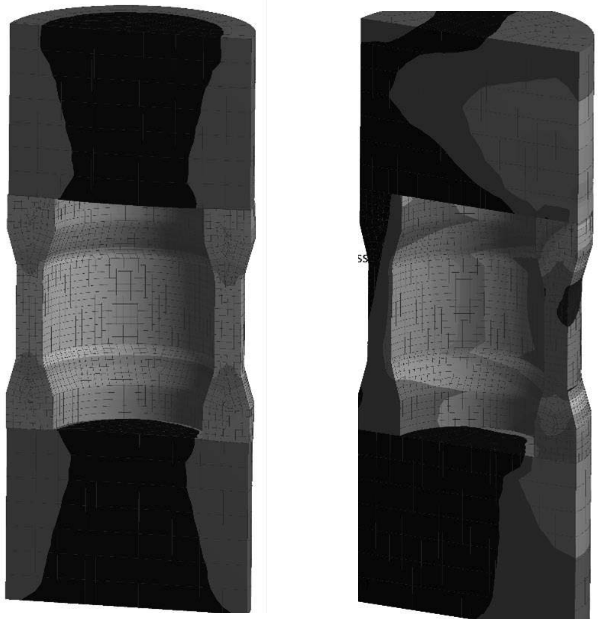

Fig. 2 *The change in the strain flow on the sensor with shape modification.*

However, even here a complete elimination of the uneven contact surface was not achieved. For better elimination of these impacts, the sensor would need to be longer, which would in this case not be possible. The given size of the unevenness of the contact areas in the FME calculation was 0.5 to 1 (mm).

Subsequently, the sensor was manufactured according to the new construction (Fig. 2). This time, four strain gauges of the XY type T/Rosette were used. Two of them were attached to the outer side of the casing on the opposite sides. Remaining two strain gauges were attached opposite to them from the inner side. Foil resistance strain gauges were again plugged in the Wheatston bridge. Owing to this configuration, both the bending of the coating and the effect of the temperature can be compensated. Moreover, amplification of the signal from strain gauges increased measurement sensitivity were also achieved. Calibration of the new sensor exhibited significant improvements of the results, even in case of it's inserting into the stand. However, the measurement devitation was still found around 3.5 (%) (Fig. 3, D) and was substantially determined by the change of the position of the sensor. It was, therefore, necessary to verify the impact of the compression damage of soft contact surface of the stand. Areas with damaged surface due to compression were removed by machining and then hardened washers were inserted into them.

RESULTS AND DISCUSSION

The final modification of the shape of the sensor led to further reduction of the measuring devitation (Fig. 3, E). Due to the modification of the contacting areas, manipulation of the sensor is enabled without causing indefinite change of measurement properties of the sensor. However, the precision of the sensor strongly depends on following certain conditions. Its dimensions limit the range of use in terms of size of the used bolts, and by that the magnitude of the measured pretension in the bolts. Reliable results can only be guaranteed only for clamping force exceeding 80 (kN). Furthermore, either sufficiently hard contacting areas or elimination of any source of uneven strain need to be ensured.

Considering these limits. it can be concluded that the use of resistance gauge strains for sensors of pressure force is not suitable. Modification of the contacting areas to a spherical shape can be considered, however precise manufacture would be demanding and expensive. Thus, it is proper to consider a completely different principle of the measurement. The principle of magnetostrictive sensors might be a possibility. As a result of deformation arising as a result of acting external forces, a change of permeability of the ferromagnetic is observed. Thus, the inductivity changes, which can be evaluated using methods of the measuring bridge *(Hoffmann, 1989)*. However, the design of such sensor needs to be subjected to thorough experiment. Further method of measurement is utilisation of hydraulic or pneumatic mechanism. Measured parameters would be shifting or change of pressure, and would then by converted to the magnitude of the bolt pretension.

