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Possibility of Using of Tensometry in Deformation Analysis in Areas With Sudden Change of Geometry

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Abstract In the process of design of machines and equipment high attention has to be given to structural notches, defects of materials and surface quality, because they have high impact to their fatigue strength. In the paper is presented proposal of methodology concerning deformation analysis near stress concentrators by using strain gages. The experimental measurement was realized on bended U-shape specimen with notches. The results gained by experimental measurements were verified by numerical modelling by the finite element method.

Keywords: *stress concentrator, tensometry, finite element method, strain gage*

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1. Introduction

Nowadays, big attention is given in machinery to optimization of shapes and geometry of machine parts as well as machines and equipment in order to decrease their weight under the same strength and stiffness parameters. The geometry of machine part can have discontinuities such as holes, notches, slots and so on, which can lead to the local increasing of stress. Stress concentrator is in called a notch. In the design process, special attention has to be given to these elements, because they significantly decrease their toughness against fatigue damage. Increasing of local stress level leads to the creation of fatigue cracks. The notch can be characterized by so-called shape coefficient, which is defined as ratio of maximal to nominal stress. The shape coefficient takes into account increasing of stress level due to local geometry of body, as well as due to local changes of force flow in the body. It has to be mentioned that in such context, only one component of stress is increased [1,2].

The values of shape coefficients for individual loading types and sudden geometry changes are bases of theory of notches and shape toughness of bodies. As a rule, not only notches are considered for these computations, but also all locations, where the machine part changes their properties, stiffness, or where it has various discontinuities. The notch influences are also visible in surface layer that has decreased stiffness, and as a rule, irregular microgeometry. The structural notches, defects in material and surface undulation have big influence to the fatigue toughness of bodies. To this time, we considered only linear stress states in bodies. The most values of α, especially in case of cracks, defects and sharp technological notches is bigger than $\alpha = 2$. Because the dimensioning of machine parts is mostly based on safety measures with respect to the yield point and such safety is not bigger than 2, it is obvious that in small locations of material plastic deformations occur [3].

The presence of various nibs, delves, holes, notches and further sudden geometry changes invokes very complex stress distribution in comparison to machine parts of simple shapes. The local increasing of stress is this influence in many situations expressed by shape coefficient [1,4,5]

$$\alpha = \frac{\sigma_{\max}}{\sigma_{nom}} \quad \text{for normal stresses,}$$

and

$$\alpha_t = \frac{\tau_{\max}}{\tau_{nom}} \quad \text{for shear stresses.}$$

2. Proposal of Methods for the Analysis of Stress Gradients Near Notches by Tensomery

In the paper, the attention is given to analysis of stress and strain distribution near U-shaped notches in specimen loaded by bending moments. The dimensions and shape of test specimen is given in Figure 1. The strain gage method was chosen for stress and strain analysis.

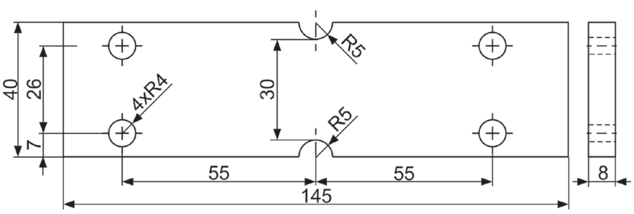

Figure 1. Dimensions and shape of test specimen

2.1. Basic Principles of Tensometry

The measurement of strains goes out from the presumption that the deformation of object is transferred to the strain gage. The condition for that is a strength connection between strain gage and measured object. In many cases, the measurement can be accomplished only on free and loading free surfaces of measured objects. The desired strength connection between measured object and strain gage can be realized by special glue recommended by producer. The work of metallic strain gages is based on Wheatston and Thomson effect of dependence of strain on electric resistance in electric wire. Every electric wire changes its resistance due to mechanical loading. The resistance of the wire changes during its deformation and the change depends on change of wire length ℓ, cross-section area A and specific resistance of wire ρ by relation [6]

$$R = \rho \cdot \frac{\ell}{A}.$$

The deformations measured by strain gage are obviously very small and accordingly small are the resistance changes. They cannot be measured directly by ohmmeter. It is necessary to use so-called measurement chain which allows precise determination of small resistance changes (Figure 2).

