ENCAPSULATION AND UNCERTAINTIES OF STRAIN-GAUGE SENSORS FOR STRESS-MONITORING OF CONSTRUCTIONS

Tegtmeier, F. and Peters, M.

Physikalisch-Technische Bundesanstalt, D-38116 Braunschweig, Germany

ABSTRACT

Strain gauges are an important tool in measuring techniques applied to determine loads and detect damages. Due to their high signal-resolving power, they are also suitable for stress analysis in building constructions. Without specific encapsulation, they are, however, suitable only for short-term measurements.
Therefore, a completely new encapsulation type was developed at PTB. The strain gauges were placed in a sensor housing which protects the sensitive technology - similar to common force transducers - and is fitted into a small measurement borehole of the structure. These applied investigations were part of the work of a collaborative research center of the German Research Foundation.
Based on these investigations, the measurement uncertainty of the sensor will be analyzed and the final design for commercial production and calibration of this new sensor type presented. An additional important result of this research project was the development of a new type of plastic encapsulation for the strain gauges inside that sensor. The encapsulation was tested in thermostatic hot water baths, in climatic chambers similar to those of DIN IEC 68 2-30 and in outdoor tests.

1. INTRODUCTION

In Europe, a sustained structural change is observed in the area of civil engineering and building construction. With above-average growth rates, the redevelopment of buildings has the most important share in building industry. With a total value of the structures available in Germany (almost 20 billion €) and an assumed lifetime between 50 and 100 years, considerable financial requirements for maintenance and redevelopment will have to be met in future. Against this back-ground, a collaborative research centre of the German Research Foundation (DFG) was established at the Braunschweig Technical University whose work is aimed at developing methods and procedures for early structural defect prediction. A particular project is placed at the Physikalisch-Technische Bundesanstalt. For determination of states of stress in the structure and early detection of damages, compact force transducers based on strain gauges were developed to be implemented in the structure in a small measurement borehole. The following tasks had to be performed:

- Determination of a suitable adaptation form for the sensor in the borehole
- Calibration method and determination of the transformation matrix
- Specification of the general conditions such as measurement range and measurement uncertainty
- Development and testing of a measurement method for defect detection
- Verification of sensor and measurement method using dummy structures
- Development of a durable encapsulation

The measurement method, the dummy structures and the concept for adaptation of the sensor inside the measurement borehole have already been presented in former publications /1-2/. The successful completion of this research project was aimed at presenting the measurement uncertainties and the capsulation of the sensor in its final layout.

2 MECHANICAL OUTLINE AND CALIBRATION OF THE SENSOR

The mechanical adaptation of the sensor inside the measurement borehole is decisive for the measurement accuracy. Various concepts were investigated and a process of mechanical distortion of two conical bodies developed so that the useful measurement range covers the range of elastic deformation of construction steels. The principal innovation of the newly developed adaptation model is the edge-shaped form /2/ of the clamped sensor as shown in Fig.1.