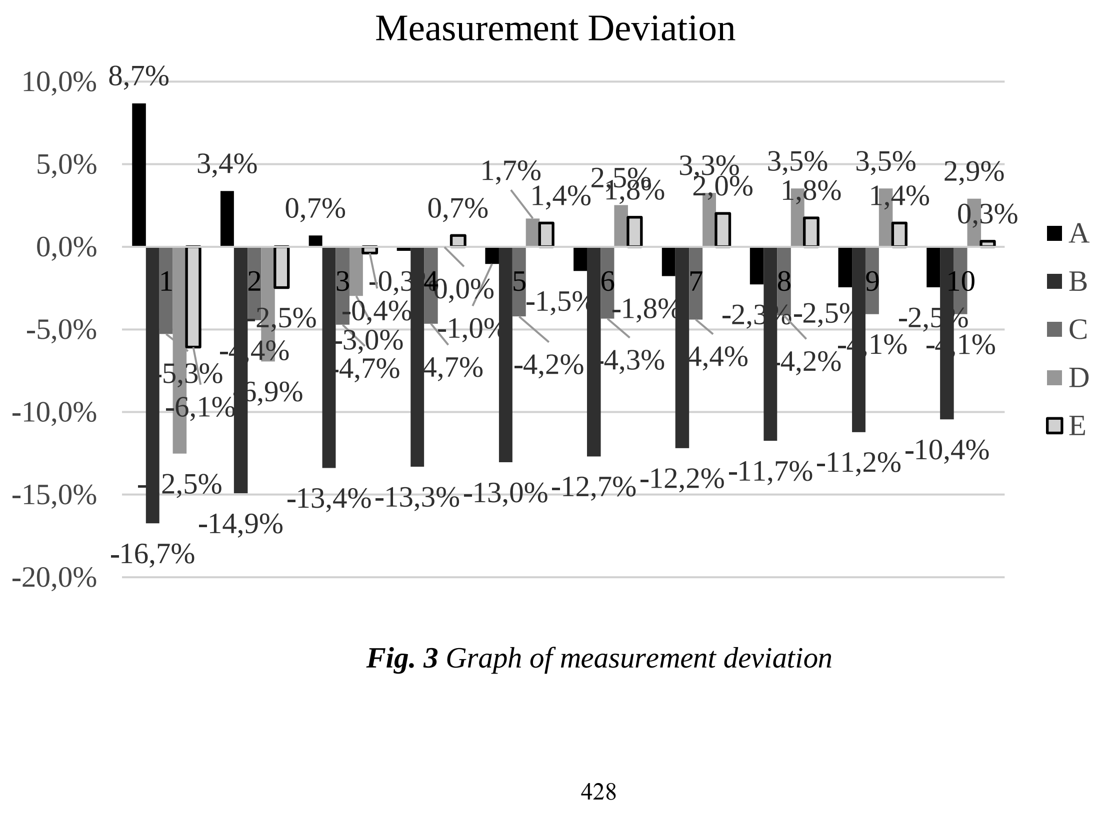

Fig. 3 *Graph of measurement deviation*

Fig. 3 shows the results of all measurements. In Tab. 1 is a detailed description of the groups in which the measurements were divided.

Tab. 1 Detailed description of measurement groups.

Measuring group	Measurement process
A	Measurement with a cylindrical sensor situated in the tear machine.
B	Measurement with a cylindrical sensor situated in the testing device (stand).
C	Measurement with a cylindrical sensor situated in the stand, after a change of the position of the sensor.
D	Measurement with shape modification sensor without hardened contact surfaces.
E	Measurement with shape modification sensor but with hardened contact surfaces.

CONCLUSION

It was shown that the design of the strain-gauge resistance sensor for measurement of the pretension in bolts is largely complex. This is, in particular, if the relative high precision of its measurement (up to 3 %) is required in a large strain interval. Based on the measured data and empirically observed phenomena, a modification of the original sensor with a simple cylindrical geometry was introduced in a way, that enables improvement of the measurement precision. It was proven that unmodified cylindrical shape is unable to satisfy the requirements of the sensor. The resulting evaluation of the data (Fig. 3) was proceeded by a series of experimental measurements on a universal tear machine, where various combinations of strain, sensor area and pressure-force distribution were tested. Subsequently, the causes of the experimental error were determined. These were then at least partially eliminated.

Nevertheless, the conditions under which the resistance strain-gauge sensor is able to produce precise measurements are too limiting. Considering these limits, new and more suitable principles of measurements were introduced, The most suitable principle seems to be the one of magnetostrictive sensor. However, it is necessary to verify everything by experiment.

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