The first member of measurement chain is a strain gage. It converts mechanical deformation to change of electrical resistance. The second part is a measurement circuit, where the strain gage is a part of one branch. Strain gage and measurement circuit are passive members in the physical sense. They have to be supplied by energy in order to produce usable signal. This energy is taken from special source. In case, the resistance of strain gage is changed due to deformation, the bridge circuit is not balanced and the change of bridge voltage occurs. This change is proportional to the imbalance of bridge. The third member consists of amplifier, which the output voltage of bridge increases to the value that can be measured. For the linear amplifier is its output voltage proportional to input voltage of amplifier and accordingly proportional to the measured deformation. The fourth member of measurement chain consists of displays. They transform output signal of amplifiers to the usable form. Given description of measurement chain (Figure 2) shows schematically all necessary parts. In practice, the measurement chain consists of various additional parts, e.g. equipment for switching measured location, filters, switchers of maximal values, recorders, and so on. Beside of this, various electronic systems can be used for replacement of displays in order to process data.

2.2. Selection of Strain Gages and Realization of Experimental Measurements

One of the main criterions for selection of sensor is its location on measured object. In case of big enough object, strain gages of optimal length 3÷6 mm can be used from the point of view of quality as well as application. In order to arrange soldering points on the sides of measurement grid we have to take into account available space. The meaning that the sensitivity of strain gage depends on its length is not truthful. The measurement signal from the strain gage is proportional to the relative and not absolute change of length. Accordingly, the absolute length of strain gage has no effect to its sensitivity. Despite of this extremely small strain gages should be used only in locations, where it is necessary from the technical point of view, i.e. for measurement of stress near notches. The producers support us with strain gages of various shapes and dimensions.

Beside of various lengths of measurement grid we can meet different shapes and designs of soldering points. Variety of dimensions and shapes is a result of necessity to arrange measurement to different tasks. The experimenter has to eliminate possible creation of measurement errors with respect to ratio of strain gage length and dimension of part [6,7] that can be seen especially in case of determination of extremal value, or local deformation in inhomogeneous stress field, e.g. in notch. In Figure 3 is shown schematically dependency between measured value of strain and the length of measurement grid. Figure 3 documents that in this case it is useful to use short measurement grids, because long strain gages could measure inappropriate average value.

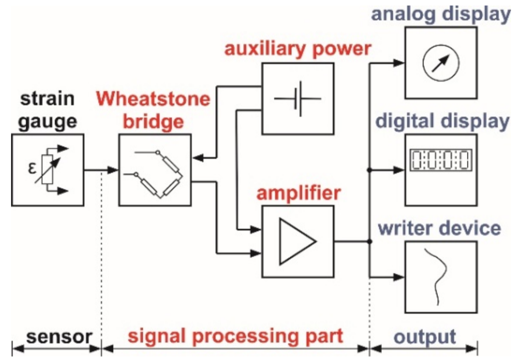

Figure 2. Scheme of measurement chain for the measurement of deformations by strain gages