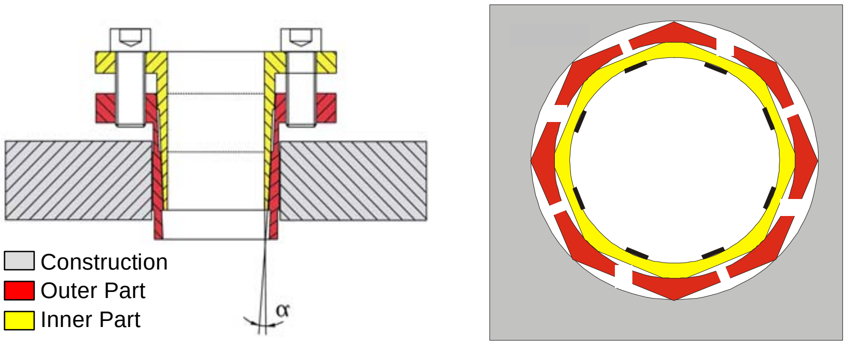

Fig. 1: Concept of the square-shaped sensor

For surface contact at the borehole circumference, the grip between sensor and building sets a relatively low limit for the hysteresis-free measurement range. The radial initial stress caused by the bracing results in a tangential grip which may not be interrupted at any point on the inner surface of the borehole as otherwise hysteresis will occur. The axial, line-shaped contacts shown in Fig. 1 of the angular sensor ameliorate the restrictions in the measurement range of the surface extension transmission described above. The extension is integrated along the circumference between these contact points and transmitted to the inner component with its attached strain gauges. The radial clamping of the line contacts leading to the grip and the tangential elasticity of the sensor were adjusted so that - within the elastic range for steel - an almost hysteresis-free, linear transmission characteristic was achieved.
The relationship between the measuring signals of the sensor and the stress in the borehole area must be defined with the aid of special calibration facilities. For plain stresses, which usually occur in the building environment, a calibration procedure /2/ was developed which uses a wheel-shaped, rotatable calibration body. During the calibration, several base points with different angular positions were measured at constant load. Using the least squares method, sinusoidal functions were fitted to these base points. From these measurement signals $M(\varphi)$ with appropriate principal stresses and their orientations, a characteristic calibration formula may be derived (1)

$$M(\varphi) = C_1 \cdot (\varepsilon_{H1} + \varepsilon_{H2}) + C_2 \cdot (\varepsilon_{H1} - \varepsilon_{H2}) \cdot \cos(2\varphi - \sigma) \qquad (1)$$

Here, M is the measured value of one of three full bridges inside the sensor in mV/V, ε_{H1} the principal strain, ε_{H2} its second component, φ the angle between the principal strain or stress direction and the sensor. C_1, C_2 and ρ are so-called calibration constants of the sensor. As the states of strain in the calibration body are well known, the calibration constants could be established with the aid of the measured sinusoidal function $M(\varphi)$.
With the calibration constants known, the three components of a plain strain distribution could be established in subsequent measurements by solving the system of the three equations of the sensor's measuring channels.

3 MEASUREMENT UNCERTAINTIES OF THE SENSOR

Determination of the measurement uncertainties of the microsensor in accordance with GUM /3/ requires a mathematical model. This is why all relevant uncertainty sources have to be considered in the accompanying model of the relative, composite standard uncertainty. Fig. 2 shows a model of the measurement pass and the uncertainty contributions which are discussed in the following.

