EAN 2018
56th conference on experimental stress analysis

Use of Notches in the Shafts Loaded by Torque for Improvement in Accuracy of Strain Gauge Measurements

LOPOT František[1, a], DUB Martin[1,b], JANDA Martin[1,c] and BERKA Ondřej[1]

[1]Czech Technical university, Faculty of mechanical engineering, Technicka 4, 166 07, Praha, Czech Republic

[a]frantisek.lopot@fs.cvut.cz, [b]martin.dub@fs.cvut.cz, [c]martin.janda@fs.cvut.cz

Keywords: notch, strain gauge, stress, torque, FEM, measurement, gearbox efficiency

Abstract. One of the decisive factors for the sensitivity of the strain gauge instrumentation is the sensitivity of used strain gauges. For foil strain gauges, we talk about 1 μm / m [1]. This value is reached for steel components at a stress of about 2 MPa. It can be understood as a limiting one in terms of reliable detection. Since the ideal value of strain in the practical measurements for commonly used foil strain gauges should be about +/- 0.15 % for the wire versions and circa 0.1 % for the semiconductor versions, we talk about 20 - 25 MPa on the surface of measured steel component when the final error can theoretically decrease below 1 %. However, many engineering applications are out of this range and thus the uncertainty of the results is significantly growing. Especially in direct detection of torque on the gearboxes shafts in order to determine their mechanical efficiency, this is crucial. Generally, as well as in the case of the mentioned gearboxes, a certain possibility of solving the above mentioned problem is offered by constructional and technological notches in which the mechanical stress is locally concentrated. There are many various approaches available to estimate the rate of increase in local tension against nominal values on smooth surface of stable cross-sections, unfortunately without determining of the location of calculated extreme value. This is why we work with finite element method that eliminates mentioned drawbacks and allows us to reliably apply the direct strain gauge measurement in applications with extreme demands on accuracy of results as the mentioned efficiency of gearboxes is.

Introduction

One of the decisive factors for the sensitivity of the strain gauge instrumentation is the sensitivity of used strain gauges. For foil strain gauges, we talk about 1 μm / m [1]. This value is reached for steel components at a stress of about 2 MPa. It can be understood as a limiting one in terms of reliable detection. Since the ideal value of strain in the practical measurements for commonly used foil strain gauges should be about +/- 0.15 % for the wire versions and circa 0.1 % for the semiconductor versions, we talk about 20 - 25 MPa on the surface of measured steel component when the final error can theoretically decrease below 1 %. However, many engineering applications are out of this range and thus the uncertainty of the results is significantly growing. Especially in direct detection of torque on the gearboxes shafts in order to determine their mechanical efficiency, this is crucial. It is, therefore, desirable to detect the transmitted loads with the highest possible accuracy. Generally, as well as in the case of the mentioned gearboxes, a certain possibility of solving the above mentioned problem is offered by constructional and technological notches in which the mechanical stress is locally concentrated. In literature [e.g. 2, 3], there are many various approaches available to estimate the rate of increase in local tension against nominal values on smooth surface of stable cross-sections, unfortunately without determining of the location of calculated extreme value. This is why we work with finite element method that eliminates mentioned drawbacks and allows us to reliably apply the direct strain gauge measurement in applications with extreme demands on accuracy of results as the mentioned efficiency of gearboxes is.

Motivation

In frame of preparatory conduct in a suit between a supplier and its client on reconditioning of his manufacturing line, evaluation of the true mechanical efficiency of the line driving unit became necessary. The reason for that requirement were repeated problems with motors overloading after replacement of the gearbox done during the partial manufacturing line reconditioning. The first stage of the gearbox is realized by curved bevel gearing. The second stage is planetary with three planets and fixed crown wheel with straight teeth. Power from the first stage is brought to the sun wheel. With regard to the closed setup of the line and practical impossibility to shut down the line for a longer time (already interval of a few hours was unacceptable), it was not possible to use a conventional torque sensor and direct measurement of the gearbox shaft used instead.

Measurement was performed on smooth surfaces of the in- and outgoing shafts. The finite elements method was used here merely to check that vicinity of notch and clutch hub placement either would not affect the measurement. Nevertheless, results of the FEM computations suggested that by exploitation of stress concentration in notches, measurement accuracy could be effectively increased. The presented work deals with this idea and proposes a way how to work with the FEM computation to prevent its becoming a source of uncertainty in processing of measured data and its evaluation.