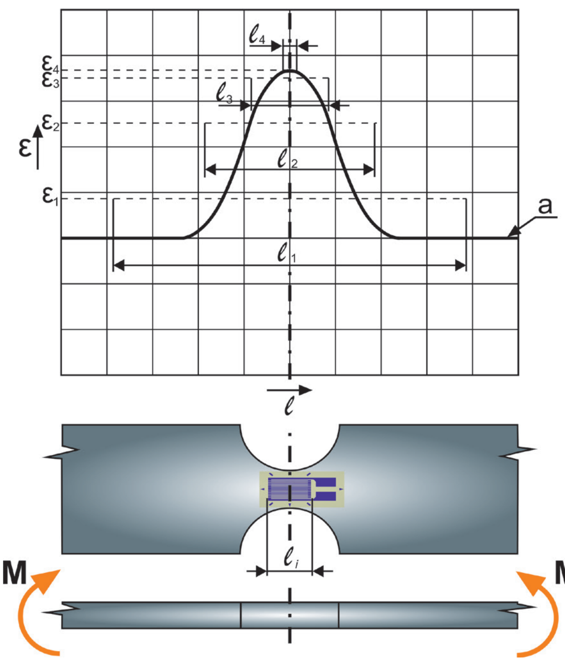

Figure 3. Influence of grid length ℓ_i to the measured value of strain

As we can see from Figure 3, ideal is a grid of null length. However, there exists certain limit. It is possible to produce a strain gage with length 0,2 mm, but the short strain gages lead to problems with transmission of deformation to measurement grid. They are used especially in applications near notches and they lead to big measurement errors. Beside of this, it has to be taken into account that the heat removal from small measurement grid is small. It means that Joule heat created by input current has to be small which has to be taken into account during selection of appropriate energy source

Accordingly, it is necessary to choose suitable length of strain gage. In general, the length of measurement grid should be smaller than one-half of notch radius.

The shapes of strain gages used for the measurement of stress gradient are given in Figure 4. It is typical for strain gage chains that on the end of every chain are a measurement grid which can be used as compensation strain gage.

As was mentioned above, the stress analysis in areas with huge gradient are used strain gage chains where the distances between individual grids are precisely defined. On the basis of author opinions, the strain gage chain KY21-2/120 (Figure 5) consisting of ten grids was chosen with the grids oriented in direction of analyzed specimen axis. The dimensions are seen on Figure 5. The radius of notch is $r = 5\ mm$ and the length of measurement chain is 1,7 mm. Accordingly, the above mentioned rule is fulfilled.

The first measurement grid has to be applied near notch (Figure 6).

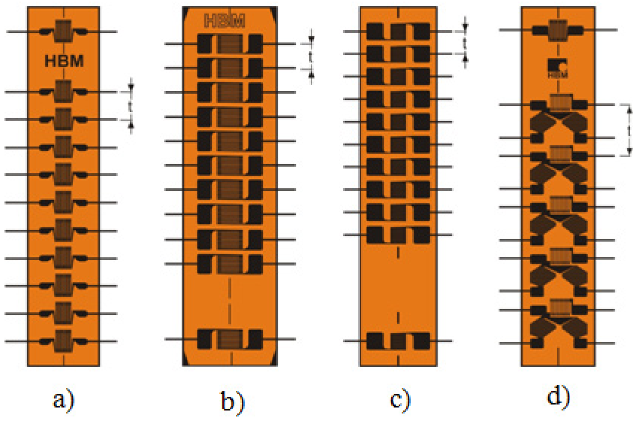

Figure 4. Shapes of strain gage chains. a) direction of measurement grid is parallel with longitudinal axis of chain, b) direction of measurement grid is perpendicular to longitudinal axis of chain, c) direction of measurement grid is oriented parallel or perpendicular to longitudinal axis of chain, d) measurement grids are in groups with three and angles 0°/60°/120° with respect to longitudinal axis of chain [8]

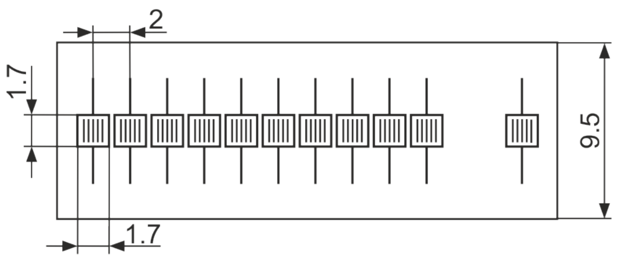

Figure 5. Basic dimensions of strain gage chain KY21-2/120 [8]

In Figure 7 is a view to strain gage with soldered wires. Due to fact that the specimen will be bended and the measurement will be realized in laboratory conditions, the change of temperature is not considered, all sensors were arranged to quarter-bridge.

In Figure 8a is a view on the specimen positioned in loading equipment SCHENCK which serves for loading by bending. Set up of bending moment is ensured by indicating gauge (Figure 8a).

If we know the value of bending moment and quadratic cross-section modulus of area, we are able to determine so-called nominal value of normal stress in bending.