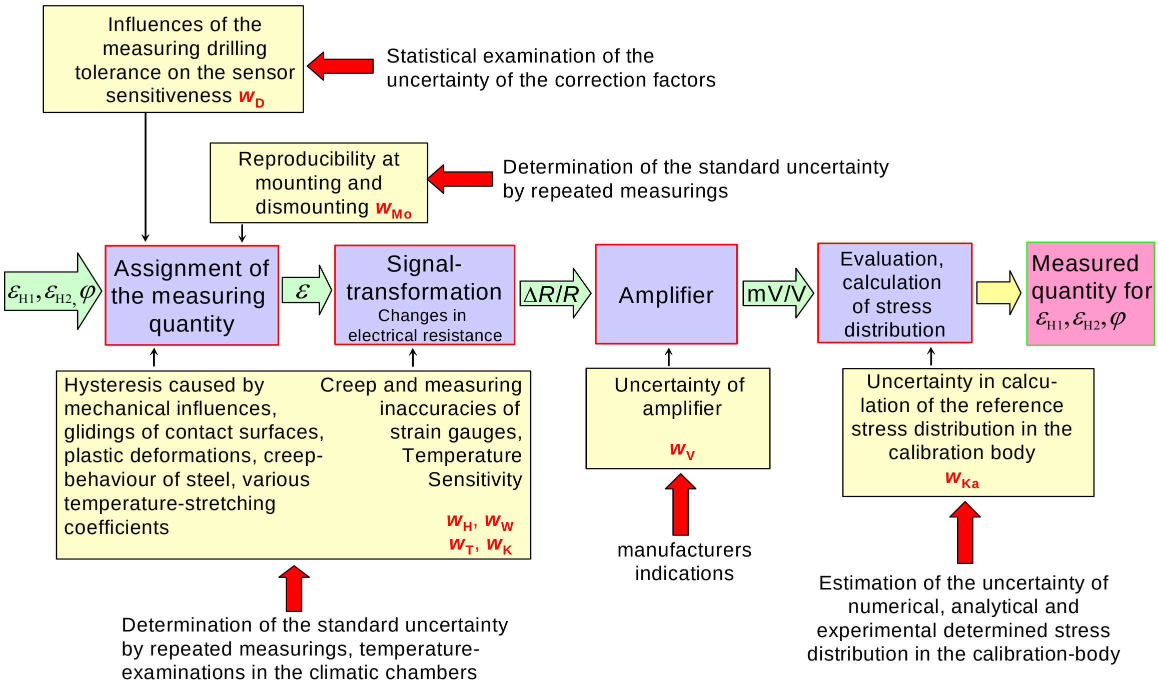

Figure 2: Measurement pass of the multicomponent strain and stress sensor

w_D caused diameter deviation and resulting sensitivity changes

The diameter of the measurement drilling is subject to unavoidable deviations which affect the sensor's sensitivity. For the 18 mm borehole, the adaptation model allows a tolerance range from -0.15 mm to +0.25 mm. To keep the sensitivity deviation small, the diameter of the drilling should be measured and taken into account by a correction factor. To determine this factor, a special tension bar with five different drilling diameters was realized. Then the sensitivity of several sensors was examined as a function of the diameter. For a change of +0.1 mm, a correction factor of 1.063 with a standard uncertainty of 0.011 was determined. For the uncertainties of the diameter of measurement boreholes, a maximum uncertainty contribution of 0.0121 could be established. To obtain a lower uncertainty, the borehole should be prepared with a reamer to a H7 tolerance (DIN ISO 286) which results in a variation of the diameter of about 0.01 mm. According to practical experience /3, chapter 4.3.9/, a technical production tolerance of this kind is actually like a triangular distribution which may be assumed as a safe approximation of a normal distribution. According to /3/, the uncertainty contribution is calculated to be 0.00143, caused by sensitivity changes due to a diameter deviation of 0.01 mm. To reduce the uncertainty, it is planned to use a reamer to obtain a more precise measurement result.

w_H and w_W , reversal error and repeatability

The mechanical assignment of the strain from the measurement borehole to the strain gauges inside the sensor housing is affected by uncertainties. Microscopically small plastic distortions in the contact area have also to be taken into account as negligibly small gliding effects at the friction-locked contact areas. In addition, the internal part of the sensor shows a slightly non-linear behavior and hysteresis due to the high pre-stress. The strain gauge and the adhesive layer also contribute to the measurement uncertainty by creeping and non-linear elastic behavior. The uncertainty contributions resulting from this are described as hysteresis or reversal error and w_W stands for the repeatability in the uncertainty model. The quantities of w_H and w_W were determined in repeat measurements. 16 sensors were tested seventy times. These examinations were performed with a maximum strain of 2.7 ‰. The average reversal error relating to the maximum signal was 0.0044, with a variance of $4.3 \cdot 10^{-6}$. The relative hysteresis in the range above 10% of maximum load (2.7 ‰) was to be lower than 0.0083. The average repeatability was measured to be 0.00086 and always lower than 0,0015.

w_K signal creeping

Temporal changes of the measuring signal may be established also at constant load of the sensor. To examine this creeping, sensors were assembled in the load bars described before and loaded for some days with constant strength in a force standard machine. To check the changes in the zerosignal after several load cycles, load bars were tested in hydraulic load facilities over a few thousand load cycles. As the result of these investigations, a normal distribution with a relative standard deviation of 0.011 for w_K has been taken into account.

w_T uncertainty caused by temperature fluctuations

The uncertainty caused by temperature changes is based on two mechanisms. The strain gauge shows a temperature sensitivity and both steel types (sensor and building structure) have a different thermal expansion coefficient. The temperature influence on the signal of the special strain gauge as described before was examined in tests in climatic chambers. The influence of the steel combinations for sensor and construction was calculated and measured. The results of the temperature sensitivity were obtained as a normal distribution over a temperature range; in 99 % of the cases, they lay within ±25 °K of the average temperature. After addition of their variances, all influences together cause a standard uncertainty of 0.0029.

w_{Mo} uncertainty due to the assembly process

The assembly and disassembly process for installation of the sensor in the calibration body and, afterwards, in the measurement borehole in the building involves another uncertainty contribution. Its uncertainty contribution was statistically determined by repeat measurements. For this purpose, different sensors were repeatedly mounted in the round calibration body. After each assembly process, a set of new calibrating equations as described in chapter 2 was determined. The variance or standard deviation of their calibration coefficients was empirically determined. The relative standard deviation of fault-free sensors was for all three calibrating constants lower than 0.004.