Method

For the given task, an experimental shaft was made of standard construction steel (ČSN: 11523/EN: S355J2/W.Nr: 1.0579) according to Fig. 1.

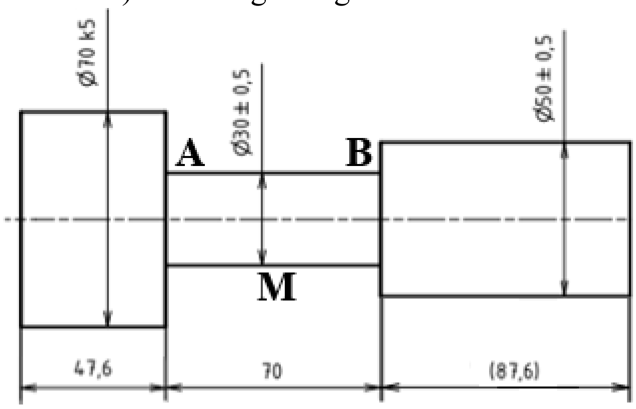

Fig. 1 Drawing of the test shaft (cut-out from the drawing)

The given shape was selected to correspond to notch on the shafts of the above described gearbox and accounted also for chucking jaws of the lab stand. Diameters of the tested shafts are four-times smaller than those of the measured gearbox. Surfaces were turned with high accuracy with roughness not exceeding Ra1,6.

Fig. 2 shows arrangement of the measurement station. The torque was induced by placing a load on the revolving segment arm of the test stand.

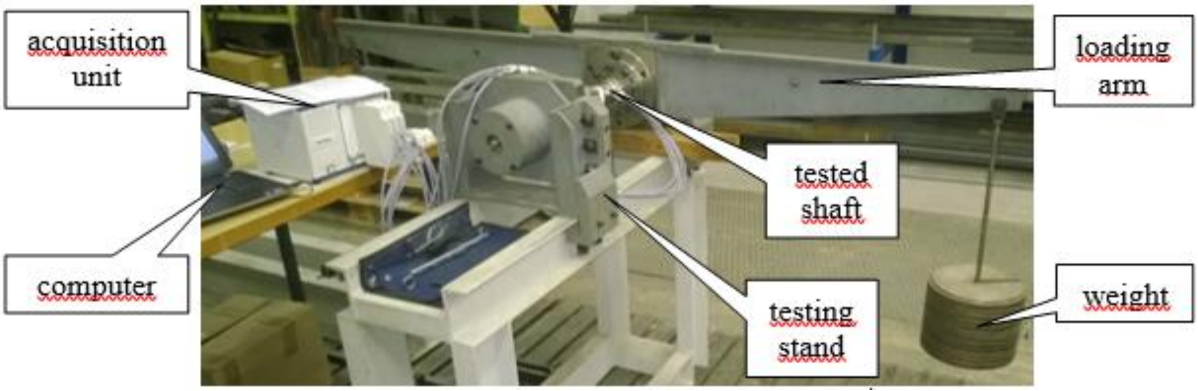

Fig. 2 Measurement work station setup

Standard foil strain gauges 1-XY21-1,5/120 (HBM) connected in complete Wheatstone bridge were used to avoid signal distortion by a possible effect of flexion (bending). Measurement instrumentation was set using components made by National Instruments and Dewetron connected to a standard PC. At that stage, the aim of the measurement was to verify the outcomes of the FEM calculations.

Two computational finite element models were prepared and used. Both FE-models have the same geometry corresponding to the experimental shaft and use a linear elastic isotropic homogeneous material. The calculation conditions correspond to a static linear task. The first 3D model works with A 20-node quadratic brick elements, the second 2D model uses An 8-node generalized biquadratic axisymmetric quadrilateral elements [4]. Both models are based on a method of reduced integration. Boundary conditions are defined using coupling constraints, when one end of the model is clamped and the other is loaded by torque. Fig. 3 enables quick comparative visualization of both models.