In Figure 8b is given a view to measurement chain with strain gage apparatus P3. The magnitudes of strains in individual measured locations are given in Table 1.

Grafic representation of measured data (Figure 9) documents chart of strains near U-shaped notches.

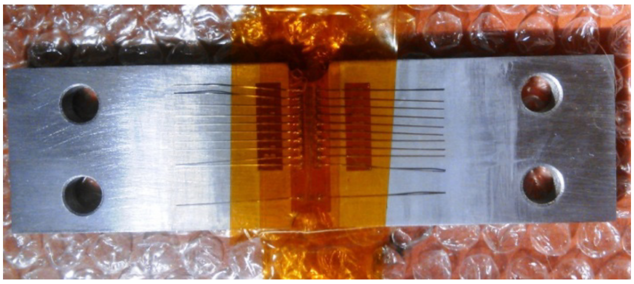

Figure 6. Position of strain gage chain

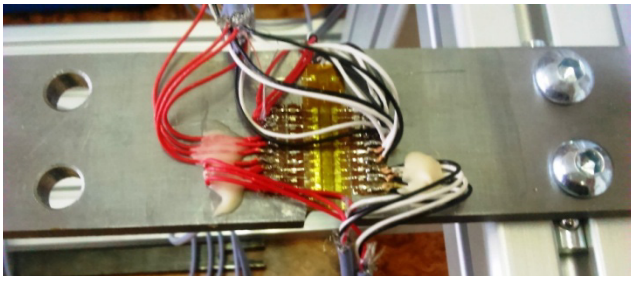

Figure 7. View to applied strain gage chain with soldered wires

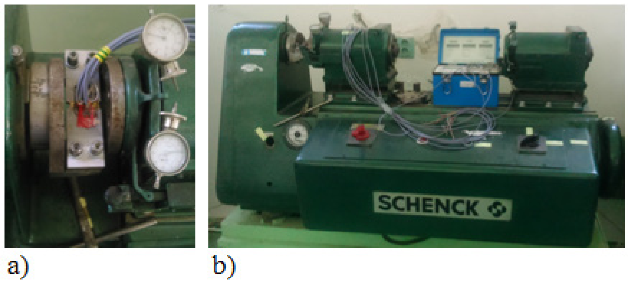

Figure 8. Loading equipment SCHENCK. a) location of test specimen in working space, b) view to measurement chain

Table 1. Magnitudes of measured strains in locations 1 - 10

Measured location	Strain	Measured location	Strain
1	146.4	6	147.9
2	145.2	7	151.4
3	144.4	8	155.2
4	144.7	9	161.1
5	145.8	10	176.9

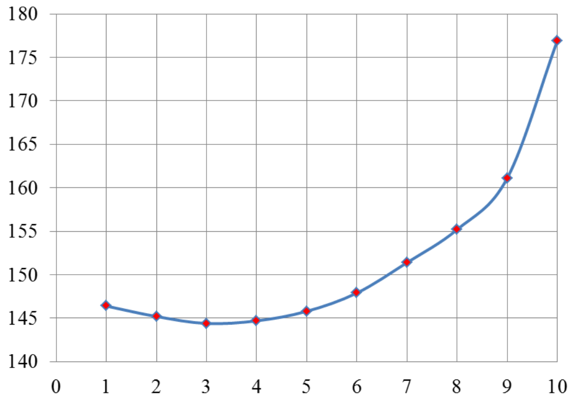

Figure 9. Graphical representation of measured data

On the basis of measured data can be stated that the results confirmed influence of notch to the stress state in their neighbor. The drawback of tensometry is a fact that it could not be possible to measure value on the border of notch. This was a reason for verification of measured data by the finite element method.

3. Stress Analysis Near Notches by the Finite Element Method

Deformation and stress analysis near notch was accomplished by numerical methods. The specimen was modelled as a 3D object the model of which was analyzed by the finite element method (FEM). The boundary conditions were chosen in order to correspond with bending invoked by loading machine SCHENCK, (Figure 10).

For the comparison of result, the strain gages were located in points on the surface of body, (Figure 11). Advantage of numerical simulation lie in fact that the data can be scanned also on the edge of model, sensor in location 11 (notch root).