w_{Ka} uncertainty caused by examination of the calibration constants

To be able to determine the three components of a plane tension or stress distribution, the calibration constants of equation (1) must be known. Their knowledge, is, however, affected by an uncertainty. Examination of the calibration constants is influenced by the uncertainty of the mounting process, by the repeatability of the measurement of single base points for the sinusoidal function during the calibration process, and it is especially influenced by the knowledge of the exact plain stress distribution of the calibration body, while the stress distribution was numerical simulated, analytically calculated and measured with strain gauge. Each single result was compared with the results of the other concepts to estimate the uncertainty of the realized reference-stress-distribution. Its variance was added to the variances of mounting and the sinusoidal function was estimated using 36 base points with different angular positions of the calibration body. For w_{Ka}, an uncertainty of 1.58 % was obtained.

Model of the relative, combined standard uncertainty

The sensor could be used for two different applications: to compare the signals of different sensors for the differential measuring /1/ method in order to detect damages like scratches or material weakness or for strain and stress analysis in the structure. For both ap ications, a combined standard uncertainty should be calculated.

When the sensor signals are compared with each other with the aid of the differential measurement method, only the repeatability and the reversal error have an effect on the measurement result. Knowledge of the exact stress distribution is not necessary, because only changes in the relation between the signals of different sensors are recorded. The two uncertainty contributions for this application have a normal distribution and a sensitivity coefficient of about one. So their variances could be simply added, and the combined standard uncertainty amounts to approx. 0.0045 in a deformation range up to 2.7 ‰. The uncertainty model using the sensor for strain and stress analysis is more complex. All contributions as described before show a normal distribution or have been accuracy-approached to the distribution according to GUM /3/. The influence of the uncertainty of the calibration constants C_1, C_2 and ρ on the combined standard uncertainty has, however, to be discussed for the non-linear part of the equation. The cosine term must particularly be taken into account. In the end, to obtain an accuracy model for the uncertainty, it was decided to linearize the non-linear equation system at the point of the circular function, where changes in ρ have the largest effect on the measurement result. This largest possible uncertainty was adapted in a linear uncertainty model. As usual for uncertainty models of force transducers, the uncertainty components were introduced into the mathematical model as correction factors (4).

$$E_{\mathrm{BS}} = E_{\mathrm{Anz}} \cdot c_{\mathrm{i}} \prod_{i=1}^{N} X_{\mathrm{i}} \qquad (2)$$

E_{BS} being the measurement result of the building sensor, E_{Anz} the so-called observed quantity at the output device, the best known estimated value which ideally corresponds to the true value transferred by the measuring chain by the average of a variety of multiple observations. This observed quantity is multiplied by the correction factors X_{i} and the sensitivity coefficients c_{i}. By this, the accompany-ing uncertainties exert an influence on the sum model of the combined standard uncertainty. The single correction-factors X_{i} are listed in Table 1:

Table 1: Uncertainty contributions

Correction factor	Uncertainty contribution and causation		Estmated value	Sensivity coefcient	Distribtion function	Rel. standard uncertainty contribution
X_1	w_{Mo}	Assembly process	1	1	Normal	0,0058
X_2	w_{D}	Tolerance of borehole	1	1	Normal	0,0014
X_3	w_{H}	Reversal error	1	1	Normal	0,0044
X_4	w_{W}	Repeteability	1	1	Normal	0,0009
X_5	w_{K}	Signal-creep	1	1	Normal	0,0110
X_6	w_{T}	Temperature-influence	1	1	Normal	0,0029
X_7	w_{M}	Amplifier	1	1	Normal	0,0003
X_8	w_{Ka}	Calibration	1	1	Normal	0,0158

The uncertainty model of the relative combined standard uncertainty for the sensor is defined by the following equation (3). With the values listed in Table 1, w_E is approx. 0.0208 for a long-term stress analysis. For a short-term analysis with-out influences of creep and with known temperature, the combined standard uncertainty is approx. 0.0173.

$$w_{\mathrm{E}} = \sqrt{w_{\mathrm{MO}}{}^2 + w_{\mathrm{D}}{}^2 + w_{\mathrm{H}}{}^2 + w_{\mathrm{W}}{}^2 + w_{\mathrm{K}}{}^2 + w_{\mathrm{T}}{}^2 + w_{\mathrm{M}}{}^2 + w_{\mathrm{Ka}}{}^2} \qquad (3)$$