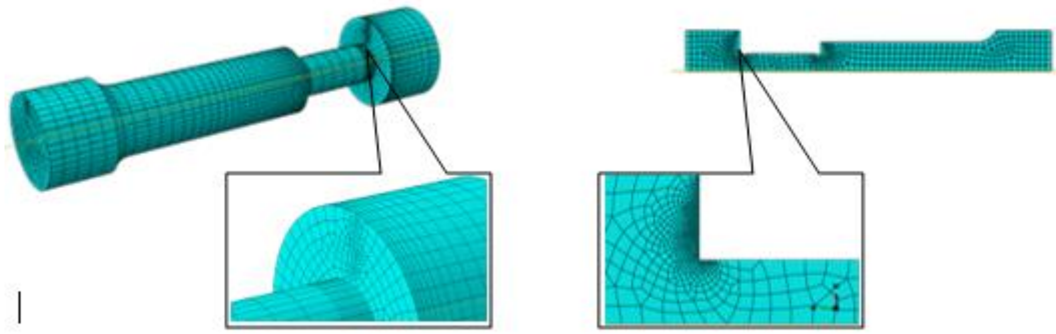

Fig. 3 3D (left) and 2D (right) model of the shaft

The 3D model was created and used mainly as a golden FEM standard for a 2D model as it corresponds very well to a real shaft without significant simplifications. However, because tuning of the 3D model has high demands on computational power and time and because the subject of investigation are shafts loaded by a torque detected by a possible bending effects eliminating instrumentation, only the 2D model was used after verification further.

The following procedure documents how to identify that the mesh and other settings correspond to the investigated situation and that the results obtained are reliable. Fig. 4 displays course of the stress caused by a given torque in dependence on mesh parameters for a site of 30 mm in diameter located between notches (see also Fig. 1).

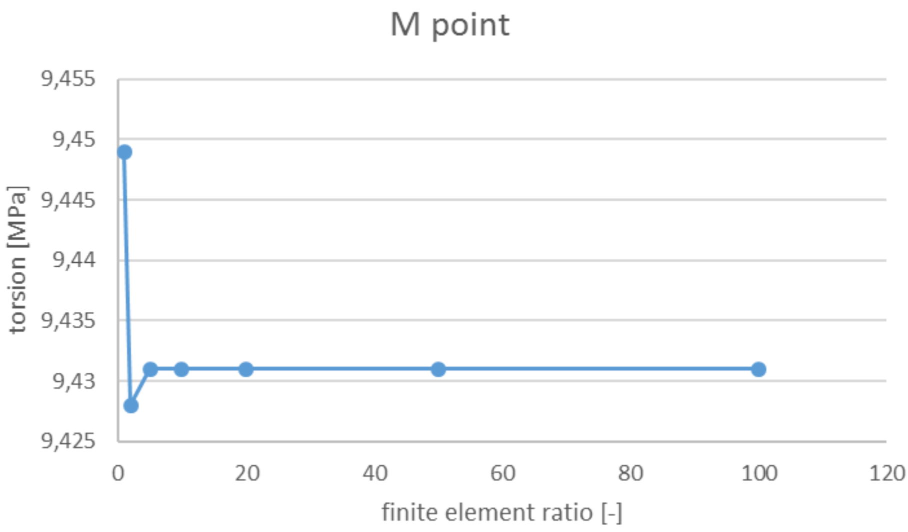

Fig. 4 Cylindrical section of 30 mm in diameter: stress vs. the element size
(finite element ratio = size of the biggest element / actual size of the local element)

From the course it is apparent that value stabilization is achieved already with the first mesh refinement.

Fig. 5. Displays the dependence for the notch A, left (according to Fig. 1), i.e. at shaft shoulder from 70 to 30 mm. Values for the plot are taken always from the same site of the model, once a fixed interface – user node - with regard to the initial geometry has been created. This user node is at a distance of 0,5 mm from the front plane of the shaft shoulder and the value corresponds to localization of the active area center of the glued-on strain gauge.