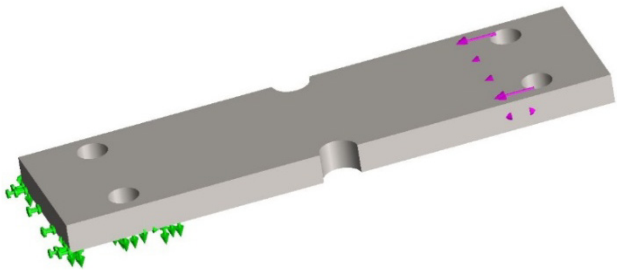

Figure 10. Model of analyzed specimen with boundary conditions

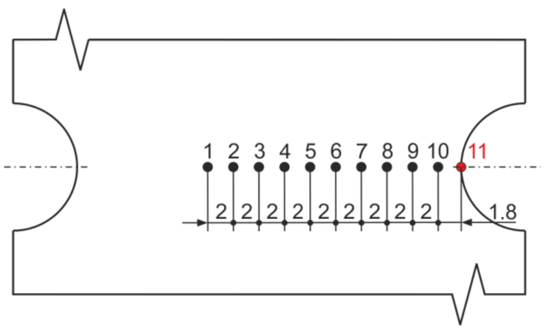

Figure 11. Numbering of sensors on analyzed model

The specimen was meshed consisting of individual finite elements. The mesh of created finite elements with maximal size of 2 mm and refined part in location of sensors (maximal size of element is 0.5 mm) is given in Figure 12. The mesh consists of 105 282 tetrahedron elements with 155892 nodes.

In Figure 13 is shown a field of strains ε_x near analyzed notches. The values are scanned in locations of sensors and they are given in Table 2.

Detail of field of strains ε_x near analyzed notches is shown in Figure 14.

On the basis of comparison of results given in Table 1 and Table 2 can be stated that the proposed method of deformation analysis near stress concentrators was appropriate. This was confirmed by results gained from numerical modelling. The difference in strains on specimen did not exceed 5%.

Figure 12. Meshed model with refined mesh near stress concentrators

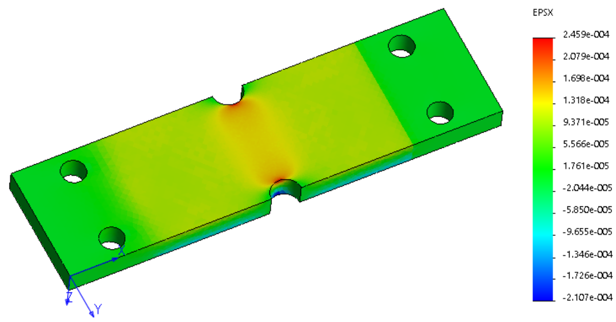

Figure 13. Strain field ε_x for defined loading

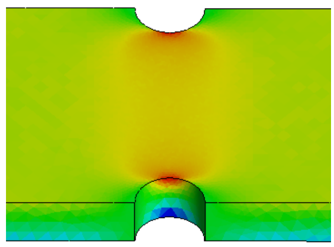

Figure 14. Detail of strain field ε_x near analyzed notches

Table 2. Magnitudes of measured strains in locations 0 - 11

Sensor	Strain [με]	Sensor	Strain [με]
1	142.1	6	143.4
2	140.9	7	145.9
3	140.5	8	149.3
4	140.7	9	154.9
5	141.5	10	169.8
		11	261.3

4. Conclusions

In practice we are many times in situation that we are not able to determine notch coefficient from available diagrams (Peterson diagrams). In such a case the notch coefficient can be determined by numerical modelling, or by experimental measurement.

On the basis of results gained from experiments and from numerical modelling was confirmed that the following rules can be stated for magnitudes and charts of stresses near notches:

- Notches and generally every change in force flow lead to local stress concentration.
- The local stress state is changed near notch to the form of three-dimensional stress state.
- The higher stress concentration, the higher stress gradient, so that their ratio is approximately constant for a given loading type.

Acknowledgements

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