4 ENCAPSULATION OF THE STRAIN GAUGES

A permanent enclosure of the strain gauges for protection against external influences must be guaranteed to ensure a useful life adapted to the structure. State-of-the-art for such a capsulation is a metallic, hermetic encapsulation. This way, the cone point of the sensor's inner part with the strain gauge inside is laser-welded with a thin steel foil. A glass lead-through for the wiring could not, however, be realized in such a small size. Therefore, some special plastics were used. However, nearly all plastics allow considerable water diffusion (a 20 g sample of conventional silicon rubber absorbs, for example, up to 0.5 g of water). So it was necessary to protect the strain gauges with an additional inner capsulation. Different coating materials were therefore tested in a temperature-regulated water bath. The strain gauges provided with protective coatings were mounted on a refined steel plate. A great number of rubber types, acrylates, epoxy resins and wax layers were investigated. In addition to the water bath, the above test samples as well as sealed sensors incorporated in tension bars were tested in air-conditioned test chambers.

These investigations were based on DIN IEC 68 2-30. Between the climatic test cycles, the sensors incorporated in the tension bars were additionally tested in a force standard machine for changes of their zero signals and sensitivities. Test plates were also exposed to outdoor climatic influences on the roof of a building to determine correlation with artificial aging in the water bath. The results show a factor larger than 200. These investigations are aimed at predicting a reliable service life.

To protect the strain gauges against humidity, a layer comprising polymethyl-methacrylate (PMMA), a humidity-resistant adhesive from dentistry and a butyl rubber surface layer have proved to be suitable. Of particular importance for permanent enclosure of the strain gauges is the boundary layer between special steel and sealing compound. The PMMA reacts above all with the oxides of the metal which in the case of special steels are, however, available only to a very limited extent. For special steels, the bond of the adhesive is therefore mainly based on van-der-Waals forces. These are sensitive to the highly polar water and infiltrated in the long term. For a permanent, chemically stable bond between stainless steel and PMMA, special adhesion catalysts are required which contain a mercapto group for the steel and a vinyl group for the adhesive as active bonding agents. Another problem to be solved was the polyethylene insulation layer of the wiring. Moisture may diffuse along the isolation. As a consequence, the wires are now stripped down to 5 mm and tinned. Coating the tin with adhesion catalysts as for stainless steel is advantageous for the expected lifetime. In addition to the protective layer on the strain gauge, the sensor is completely filled with a special grease which is impermeable to water. All the efforts described for encapsulation ensure an estimated lifetime of more than 30 years. Great effort is still involved in the manufacture of the protective layer. To reduce this effort, new plastics, which were developed for the protection of moisture-sensitive organic LEDs, and which will simply be painted on the strain gauge, are at present being tested.

CONCLUSIONS

The sensor enables long-term stress analysis with a combined standard uncertainty of approx. 0.0208. The durability of the encapsulation is guaranteed by detailed examinations. With the successful realization of the new sensor type, the research project at PTB in cooperation with the German Research Foundation has now been concluded. The sensor is patented and will be manufactured in license. The investigations into new plastics for strain gauge capsulation as used for OLEDs will be continued in cooperation with the Braunschweig University.

REFERENCES

[1] F.Tegtmeier, M. Peters: "Determination of structural damage to buildings using microsensors based on strain gauge technology“, Proc. of the XVI IMEKO World Congress, Vienna, September, 2000,pp. 25-28

[2] F.Tegtmeier, M. Peters: “Multicomponent Sensor for Stress Analysis in Build-ings”, Proceedings of the International Conference of IMEKO TC3, TC5, TC20; Celle, VDI reports 168 (2002),

[3] Deutsches Institut für Normung eV "Leitfaden zur Angabe von Messunsicherheiten“ German translation of the "Guide to the Expression of Uncertainty in Measurement (GUM)“, Beuth Verlag, Berlin, ISBN 3-410-13405-0, 1995

Addresses of the Authors:

Dipl.-Ing. F. Tegtmeier, Prof. Dr.-Ing. M. Peters, Divison 1 "Mechanics and Acoustics“,
Physikalisch-Technische Bundesanstalt Bundesallee 100, D38116 Braunschweig, Germany,
Phone Int +49 531 592 1122, Fax Int +49 531 592 1105, E-mail: falk.tegtmeier@ptb.de