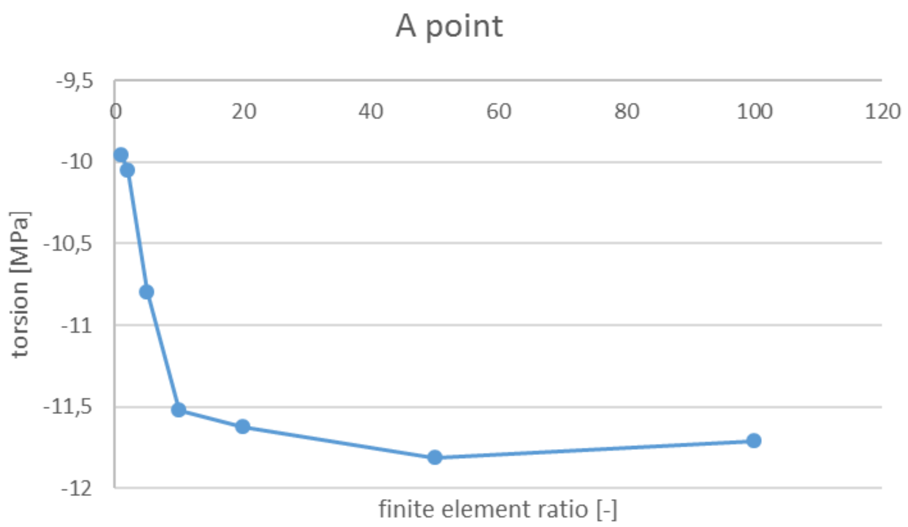

Fig. 5 Notch A, shaft shoulder 70 per 30 mm: stress vs. the element size
(finite element ratio = size of the biggest element / actual size of the local element)

Value stabilization is more gradual here – its dependence on the element size is therefore more significant than in case of a smooth cylindrical element. This effect can be expected. However, of note is “oscillation” of results around the equilibrium in dependence on the element size.

The same effect can be seen also in notch B on the right side (according to Fig.1), as is depicted in Fig. 6.

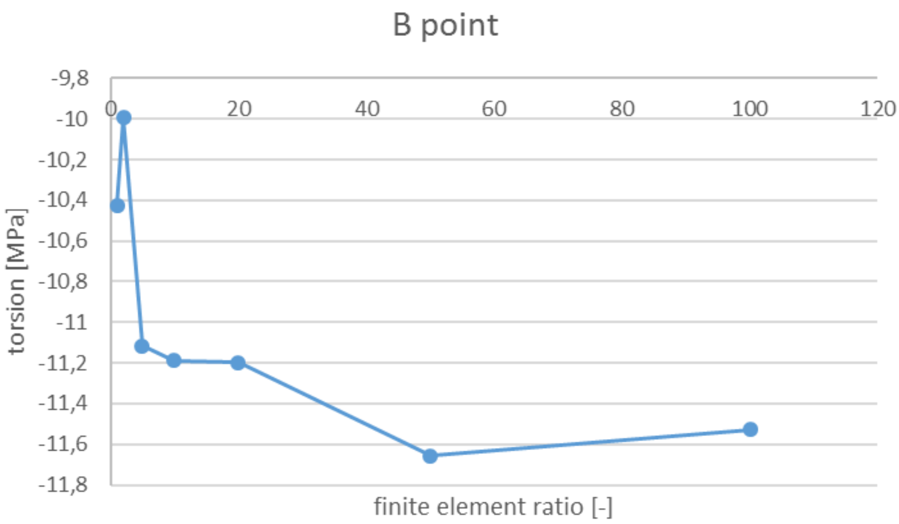

Fig. 6 Notch B, shaft shoulder 30 per 50 mm: stress vs. the element size (finite element ratio = size of the biggest element / actual size of the local element)

Results

Fig. 7 illustrates character of the obtained results. As the object of the evaluation, the course of the stress in the investigated section of the tested shaft and its FE-models with notches for selected torque loading of 50 Nm was studied.

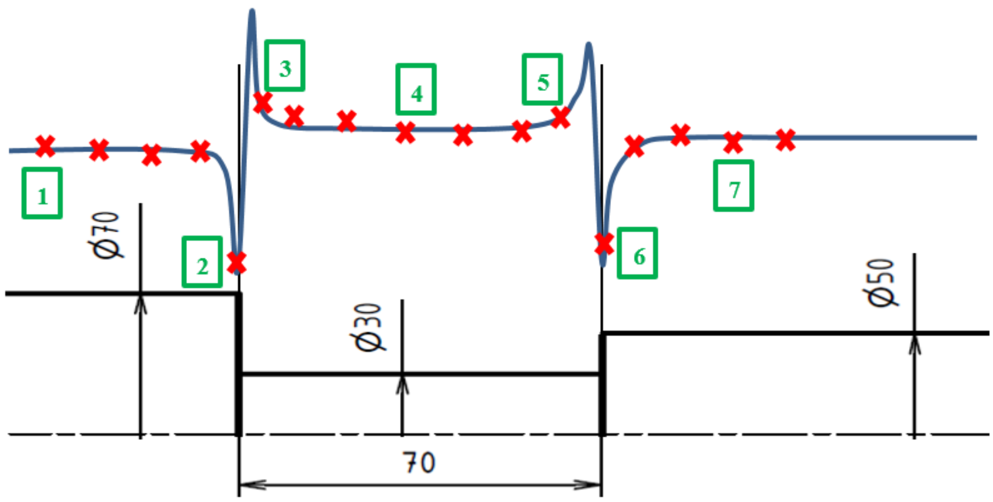

Fig. 7 Results (illustrative course of stress: x – experimental data; - - FEM)

In Tab. 1, the numerical values of the stress found by the FEM and by measurement for the selected load torque value 50 Nm are presented. For illustration of relevance of these data, both the analytically calculated values for smooth cylindrical sections of 0,742 Nmm^{-2} for Ø70, resp. 2,037 Nmm^{-2} for Ø50, resp. 9,431 Nmm^{-2} for Ø30 and Neuber's coefficient 3,16 are shown for easy comparison.

Table 1: Results (average values; position acc. to Fig. 1)

Position	1	2	3	4	5	6	7
	[N/mm^2]	[N/mm^2]	[N/mm^2]	[N/mm^2]	[N/mm^2]	[N/mm^2]	[N/mm^2]
FEM	0,744	0,000	11,740	9,431	11,636	0,000	2,039
Experiment	0,732	0,000	11,775	9,424	11,656	0,000	2,031

In the notch A and B, respectively, the stress value is 1,245- and 1,233-higher, respectively, than in a smooth cylindrical segment. Considering absolute measurement error of 2 MPa, the relative error in detection of torque, which induces the given signal, will be 1,245- and 1,233-times lower, respectively, than the relative error in measurement on a cylindrical section.

Discussion

Reaching of equilibrium of the stress value in a selected site is suggested as a sign of a sufficient refinement of the mesh to obtain relevant results applicable for placement of strain gauges for practical measurements and calculation of torque on the assessed shaft. The issue for discussion is thus mainly the oscillation of the calculated stress around the apparent equilibrium point (Fig. 5 and 6). This phenomenon can be caused by the above described definition of the user node for the site at which the evaluated stress value is to be read. The reading is taken always at the mesh node, the mentioned user node can possibly induce the mesh deformation at that site and induce some error. In 3D modeling, this problem is going to be solved by application of the so called truss elements, by means of which the length of the active strain gauge part could be effectively simulated. The read value would be an average of nods of the area defined in this way. This approach appears close to reality and should thus function well. If it does not prove to be feasible, it is still possible to adjust the condition for the mesh settings and for the recalculation of values use the equilibrium around which the calculation values would oscillate. More appropriate approach can be decided upon by an experiment.

Conclusions

The main aim of our contribution was to prove good agreement between appropriately set FEM and experimental data on basis of which a correct setting of the mesh in the model used can be defined.

On the basis of the above mentioned results obtained so far, the following conclusions can be formulated:

- Good agreement between measured data and FEM has been confirmed, for other measurements smaller strain gauges are required.
- The 3D FE-model generates usable results for the strain gauge area only after the mesh is very carefully set up.
- The 2D FE-model with axisymmetric elements generates usable results for the strain gauge area with less carefully adjusted mesh; this model is definitely the approach of choice in gearbox transmission efficiency tasks.

Despite some drawbacks, regarding the facts mentioned above, we believe that our approach extends the use of strain gauge measurements to the field of direct data detection for precise applications, like e. g. for measurement of mechanical efficiency of transmissions.

References

[1] Information on: https://www.hbm.cz/wp-content/uploads/s3996.pdf

[2] Information on: https://www.efatigue.com/constantamplitude/stressconcentration/

[3] Information on: https://babel.hathitrust.org/cgi/pt?id=uva.x000261815;view=1up;seq=1

[4] Information on: http://abaqus.software.polimi.it/v6.14/books/usb/pt06ch28s01alm01.html